

Universidade de Évora - Instituto de Investigação e Formação Avançada

Programa de Doutoramento em Ciências da Terra e do Espaço

Área de especialização | Processos Geológicos

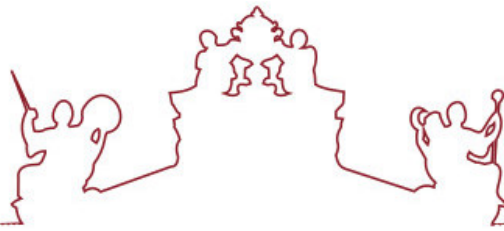
Tese de Doutoramento

**Geology of the Clarion-Clipperton Zone: Fundamental
Attributes in Polymetallic Nodule Resource Development**

John Michael Parianos

Regime Especial de Apresentação de Tese
Évora 2021





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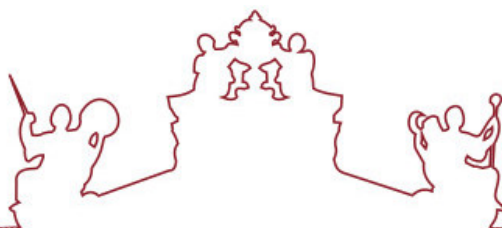
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A tese de doutoramento foi objeto de apreciação e discussão pública pelo seguinte júri nomeado pelo Diretor do Instituto de Investigação e Formação Avançada:

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Abstract: Geology of the Clarion-Clipperton Zone: Fundamental Attributes in Polymetallic Nodule Resource Development

The Pacific oceanic plate segment known as the Clarion Clipperton Zone (CCZ), contains polymetallic nodules of superior consistency, tonnage and quality, to those known from other deep seabed areas.

Regional scale mapping reveals structural and geomorphological features that result from variance in plate segment motion rates, and other trans-plate factors, which help to contextualise and better define the environment and exploration potential of this deposit.

Exploration survey datasets from the central and eastern parts of the CCZ area allow for local geological mapping that contribute to regional models on nodule formation and distribution. Stratigraphically, basement abyssal hills include flatter areas with chain(s) of volcanic knolls. Mid Eocene and younger deep-sea chalks of the Marquesas Formation, include fault escarpment exposure, potholes and "carbonate strata breccias". Early Miocene to present silicious clay-ooze of the Clipperton Formation show surficial development of ripples, slumping and sediment drifts. The clay-ooze hosts the deposit of polymetallic nodules. Unconformable volcanic rock units include single and composite knolls, seamounts, dykes and sills.

Nodule forms and abundance relate to the facies scale conditions of their formation. The thickness and stability of the geochemically active layer is shown to play a crucial role on their growth. Multielement chemistry indicates differing metal contributions from silicic versus calcic primary productivity. This study confirms nodule densities, host clay-ooze bulk densities and packing densities, as well as moisture content. Moreover, it is shown that nodule handling forms attrition fines that may affect safe transport at sea.

Mineral resource estimation is important to resource owner and developers. Further conversion of mineral resources to reserves requires multidisciplinary modifying factors, which include: logging of fauna; concepts behind a nodule collection system; and pyrometallurgical experiments. This study aims to improve the resource classification of the CCZ deposit in specific contract areas of the International Seabed Authority.

Resumo: Geologia da Zona de Fratura de Clarion-Clipperton: Atributos Fundamentais no Desenvolvimento dos Nódulos Polimetálicos como Recurso Geológico

A área do fundo marinho conhecida por zona de fratura de Clarion-Clipperton (CCZ), no Pacífico, alberga um depósito de nódulos polimetálicos de tonelagem e qualidade superiores quando comparado com outros depósitos minerais do oceano profundo.

A cartografia à escala regional permite reconhecer estruturas e características morfológicas que resultam da variação da taxa de alastramento do fundo marinho, bem como de outros fatores que afetam a evolução da CCZ e que contribuem para definir com mais detalhe o potencial envolvido na prospeção daquele depósito mineral.

Os dados recolhidos no decurso de campanhas conduzidas nas zonas central e oriental da CCZ permitem realizar cartografia geológica que contribui para a formulação de modelos regionais para a formação e distribuição dos nódulos polimetálicos. Estes ocorrem associados à formação de Clipperton, com idade entre o Miocénico inferior e a atualidade.

Neste trabalho é particularmente evidenciado o papel da espessura e estabilidade da camada geoquimicamente ativa no crescimento e forma dos nódulos, bem como da sua distribuição. A geoquímica multi-elementar indica diferentes contributos da produtividade primária (siliciosa versus carbonatada) para a distribuição dos diferentes metais que constituem os nódulos. Neste estudo são, igualmente, estabelecidos valores para diferentes parâmetros físicos relevantes para as atividades de prospeção, como sejam a densidade dos nódulos e dos sedimentos argilosos onde ocorrem.

A classificação e estimativa de recursos minerais é relevante quer para as entidades que detêm a jurisdição sobre esses recursos quer para as entidades interessadas no seu desenvolvimento. A conversão de recursos para reservas minerais requer a aplicação dos designados por modifying factors, os quais incluem, entre outros: a descrição da fauna, o conceito associado ao desenvolvimento de colectores, testes pirometalúrgicos. Este trabalho pretende melhorar, de forma significativa, a classificação de recursos da CCZ em áreas associadas a contratos administrados pela Autoridade Internacional dos Fundos Marinhos.

Keywords: Clarion Clipperton Zone, regional geomorphology, geological mapping, polymetallic nodules, nodule geochemistry, mineral resource estimation, resource reserve modifying factors

Extended Abstract

The stratigraphy and setting of the Clarion Clipperton Zone (CCZ) oceanic plate segment controls the formation and distribution of a major seabed mineral deposit, specifically manganese-nickel-copper-cobalt nodules. Such polymetallic nodules are found in all the world's oceans, but the CCZ deposit has consistency and quality superior to the others. The CCZ deposit lies in international waters and is currently the subject of development, conservation, and regulatory efforts at the multinational level.

The CCZ is a plate segment of Pacific Ocean crust that has been spreading west-southwest since the Cretaceous era, but is moving overall to the northwest, and is interacting with the plate segments adjacent to the north and south. 1:4,000,000 scale mapping of the entire segment is based on GEBCO bathymetry in conjunction with limited 12 kHz bathymetry, magnetic isochrons and other data. Variances in plate segment motion rates, and other trans-plate factors, manifest in regional scale structural features and geomorphological features (including units of abyssal hill plains, abyssal hill lows, abyssal hill highs, troughs, a step, fault zones, seamount chains and small rifts). The extents, ages and features of each mapped unit help contextualise exploration in that area. Many nodule development priority areas are located at certain unit contacts, due perhaps to depth changes versus the lysocline, or influence on seabed currents.

States parties to the United Nations Convention on the Law of the Sea can sponsor public or private groups or enterprises. These "Contractors" may apply to the International Seabed Authority (ISA) for approval of plans of work for exploration for mineral resources (such as polymetallic nodules). A typical first pass survey involves ship based 12 kHz multibeam echosounder (MBES) coverage of contract areas. Second and subsequent surveys often include more detailed sonar and photographic data collection (from a deep towed system or autonomous underwater vehicle) and sampling of the seabed and water column. Local scale (1:250,000) surface geological mapping is presented from the areas of three Contractors in the central and eastern parts of the CCZ. It is based on MBES bathymetry and backscatter, supported by side-scan sonar and sub-bottom profiler, seabed photos and nodule and sediment samples. This results in seven discretely mapped areas, each with distinctively different geology, even though they are all fundamentally composed of sediment coated basaltic abyssal hills.

Within the CCZ, abyssal hills typically range between 1 and 5 km frequency, 50-300 m amplitude and 5-100 km in strike but in some areas can double or even triple those dimensions. The hills form both full and half-type horst-grabens, with side slopes that can include rocky fault escarpments. Most mapped areas have at least one topographic break between generally higher and lower abyssal plains, that in some cases correlate with the regional scale geomorphological units. Some areas have localised expression of secondary orientations of abyssal hills, and others flatter areas of seafloor with subdued to absent abyssal hills. The flatter areas can be associated with a chain(s) of volcanic knolls and presumably higher heat-flow.

Overlying the basaltic basement is 75-100 m of mid Eocene and younger deep-sea chalks of the Marquesas Oceanic Formation. This unit formed above the calcite lysocline on the equatorial carbonate mound and was transported northwest with plate movement to its present position below the calcite lysocline and near the calcite compensation depth. This formation is occasionally exposed in escarpments, in the side of potholes and as shoaling outcrops on the tops of the abyssal hills (in some cases associated with structural domes). Potholes are progressively more common to the west and their formation thus likely relates to the time they have spent below the calcite lysocline. In the valleys of the abyssal hills, sub-bottom profiles show that carbonate collapse can be widespread via "carbonate strata breccias" which have some features in common with cave collapse breccias on land.

In turn the chalk is overlain by up to 27 m of early Miocene to present silicious clay-ooze of the Clipperton Oceanic Formation. This highly mobile material is a combination of bio-siliceous ooze and detrital clay minerals and is often poorly consolidated and reworked, with surficial development of ripples from the centimetre to hundred metre scale, slumping on hill side-slopes and common development of sediment drifts, including some likely contourites. The clay-ooze hosts the polymetallic nodules, with the degree of

nodule coverage mappable (qualitatively) by MBES backscatter. The distribution and nature of this unit is a major factor in determining the prospectivity of different areas for polymetallic nodule mineralisation.

The above stratigraphy is unconformable on, or crosscut by, a wide variety of volcanic rock units. These form edifices, distinct from the abyssal hill basement, including numerous single and composite knolls, seamounts, dykes and fissure products, and sills/laccoliths. Outcrop includes coherent facies (pillow, lobate and blocky lavas) and noncoherent facies (talus, autobreccia, hyaloclastite).

Polymetallic nodules have several key properties which require consideration when considering commercial development. Classification of nodule forms can be readily further qualified from the schema of prior workers. Then the range of nodule forms and abundance can be related to the facies scale conditions of their formation; specifically, the thickness and stability of the geochemically active layer in which they slowly grow. This often extends to their size distribution in any given area. Highly prolate nodules are shown to grow as a result of the influence of seabed currents and the occurrence of diagenetic ferro-manganese crusts elaborated. The mineralogy of nodules is summarised with contributions in the disposition of mineral types and metals of interest.

Bulk chemistry of the sampled nodules is generally typical of the CCZ, but the samples also span much of the CCZ, allowing for new multielement regional scale analysis. Regional trends in cobalt grade can be explained by differing metal contributions from silicic versus calcic primary productivity. Local trends in chemistry can sometimes be related to different nodule facies and thus the locally variable conditions in which they grew. Detailed study confirms nodule densities average between 1.90 and 2.07 g/cm³. Host clay-ooze bulk densities ranging between 1.12 and 1.24 g/cm³ at surface increasing gradually with depth, more slowly in younger sediments. Packing densities for nodules are 0.61-0.67, depending on their particle size distribution and form. Nodule free moisture content is around 28% of wet weight plus there is 16% water of crystallisation remaining in nominally dry nodules. There are significant caveats required regarding their ideal drying temperature and their hygroscopic nature. Nodules are also prone to forming attrition fines, initial testing indicates some care is advised in the design of transport systems to ensure safe bulk transport in any future mining operations.

The local scale geology of the areas and the above-mentioned key factors then contribute to the topical discussion on polymetallic nodule mineral resource estimation. Mineral resource estimation is important to the owner of the resource (all of mankind; and managed by the ISA) and to developers (groups holding contracts with the ISA). The Committee for Mineral Reserves International Reporting Standards was developed for the land-based minerals industry and adapted in 2015 for ISA-managed nodules. Nodules can be sampled in a meaningful manner using mechanical devices, albeit with minor issues of bias. Grade and moisture content are measured using the established methodology for land-based minerals. Tonnage of resource is determined via the abundance of nodules in kilograms per square metre of seabed. This can be estimated from physical samples and, in some cases, from photographs. Contemporary resource reporting for nodules classifies the level of confidence in the estimate, by considering deposit geology, sample geostatistics, etc. The reporting of estimates also addresses reasonable prospects for eventual economic extraction, including factors such as mining technology, the marine environment, metallurgical processing, and metals markets. Other requirements are qualified persons responsible for estimation and reporting, site inspection, and sample chain of custody.

Conversion of mineral resources to mineral (ore) reserves is required for project development and valuation. Reserves require a wide range of multidisciplinary modifying factors. Some published contributions in this area include: improved abundance estimation processes; comprehensive logging of megafauna morphotypes; concepts behind a novel decoupled nodule collection system and its testing; and small-scale optimised pyrometallurgical experiments.

Ultimately the CCZ is a remarkable mineral deposit. It is deemed the common heritage of mankind and cannot simply be sidelined. Further understanding of its formation and distribution will hopefully assist us make the best decisions for its future.

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List of acronyms

Excluded from this list are:

- Most units of measurement (Système International, and imperial);
- Chemical elements per the periodic table;
- Most geological mapping codes (per Table 3-1, Table 3-3, Table 3-4 and Table 3-6)

°C	Degrees centigrade
AABW	Antarctic Bottom Water
AAS	Atomic Absorption Spectroscopy
Abl	1:250,000 scale map unit abyssal hills flatter area
AFERNOD	Association Française d'Étude et de Recherche des NODules océaniques (French exploration joint venture from 1974)
AFM	alkali-iron-magnesium chemical diagram
ALS	Laboratory company (formerly Australian Laboratory Services)
AMC	Consulting company (formerly Australian Mining Consultants)
ANT	Antenna
APEI	Areas of Particular Environmental Interest
ASCII	American Standard Code for Information Exchange
ASX	Australian Securities Exchange
AUV	Autonomous Underwater Vehicle
Av or av	average
BC	Box-corer
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources)

BGS	British Geological Survey
BMA	bulk mineralogical analysis
BS	Backscatter (multibeam)
CA	Concentrator Array
CARIS	Computer Aided Resource Information System
CBRR	Brazilian Commission for Resources & Reserves
CC	Clarion – Clipperton (plate segment)
CCD	calcite compensation depth
CCRR	Comisión Colombiana de Recursos y Reservas Minerales
CCZ	Clarion Clipperton Zone
CCZ15-B##/#	CCZ15 expedition box-core site/sample
CCZ15-F##	CCZ15 expedition towed photo line
CCZ15-M##	CCZ15 expedition towed sidescan sonar, sub-bottom profiler line
<i>cf</i>	confer/conferatur, latin meaning make a comparison with
CG	Clipperton - Galapagos (plate segment)
CIIC	Cook Islands Investment Corporation
CIM	Canadian Institute of Mining, Metallurgy and Petroleum
CL	Cathodoluminescence
cm/a	centimetres per annum (year) typically relating to plate movement
coax	Coaxial (power/communication cable)
COMRA	Chinese Ocean Mineral Resources Research and Development Association
CP	Competent person under the Joint Ore Reserves Committee code
CRC	Cooperative Research Centres (Australia)
CRD	Cellular Robotics Drilling rig
CRIRSCO	Committee for Mineral Reserves International Reporting Standards
CSB	Carbonate Strata Breccias
CSU	Concentrator Steering Unit
CTD	Conductivity temperature depth (subsea sensor package)
CV	coefficients of variation
dB	Decibels
DC	Direct current
DEME	Dredging, Environmental & Marine Engineering or DEME Group
DOMES	Deep Ocean Mining Environmental Study
DORD	Deep Ocean Resources Development Company (Japanese Consortium)
DP	dynamic positioning
DSAO	Detailed Survey Area (NORI D sub-area)
DSDP	Deep Sea Drilling Program
DSHMRA	Deep Seabed Hard Mineral Resources Act (USA) of 1980
e.g.	exempli gratia, Latin meaning “for example”
EDS	Energy dispersive spectroscopy
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
EMMP	Environmental Management and Monitoring Plan
ENE	East North East
EPMA	Electron probe microanalyser
EPR	East Pacific Rise
EPSG	Database of very detailed geodetic parameters from a range of sources and authorities. www.EPSG.io
ESE	East South East
et al	et alia, latin meaning and others
FFG	Free-fall grabs
GAL	Geochemically Active Layer
GCS	Geographic coordinate system
GEBCO	General Bathymetric Chart of the Oceans
GEMONOD	Groupement pour la mise au point des MOyens nécessaires à l’exploitation des Nodules (company)

GIS	Geographic information system
GLOBSED	Global sediment (database)
GPS	Global positioning system (usually meaning the Navstar radionavigation satellite system)
GRD	Generalized Rayleigh distribution
GSR	Global Sea Mineral Resources (company)
Gt	Giga (billion) tones
G-TECH	G-Tech Sea Mineral Resources (company)
HIPS	Hydrographic Information Processing System (MBES software)
HMPE	High modulus polyethylene (rope)
i.e.	id est, latin, meaning that is
ICMM	International Council on Mining and Metals
ICP	Inductively coupled plasma spectrometric
ICPAES	Inductively couple plasma atomic emission spectrometry
ICP-MS	Inductively couple plasma mass spectrometry
ID	Identification number
IDSSE	Institute of Deep-Sea Science and Engineering
IEC	International Electrotechnical Commission
IFREMER	Institut Français de Recherché pour l'Exploitation de la Mer (French Research Institute for Exploitation of the Sea)
IHO	International Hydrographic Organization
IMO	International Maritime Organisation
IMSBC	International Maritime Solid Bulk Cargoes Code
IMU	Inertial motion unit
IOC	Intergovernmental Oceanographic Commission
IODP	Integrated Ocean Drilling Program
IOM	Interoceanmetal Joint Organisation (Bulgaria, Cuba, Czech Republic, Poland, Russian Federation and Slovakia Consortium)
IONF	Indian Ocean Nodule Field
ISA	International Seabed Authority
ISBA	International Seabed Authority Assembly (document reference)
ISBN	International Standard Book Number
ISO	International Organization for Standardization
ISOPE	International Society of Offshore and Polar Engineers
ISQ	Instituto de Soldadura e Qualidade
JEOL	Japan Electron Optics Laboratory (company)
JORC	Joint Ore Reserves Committee (Australasian code for Reporting of Exploration Results, Mineral Resources, and Ore Reserves)
KAZRC	Kazakhstan Code for the Public Reporting of Exploration Results, Mineral Resources and Mineral Reserves
KC	KC Denmark (company)
KCON	Kennecott Consortium
KIOST	Korean Institute of Ocean Science and Technology
KODOS	Korea Deep Ocean Study
KOMBERS-KCMI	Komite Bersama – Komite Cadangan Mineral Indonesia
KORDI	Korean Ocean Research and Development Institute
L	Left
L/D	Length over diameter
LA	Long axis
LAE	Long Axis Estimation (pertains to estimating a nodule's weight)
LLC	Limited liability company USA)
LOI	Loss on ignition
MAK-1M	deep-tow low frequency sonar system by Yuzhmorgeologiya
MAPR	mini-autonomous plume recorder
MARA	Marawa Research and Exploration Limited
MBES	Multibeam Echo Sounding
mbsl	metres below sea-level
MC	Molokai – Clarion (oceanic plate segment)

MDPI	Multidisciplinary Digital Publishing Institute
MEBO	Meeresboden-Bohrgerät
MFES	Multi-Frequency Exploration System
MGN	Marine Guidance Note (United Kingdom)
MLE	Maximum Likelihood Estimation (mathematical fit)
MPIGM	Mongolian Professional Institute of Geosciences and Mining.
MSS	Mooring Sites
Mt	Mount as in R/V Mount Mitchel
N	North
NACRI	National Committee for Reporting Mineral Resources and Reserves in India
NE	North East
NI	National Instrument
N-MORB	Normal mid ocean ridge basalt
NNE	North North East
NNW	North North West
NOAA	National Oceanic and Atmospheric Administration
NOD	Nodule bearing domain
NON	No nodule domain
NORI	Nauru Ocean Resources Inc
NORI A	Nauru Ocean Resources Inc ISA Exploration Contract sub-area A
NORI B	Nauru Ocean Resources Inc ISA Exploration Contract sub-area B
NORI C	Nauru Ocean Resources Inc ISA Exploration Contract sub-area C
NORI D	Nauru Ocean Resources Inc ISA Exploration Contract sub-area D
NPP	Net Primary Productivity
N-S	North - South
NW	North West
ODP	Ocean Drilling Program
OERN	Russian Society of Experts on Natural Resources
OMCO	Ocean Minerals Co. (1970s Consortium)
OMSP	Ocean Minerals Singapore (company)
opal-CT	Opaline silica with Cristobalite and/or Tridymite
PAAS	Post Archean Australian Shales
PERC	Pan-European Reserves and Resources Reporting Committee
PetDB	Petrological Database of the Ocean Floor
PH	Pothole
PMA	Priority Mining Area
POSMV	Position & Orientation Systems for Marine Vessels
PP	Photo-profile
PRZ	Preserve Reference Zones
PSV	Production and Support Vessel
pulv	Pulverised (sample)
QA/QC	Quality Assurance Quality Control
QEMSCAN	Quantitative Evaluation of Materials by Scanning Electron Microscopy
QP	Qualified Person (per NI 43-101)
R	Right
R/V	Research Vessel (ship or boat)
r^2	coefficient of determination
REE	Rare Earth Elements
REMP	Regional Environmental Management Plan
REY	Rare Earth Elements and Yttrium
RS	Rough-smooth (type nodules)
RX	Receiver (multibeam echosounder hydrophone array)
S	South
SAGA	System for Automated Geoscientific Analyses
SAMREC	South African Code for the Reporting of Exploration Results, Mineral Resources and Mineral Reserves
SBP	Sub-bottom profiler

SE	South East
SIPS	CARIS backscatter engine (processing software)
SME	Society of Mining Engineers (USA)
SOG	speed over ground
SPP	Surface Primary Productivity
SSE	South South East
SSS	Sidescan sonar
STBD	Starboard
SW	South West
TAG	Trans-Atlantic Geotraverse
Tb	Topographic break-line
TIFF	Tag Image File Format
TML	Transportable Moisture Limit
TOML	Tonga Offshore Mining Ltd
TOML A	Tonga Offshore Mining Ltd ISA Exploration Contract sub-area A
TOML B	Tonga Offshore Mining Ltd ISA Exploration Contract sub-area B
TOML B1	Tonga Offshore Mining Ltd priority sub-area B1
TOML C	Tonga Offshore Mining Ltd ISA Exploration Contract sub-area C
TOML C1	Tonga Offshore Mining Ltd priority sub-area C1
TOML D	Tonga Offshore Mining Ltd ISA Exploration Contract sub-area D
TOML D1	Tonga Offshore Mining Ltd priority sub-area D1
TOML D2	Tonga Offshore Mining Ltd priority sub-area D2
TOML E	Tonga Offshore Mining Ltd ISA Exploration Contract sub-area E
TOML F	Tonga Offshore Mining Ltd ISA Exploration Contract sub-area F
TOML F1	Tonga Offshore Mining Ltd priority sub-area F1
TRI	Terrain ruggedness index
TX	Transmit / projection array (MBES)
UK	United Kingdom
UKSRL	UK Seabed Resources Ltd (company)
UMREK	Ulusal Maden Kaynak ve Rezerv Raporlama Kodu (National Resources and Reserves Reporting Committee of Turkey)
UNCLOS	United Nations Convention on the Law of the Sea 1982
UNECE	United Nations Economic Commission for Europe
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFC	United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources
US/USA	United States of America
USBL	Ultra Short Baseline (sub-sea navigation)
USNEL	United States Naval Electronic Laboratory
UTC	Coordinated Universal Time
UTM	Universal Transverse Mercator (coordinate system)
v	version
V/H	Vertical on horizontal (vertical exaggeration in a profile or section)
W	West
WCP	water-column profiler
WDS	Wavelength dispersive spectrometers
WGS84	World Geodetic System
WM	Wedderburn Marine
WNW	West North West
WSW	West South West
wt.%	Weight percent
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence
YMG	State Enterprise Yuzhmorgeologiya (Russian Federation)



R/V Yuzhmorgeologiya, mobilises from Betio, South Tarawa, Kiribati August 2015.

Photo credit: Nicola Parianos.

1 Introduction

1.1 Background

Marine minerals have attracted increased and controversial attention in the last decade. For example, proponents of development cite increased demand for metals, that land based deposits increasingly struggle to meet sustainably (e.g. Baxter and Schmidt, 2015; Paulikas *et al.*, 2020). Opponents to development cite the sensitivity and currently pristine nature of the marine environment (e.g. Jones *et al.*, 2017; Van Dover *et al.*, 2017). Administrators of development have increased efforts to deliver effective regulations, guidelines and standards (e.g. International Seabed Authority, 2020).

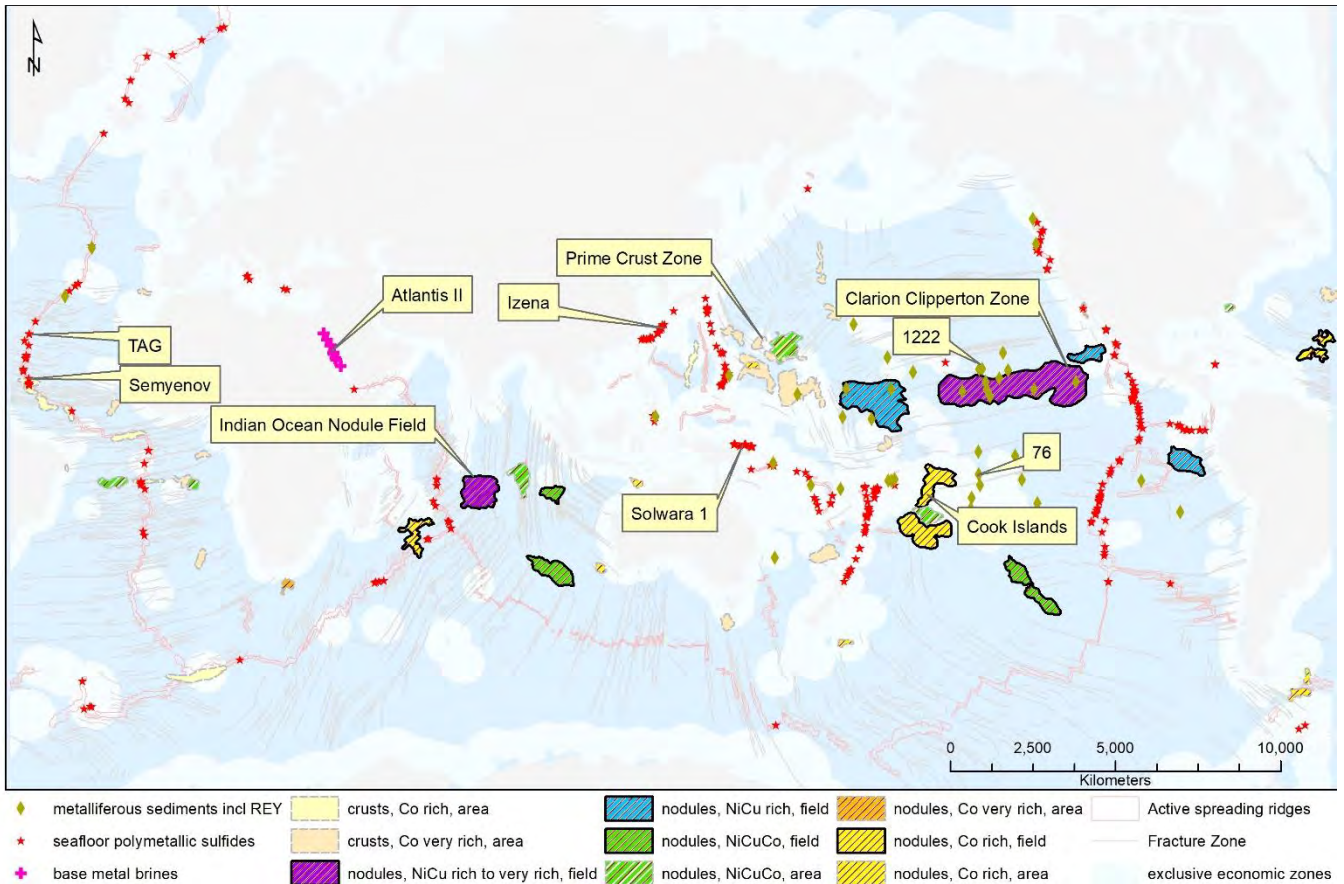


Figure 1-1: Location of selected marine mineral deposits

Adapted from (Andreev *et al.*, 2008; Kato *et al.*, 2011; Matthews *et al.*, 2011). rich Co is generally >0.4%, very rich Co is >0.8%, NiCuCo is 0.7-1.7% Ni+Cu, rich Ni-Cu is >1.7% Ni+Cu, very rich Ni-Cu is >2.5% Ni+Cu; “fields” are much better constrained from sampling than “areas”. REY are rare earth elements and yttrium.

The largest currently known marine minerals deposit is the polymetallic nodules deposit of the Clarion Clipperton Zone (CCZ deposit; Figure 1-1, Table 1-1). It is located between latitudes 5 and 15° N and longitudes 105 and 155°W, in the tropical north Pacific Ocean, on about three million km² of seabed at water depths of between 4,200 and 5,000 m. This is a bulk oxide type deposit of manganese, nickel, copper and cobalt, found as a very thin and discontinuous layer of roughly ellipsoidal concretions of ferro-manganese oxide minerals, at the interface between seafloor and the overlying deep ocean (Menard and Shipek, 1958; Mero, 1965). The CCZ deposit was essentially defined in the early to mid-1970s (Horn *et al.*, 1973), and was successfully pilot mined by two commercial consortia in 1978 (International Seabed Authority, 2004;

Brockett et al., 2008), before a multi-decade hiatus while regulatory (Guntrip, 2003) and environmental (Office of Ocean Minerals and Energy, 1981) processes were tackled.

Today most of the CCZ deposit is included within “the Area” (i.e. seabed and subsoil beyond national jurisdiction) and is administered by the International Seabed Authority (ISA) under the United Nations Convention of the Law of the Sea (hereinafter referred to as UNCLOS or Convention; United Nations, 1982, 1994). State parties to the Convention (also members of ISA) sponsor contracts between the Authority and commercial or government owned entities (termed Contractors). So far only exploration contracts have been granted, as regulations regarding exploitation (mining) contracts are still being formulated (International Seabed Authority, 2020b).

Table 1-1: Marine mineral types and published mineral inventory estimates

Mineral occurrence / deposit type	Metals of interest	Example locations (Figure 1-1) and inventory
Polymetallic nodules	Major: manganese (Mn), nickel (Ni), copper (Cu), cobalt (Co) Minor: molybdenum (Mo), REE	CCZ deposit 21-30 Gt nodules (International Seabed Authority, 2010a), IONF-Indian Pioneer Area 0.6 Gt (dry) nodules (Sharma et al., 2020), Cook Islands 3.2 Gt (dry) (Hein et al., 2015)
Polymetallic sulfides	Cu, gold (Au), silver (Ag), zinc (Zn), lead (Pb)	Solwara 1 2.57 Mt (dry) (Lipton, 2012), Semyenov 13.7 Mt (Cherkashov et al., 2013) TAG 3.8 Mt (Hannington et al., 1998)
Ferro-manganese crusts	Major: Co, Mn Minor: Ni, REE; Platinum (Pt)	Prime Crust Zone 7.5 Gt (Hein and Koschinsky, 2014)
Base metal brines	Zn, Pb, Ag	Atlantis II Deep, Red Sea 89 Mt (dry salt free) (Bertram et al., 2011)
REE clay-ooze	Rare earth elements and yttrium (REY)	Pacific site 76, 9 Mt REY oxides Pacific site 1222, 25 Mt REY oxides <i>both contained in sediments</i> (Kato et al., 2011)

Excludes near coastal alluvial deposits such as placer gold and diamonds, iron, titanium and tin sands, and dredging and construction materials (shallow water aggregates). REE are Rare earth elements namely cerium (Ce), dysprosium (Dy), erbium (Er), europium (Eu), gadolinium (Gd), holmium (Ho), lanthanum (La), lutetium (Lu), neodymium (Nd), praseodymium (Pr), promethium (Pm), samarium (Sm), scandium (Sc), terbium (Tb), thulium (Tm), and ytterbium (Yb), and often also include yttrium (Y) hence abbreviated REY.

The geological formation of the nodules within the CCZ has been well defined by past workers at a general level. Basement basaltic abyssal hills of the uppermost Pacific Plate are drifting ~WNW (e.g. Müller *et al.*, 2016). The abyssal hills are mostly covered by variably consolidated chalks and clay-oozes up to 300 m deep (e.g. Pälke *et al.*, 2009). There are signs of dissolution of the chalks and lateral movement of unconsolidated clay-oozes (Chapter 3), as well as minor amounts of recent volcanic activity such as lava and breccia flows in seamounts and knolls, and subterranean to outcropping sills and dykes.

Polymetallic nodules slowly precipitate in concentric layers at the seabed-seawater interface from a combination of hydrogenetic and diagenetic processes (Bender *et al.*, 1966; Callender and Bowser, 1980). The layers are due to alternating mineralogy from changes between oxic and sub-oxic conditions (Dymond *et al.*, 1984; Wegorzewski and Kuhn, 2014). Nodules are mostly found at the surface, but as many as 23% by abundance may be buried (e.g. Kotlinski and Stoyanova, 2006). While nodules are found in many parts of the world’s ocean floor (Horn *et al.*, 1973; McKelvey *et al.*, 1983), within the CCZ there are optimum or near optimum conditions for metal release from descending organic material which enriches the grades of the

nodules there (e.g. International Seabed Authority, 2003). These higher grades partially correlate with the position of the calcite compensation depth (International Seabed Authority, 2003), i.e. below the lysocline (Chen et al., 1988; Broecker, 2003).

The CCZ has been subject of some 50 years of ongoing research, with up to a dozen research or exploration expeditions per year. Each expedition is a relatively long and expensive exercise starting with transits to site which take five to fifteen days each way depending on port of mobilization, followed by one to two months' work on site, usually without resupply. Initial work often involves ship-based multibeam echo-sounder survey and to cover a typical contract area of 75,000 km² takes about one month of non-stop survey, in good to fair weather. The seafloor is typically accessed using tethered remote equipment winched to the seafloor e.g. box-corer, remotely operated vehicle or towed sled. Operations are limited by return times which are of the order of five hours per deployment (plus time at the seabed). At the depths of the CCZ, 12 kHz acoustic navigation systems provide locational accuracy of the order of 0.2% of slant range, equating to about ± 10 m for landed devices and ± 15 m for towed devices. Towed camera and acoustic systems are rarely able to be towed at speeds of over 2.5 kph so surveys of several hundred km² can equate to days if not weeks of vessel-work. Thus, truly autonomous devices such as free-fall grabs and autonomous underwater vehicles are preferred by some workers, and very occasionally human occupied vehicles are also used. Short summaries of the two main marine expeditions behind (otherwise unreferenced) key data in this thesis are included in 9.1 Appendix 1A, and 9.2 Appendix 1B.

1.2 Research Objective

This thesis aims to materially contribute to the geological basis of definition of the CCZ polymetallic nodule deposit. It does this through four ways by:

1. Geomorphological mapping of the entire CCZ plate segment (regional scale) to help characterize the basement to the deposit;
2. Geological mapping of some areas (local scale) to elucidate nodule fields, structures and other features;
3. Characterisation of certain key properties of nodules;
4. Presenting discussion on, and a pioneering case history of, mineral resource estimation.

The thesis also illustrates some of the challenges regarding the realisation of the mineral resource, e.g. environmental baseline, collector and lift system patents and testing, lower temperature limits for pyrometallurgical processing for metal extraction.

Coming from a background in terrestrial exploration and mining, the contributions have been made after almost a decade's work in the field by the author. The as yet pioneering nature of this field has led to diverse roles in the planning, mounting and leading of marine expeditions, development of subsea equipment, collection of samples and the publication of mineral resources, as well as contributions in the associated fields of environmental science, project economics and process metallurgy. Original contributions of the author, in conjunction with the very significant contributions of others, are included in 9.3 Appendix 1C: Statement of original contribution.

1.3 Thesis Organisation

There are seven chapters in this thesis, supported by three sections, as follows.

This **Chapter 1:** Introduction, summarises the background and objectives of the research, as well as organization of the thesis.

Chapter 2: Regional setting, is a CCZ wide interpretation of satellite-based bathymetry supported by other data such as compiled ship based bathymetric images and magnetic field/age interpretation. It defines discrete geomorphological units and associated structures, providing some constraints on formation of the basement and how in turn these might influence nodule composition and distribution within the CCZ plate segment. The topic of this chapter was presented at the Underwater Mining Conference (Parianos and Richards, 2018).

Chapter 3: Local scale geology, is centred around ship based (12 kHz) geological interpretation of parts of three exploration contract areas (those of Tonga Offshore Mining Limited, Nauru Ocean Resources Incorporated and Marawa Research Exploration Limited). It is supported by interpretation of deep towed sidescan and sub-bottom profile data and also refers to towed photo and box-core data. It defines a wide range of volcanic and sedimentary features that could affect future exploitation.

Chapter 4: Key properties of Clarion Clipperton Zone nodules, is a collection of experimental data on nodule characteristics that are as yet unpublished or not comprehensively addressed. This includes moisture content, density (nodules and host muds), propensity to generate attrition fines, packing density microanalysis and chemical variance. It also includes review summaries of other important characteristics such as regional chemistry and mineralogy including several new contributions. This includes a discussion on space-stability of the geochemically active layer with respect to nodule types, developed from a prior Underwater Mining Conference presentation (Parianos and Pomee, 2017).

Chapter 5: Aspects of estimation and reporting of mineral resources of seabed polymetallic nodules: A contemporaneous case study, is a published paper on the background and standards relating to polymetallic nodule mineral resource estimate including a case history on the first polymetallic nodule mineral resource estimates to contemporary international standards and to the highest level of confidence. The case history sources some key information from Chapters 3 and 4. The paper that comprises this chapter was published in the journal Minerals in 2021.

Chapter 6: Towards modifying factors, is a summary of a collection of 11 publications on polymetallic nodules with the author as co-author or lead author (reproduced in 9.23 Appendix 6A). These include peer reviewed papers, a conference paper, technical reports and patents. The publications all address some of the areas that need to be developed in the development of polymetallic nodules: i.e., the fields of ore characterisation, protection of the marine environment, mining technology and metallurgical processing. Within a typical project management/project valuation process, this would eventually involve the derivation of modifying factors, to enable the mineral resource estimate (Chapter 5) to be converted to a mineral/ore reserve. Work done by the author and discussed in the earlier chapters (especially Chapter 3 and Chapter 4) is a common contribution to the presented publications and their themes.

Chapter 7: Conclusions and way forward, summarises the findings of this research and discusses how the contributions of Chapters 2-6 can apply to other parts of the CCZ and indeed other areas of nodule bearing seafloor.

Section 8 is the reference list for all of the chapters. **Section 9** contains the appendices to this thesis, which are prefixed after each of chapters described above. Appendices composed of high resolution photographs, numerical data and associated calculations are only provided digitally for relevance and to save space. The 13 maps (a major portion of the work) are in **Section 10** at the end of the document.

1.4 List of associated publications

The author has been involved in a range of publications associated with deep seabed minerals during the period of marine research that eventuated in this thesis. Publications specific to the thesis subject of polymetallic nodules are as follows:

1.4.1 Peer reviewed publications

- Aspects of Estimation and Reporting of Mineral Resources of Seabed Polymetallic Nodules: A Contemporaneous Case Study. (Parianos et al., 2021) - Reproduced in Chapter 5.
- Multi-scale variations in invertebrate and fish megafauna in the mid-eastern Clarion Clipperton Zone (Simon-Lledó et al., 2020) – refer Chapter 6
- Thermodynamic and Experimental Study on Efficient Extraction of Valuable Metals from Polymetallic Nodules. (Su et al., 2020a) – refer Chapter 6
- Preliminary Observations of the Abyssal Megafauna of Kiribati. (Simon-Lledó et al., 2019a) – refer Chapter 6
- Empirical application of Generalized Rayleigh Distribution on resource prediction of seabed polymetallic nodules (Yu and Parianos, 2021) – refer Chapters 4, 6.
- Alternative Resources for Producing Nickel Matte - Laterite Ores and Polymetallic Nodules. (Su et al., 2021) – refer Chapter 6
- Geomorphology of the Clarion Clipperton Zone, tropical North Pacific Ocean (Parianos and Madureira, 2021), Journal of Maps – refer Chapter 2

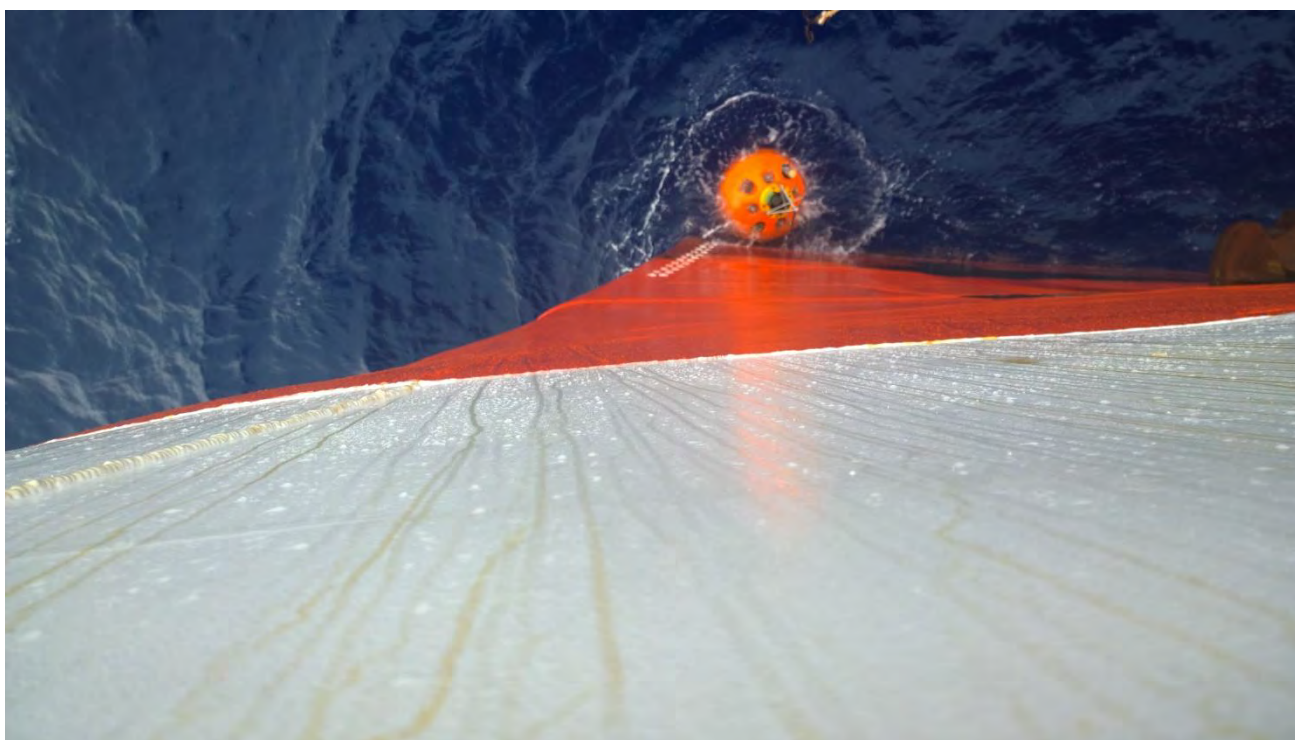
1.4.2 Other published abstracts, reports and patents

- Nodule Lateral Conveyor -A Full-Scale Test (Manocchio et al., 2020) – refer Chapter 6
- Nodule Concentrator: Lateral Conveyor -Numerical Simulation (Yu et al., 2020) – refer Chapter 6
- Model Test of Skip Lifting System for Deep-sea Mining. (Xiao et al., 2019) – refer Chapter 6
- The definition of morphotectonic domains in the Clarion-Clipperton Zone (CCZ): A step closer to understanding the controls behind nodule mineralisation? (Parianos and Richards, 2018) – superseded by Chapter 2
- Nodule types and genetic controls from the TOML Areas in the CCZ. (Parianos and Pomee, 2017) – superseded by Section 4.3.2
- TOML Clarion Clipperton Zone Project, Pacific Ocean. (Lipton et al., 2016) – refer Chapters 2-6
- EP3146154A1 Decoupled seafloor mining system. (Parianos et al., 2014a) – refer Chapter 6

- EP2956590B1 A seafloor nodule concentrating system and method. (Parianos et al., 2014b) – refer Chapter 6
- US10883252B2 Seafloor haulage system. (Berndt et al., 2014) – refer Chapter 6

1.4.3 Accepted for publication

- Geology of parts of the central and eastern Clarion Clipperton Zone (Parianos, O’Sullivan, Madureira), Journal of Maps – refer Chapter 3



Skilful interception of a runaway environmental mooring with the bow of the R/V Yuzhmorgeologiya, eastern CCZ, October 2015. The “Yuzhmor” does not have dynamic positioning.

Photo credit: author

2 Regional setting

The release of an updated global bathymetric product by GEBCO¹ (British Oceanographic Data Centre, 2020) provides an opportunity to interpret the geomorphology and structure of the Clarion-Clipperton Zone (CCZ) plate segment, albeit at a large scale (1:4,000,000; Section 10: Maps and cross-sections; Figure 2-2). This is supported by partial coverage of more detailed ship-collected multibeam data.

Understanding the large-scale geomorphology of the CCZ likely has implications in understanding the mechanisms controlling the quality (metal grade) of polymetallic nodules within the CCZ. This is because water depth vis a vis position of lysocline and primary productivity, is believed to control quality². Also, the methods used here could apply to the interpretation and exploration of other areas outside the CCZ.

2.1 Background

The CCZ is a segment of the Pacific Oceanic Plate extending between the East Pacific Rise and the Line Islands (Figure 2-1). The northern and southern boundaries of this segment are marked by the two major seabed fractures (transforms) referred to as the Clarion and the Clipperton Fracture Zones respectively. The two major transform fractures have been identified since the mid 1970's (Margolis and Burns, 1976) and are readily identified in datasets such as satellite bathymetry ((British Oceanographic Data Centre, 2014, 2020), Figure 2-1).

The interpreted age of the seabed, over the extent of the CCZ, increases from east to west (i.e., from polar reversals isochrons per Müller et al., (2016)), consistent with increasing distance from the East Pacific Rise spreading centre (EPR). The seafloor plate segments in the region also generally increase in depth from south to north i.e. the plate segment to the south (Clipperton – Galapagos) is shallower than the CCZ, which in turn is shallower than the plate segment to the north (Molokai – Clarion), Figure 2-1. The CCZ is bound to the west by the large volcanic Line Islands rise; further west is the Central Pacific Basin and the SE corner of the Pacific Triangle (Boschman and van Hinsbergen, 2016). The CCZ is bound to the east by the Mathematician Seamounts, a westerly splay off the EPR, further east is the EPR and the Rivera and northernmost Cocos microplates (Manea et al., 2013).

In the context of this regional review, it is worth recounting that ferro-manganese nodules are found in all of the world's oceanic basins (McKelvey et al., 1983). The continuous high metal grades in CCZ nodules are thought to result from: significant metal supply via net carbonate export from the surface; metal release near the nodules at the seabed via a combination of water depth relative to the lysocline; and distance from continental land masses meaning an absence of competitor minerals (Morgan, 2003; International Seabed Authority, 2010a; Lipton et al., 2016). Some aspects of this topic are explored further in Chapter 4.

The scale of the CCZ polymetallic nodule deposit, both in terms of space and time, is staggering compared to most land based mineral deposits. While typically only 10-20 cm thick, the deposit spans almost 4500 km by 500 km (equivalent to the land area of Europe). Estimates of metal content (non-CRIRISCO compliant; Chapter 5) are up to 30.7 Gt (International Seabed Authority, 2010a). The CCZ is currently covered with the

¹ GEBCO is a group of scientists operating under the joint auspices of the International Hydrographic Organization (IHO) and the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO). GEBCO is a name rather than an acronym but can also be taken to stand for General Bathymetric Chart of the Oceans.

² Note that ferro-manganese precipitation and especially nodule formation is interpreted to be controlled by smaller scale features (refer Chapter 4).

ISA exploration contracts and reserved areas, US exploration licenses and environmental reference areas (Figure 2-3).

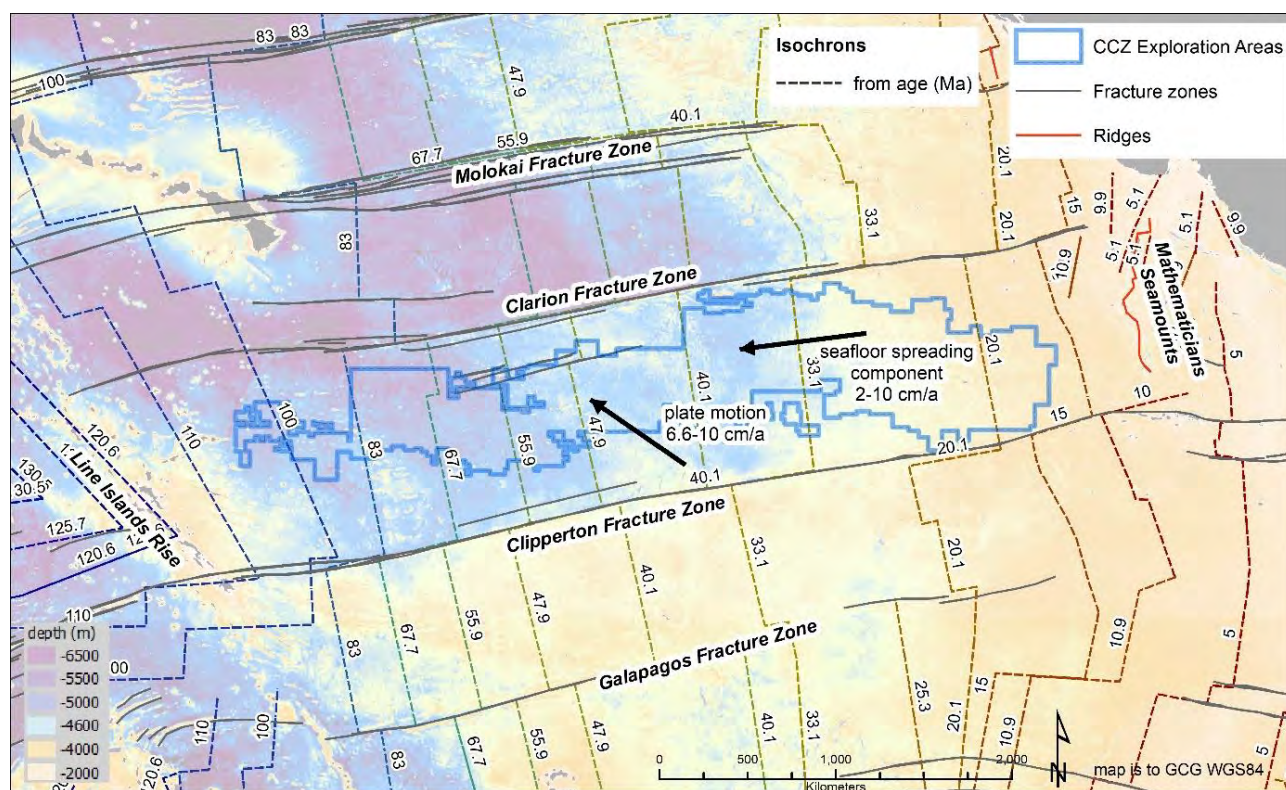


Figure 2-1: CCZ depths, basement ages and exploration areas of interest

Isochrons from Müller et al., (2016), Fracture zones and ridges from Matthews et al., (2011) and Wessel et al., (2015), seafloor spreading & plate motion directions from Morgan, (2003). Spreading rate from isochrons (last 100 Ma; Figure 2-24), plate motion back-track estimate from Pälke et al., (2009a) (accelerating over last 50 Ma).

No prior regional scale geomorphological maps of the CCZ are known. Neizvestnov et al., (2004) and Kotlinski et al., (2009) published a lineament and feature map and Kazmin, (2003) and International Seabed Authority, (2010b) reference to some of the bathymetric rises and other features described below (e.g. Eastern Central and Cooper Rises). CCZ scale maps of nodule chemistry, abundance, seabed sediment type are contained in International Seabed Authority, (2010a) and International Seabed Authority, (2010b). The interpretation described here is also compatible with the higher level global seabed classification of Harris et al., (2014) Figure 2-4, and a terrane classification similar to that included in the habitat classification of McQuaid (et al., 2019) in Figure 2-5.

2.2 Seabed Composition

The seabed in the CCZ is mostly composed of basaltic abyssal hills. These are mostly covered in a variety of siliceous and calcareous sediment, e.g. (van Andel et al., 1975; Pälke et al., 2009b); specifically thin and often poorly consolidated siliceous clays and oozes (Neogene to modern Clipperton Oceanic Formation) overly thicker calcareous nannofossil chalk (Eocene to Neogene Marquesas Oceanic Formation) that formed when the crust was located further south in the equatorial region (International Seabed Authority, 2010b). A third, older, mostly siliceous sedimentary unit is also found in the western part of the CCZ (Line Island Oceanic Formation).

The majority of abyssal hills are interpreted to have formed via normal faulting (i.e. horst and graben) in turn resulting from shrinking and subsiding driven by progressive plate cooling (Macdonald et al., 1996; Cormier and Sloan, 2018). The terminology in the literature can be a little confusing. “Abyssal Hills” almost invariably includes both the hills (horst) and adjacent valleys (grabens). “Abyssal Plains” may relate to larger units of abyssal hills (US Federal Geographic Data Committee, 2012) as done here, or used to distinguish flatter areas covered in thick blanketing sediment (Cormier and Sloan, 2018). Abyssal hills are not apparent in most of the GEBCO grid and can only be seen in 12kHz multibeam and some ship-track MBES. Within the CCZ both east facing and west facing fault scarps are common. The hills are typically: around 100-300 m high (trough to crest); have a frequency of 1-5 km; and strike for ten to several hundred kilometres. In the central and eastern CCZ the Abyssal hills mostly strike 350° (perpendicular to the direction of current plate spreading) in the western CCZ however the hills seem to strike mostly to 360° (Figure 2-8). Interspersed hills with a secondary strike are found in some areas, most commonly to $\pm 10^\circ$ (i.e., roughly perpendicular to the direction of plate motion).

While the abyssal hills show generally consistent trends and forms, they can vary in orientation, prominence, and relative elevation (see also Chapter 3). Some of these changes in relative elevation seem to relate to some of the larger scale geomorphological units described in this chapter. The CCZ seafloor deepens progressively from about ~4,200 m at 115 °W to ~4,800 m at 128 °W, then varies between ~4,800m and ~5,500 m until 161 ° W (Figure 2-6).

A range of other morphological features are present and discussed in Chapter 3. These include:

- volcanic knolls from 50 m or less in height up to seamounts that are 4 kilometres above the surrounding seabed;
- outcropping dyke/fissure lavas and sheet flows that are interpreted to have formed in relatively recent times (i.e., post much of the sediment record); and
- potholes in the Marquesas Formation carbonate strata, see also (Mayer, 1981; Moore et al., 2007; Fouquet et al., 2014). Note that seabed carbonates over much of the CCZ are currently unstable at this water depth relative to the interpreted position of the lysocline (Chen et al., 1988; Broecker, 2003).

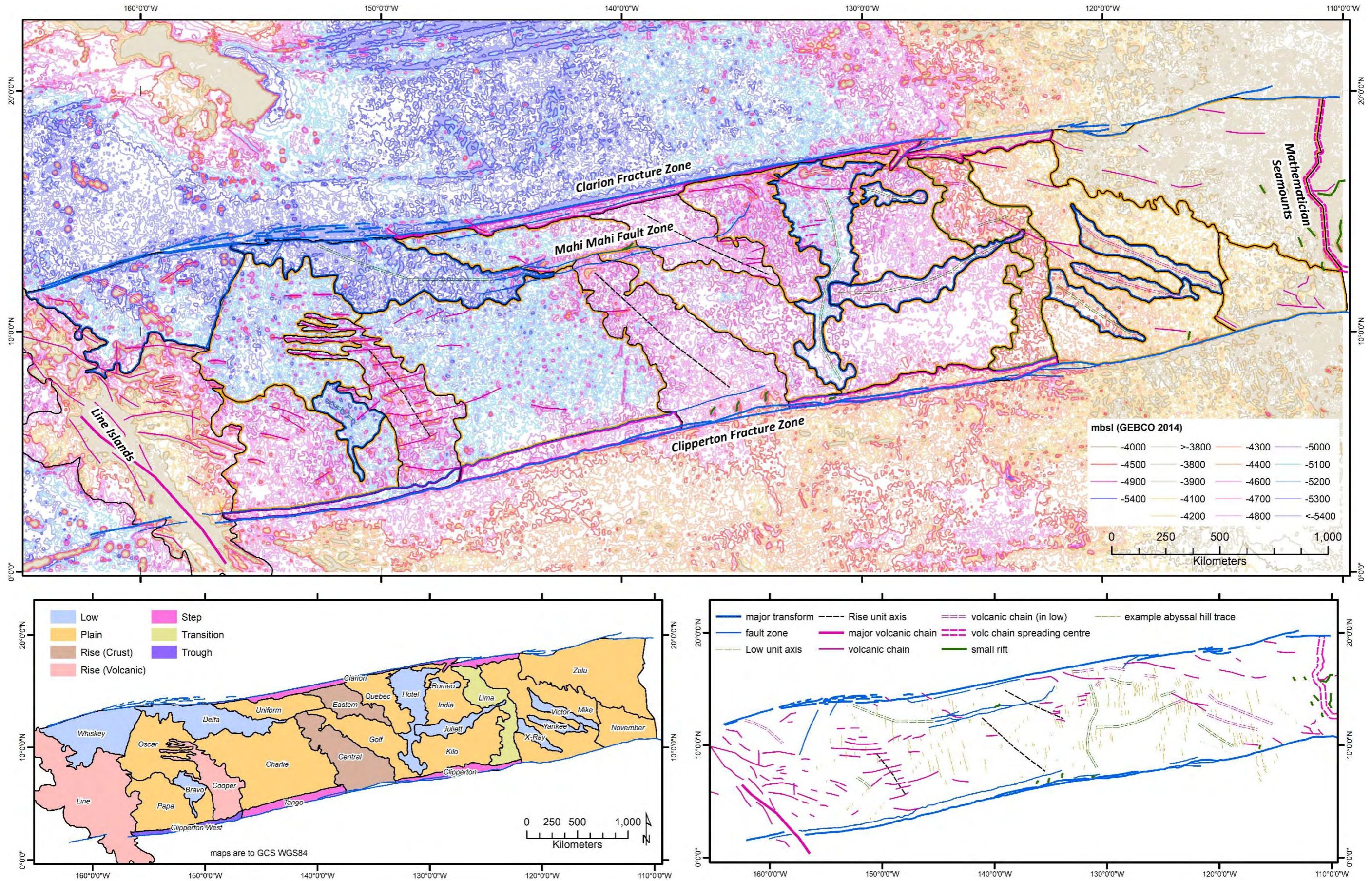


Figure 2-2. Interpreted geomorphological units and structural elements

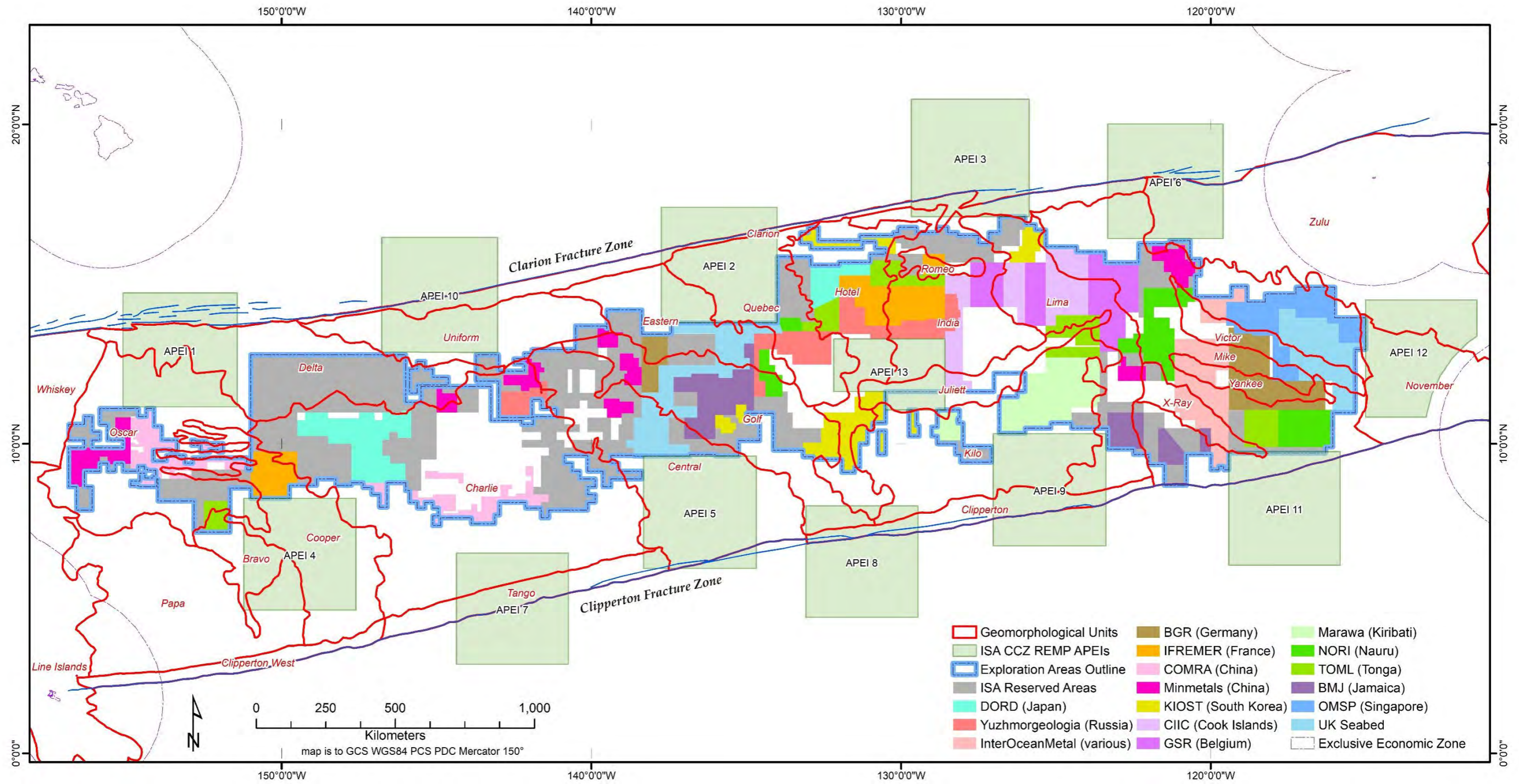


Figure 2-3: Simplified geomorphological units over exploration and environmental areas in the CCZ

Geomorphological units are as detailed later in this chapter. The border of the Exploration Areas polygon include areas of exploration under contracts with the ISA for exploration for polymetallic nodules and ISA reserved areas (International Seabed Authority, 2020a) and US Exploration Licenses (National Oceanic and Atmospheric Administration, 2016, 2017). Green squares are Areas of Particular Environment Interest (APEIs) and part of the ISA Environmental Management Plan for the CCZ (International Seabed Authority, 2012, 2021).

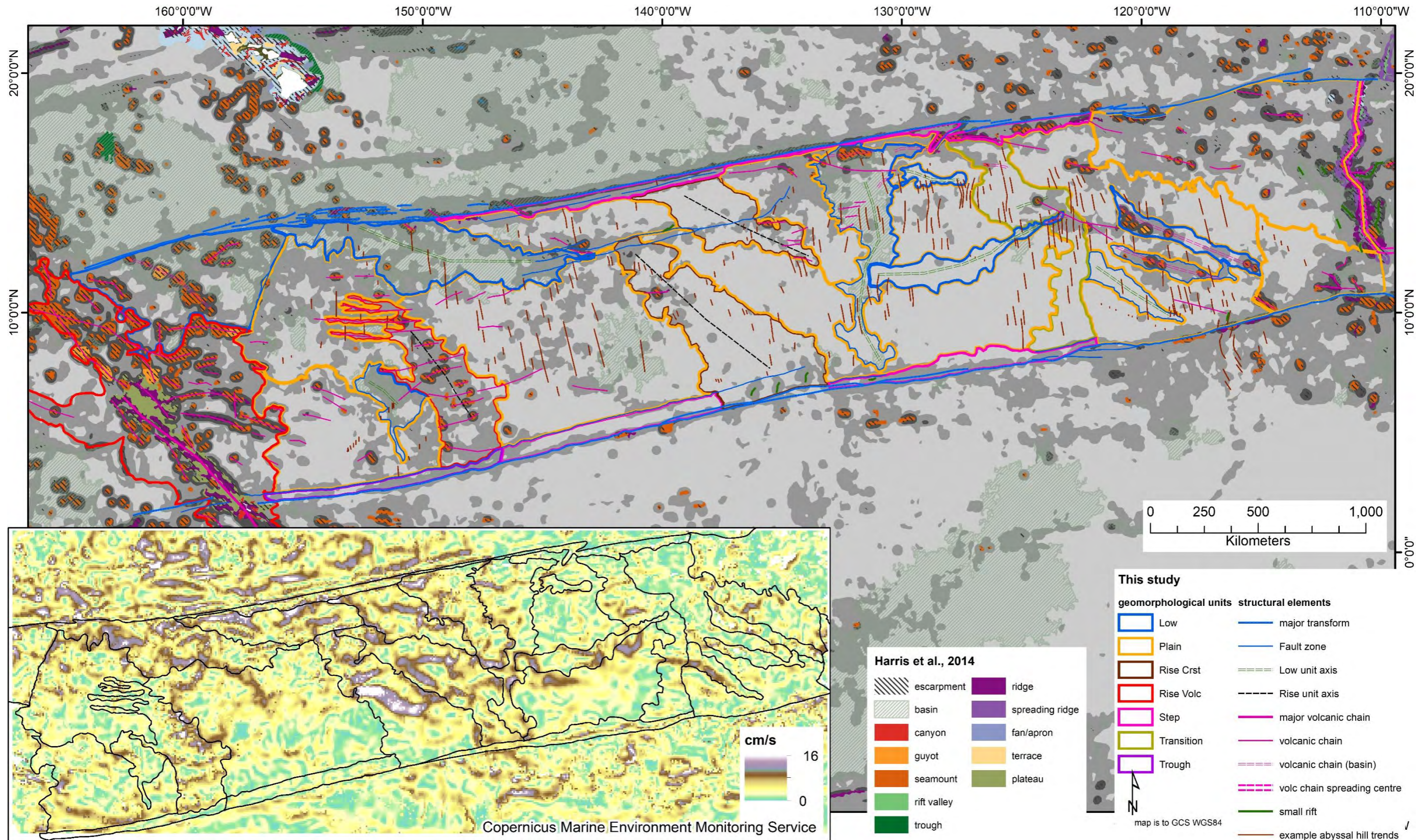


Figure 2-4: Comparison with global seabed classification and seabed currents

After Harris et al., (2014) and E.U. Copernicus Marine Service, (2021) respectively. Seabed currents processed by SAGRES Smart team and supplied to the author. Process involved averaging and resolution of modelled 1993 to 2019 eastward_sea_water_velocity and northward_sea_water_velocity at the depth levels where they reach the seabed.

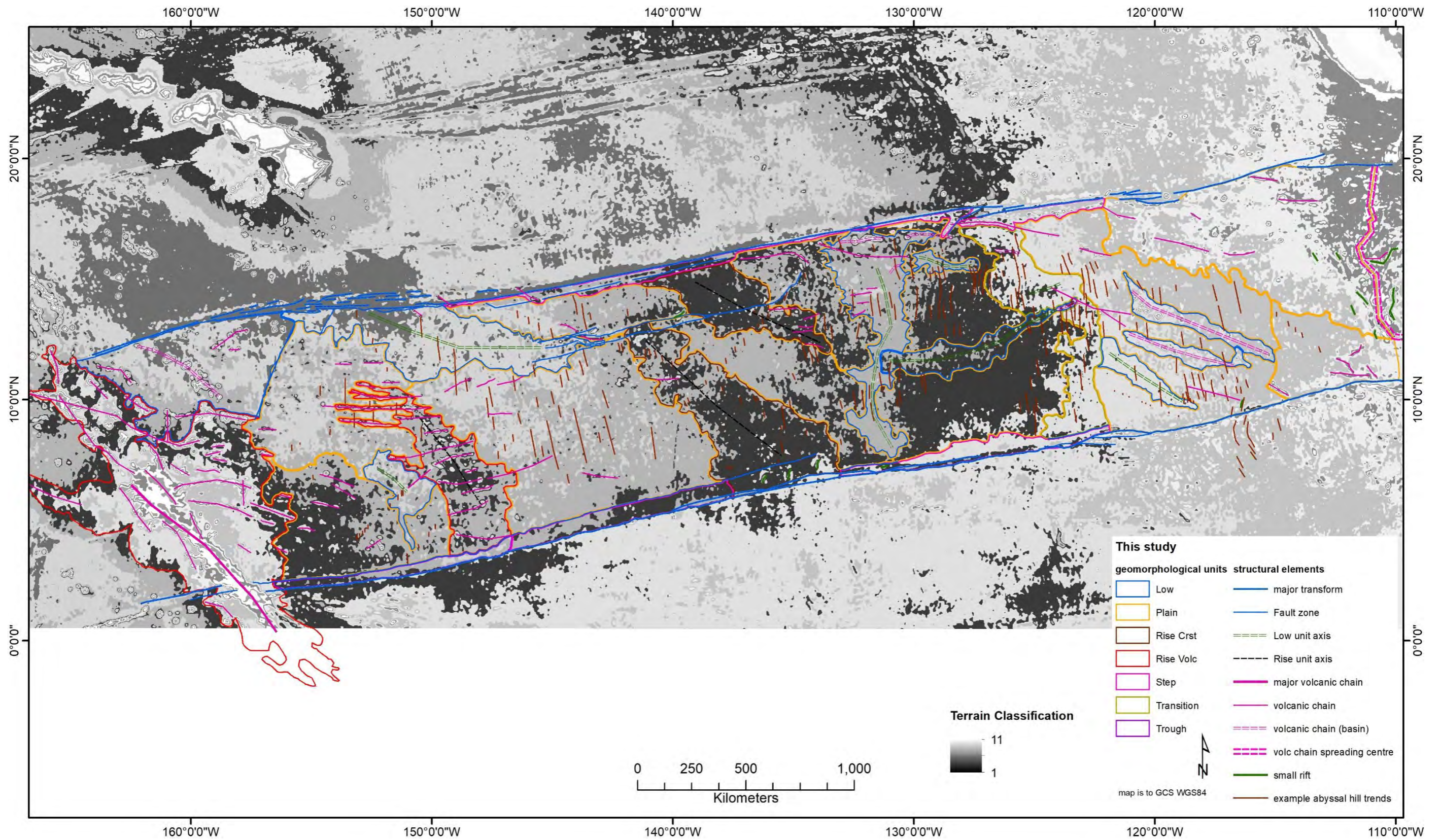


Figure 2-5: Comparison with a terrane classification similar to that included in McQuaid et al., (2019)

Classification processing courtesy Alex Fejer (Fathom Pacific) using reprojected GEBCO 2014 grid (EPSG:3832, 2km cell), depth in m, slope in radians, broad bathymetric position index (equivalent) of inner radius 1, outer radius 50, scale factor 100 km and fine bathymetric position index (equivalent) of inner radius 1, outer radius 5, scale factor 10 km (per McQuaid et al., (2019)), using SAGA GIS Hill climbing clustering algorithm with 11 clusters.

2.3 Methods

2.3.1 Data

Data used for this interpretation (e.g., **Error! Reference source not found.**) was downloaded from the following sources:

- 2014 and then 2020 GEBCO grids from British Oceanographic Data Centre, (2014) and British Oceanographic Data Centre, (2020) respectively (e.g. Figure 2-2). Within the CCZ the GEBCO 2020 grid is 87% an interpolated value guided by satellite-derived gravity data, 11% from provided multibeam data and 2% from soundings (that serve to constrain the satellite data);
- 12 kHz bathymetric images from public sources i.e. (China Ocean Mineral Resources Research and Development Association, 2010; Melnik and Lygina, 2010; Deep Ocean Resources Development Co Ltd, 2014a; Fouquet et al., 2014; Korea Institute of Ocean Science and Technology, 2014; Charlet et al., 2015; Lipton et al., 2016, 2019; Global Sea Mineral Resources, 2018; Taymans, 2019) and from data provided by three CCZ exploration Contractors (Tonga Offshore Mining, Nauru Offshore Resources Inc and Marawa Research and Exploration limited);
- Publicly available ship-track multibeam data (National Centers for Environmental Information, 2020).
- Gazetted features from GEBCO, (2020), and published seamounts and knolls derived from the GEBCO grids by Kim and Wessel, (2011) and Yesson et al., (2011).

Note that all of the ship-track data is incorporated into the GEBCO products, but the original ship-track data-products are of higher resolution.

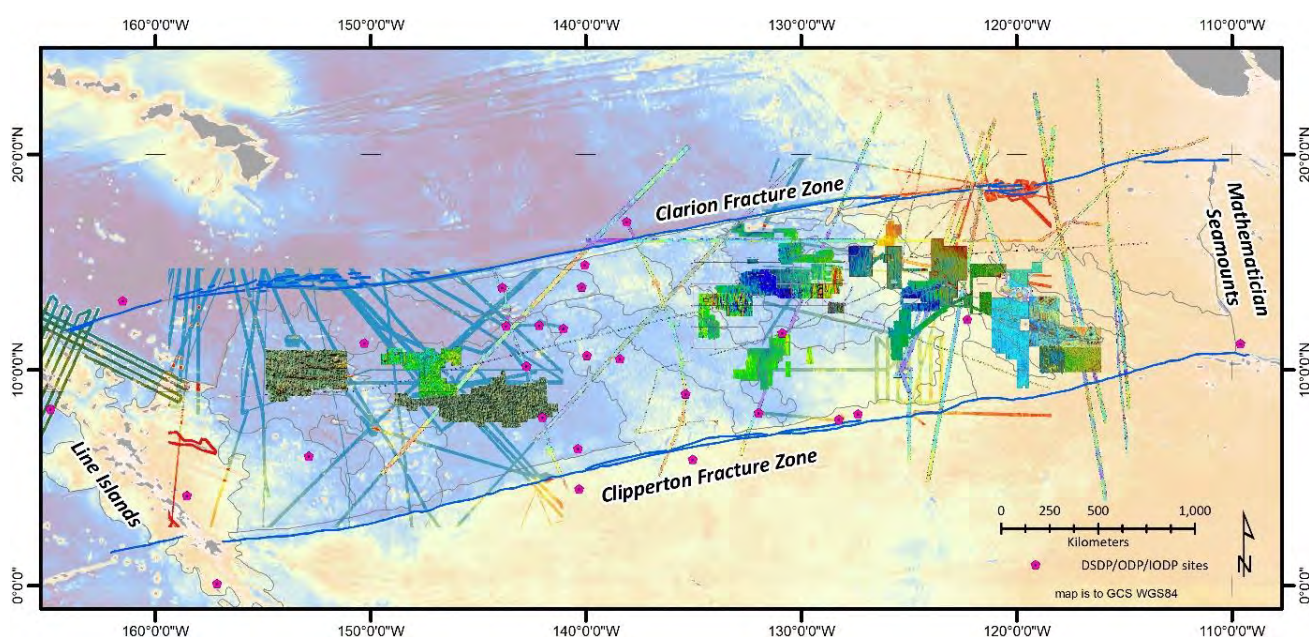


Figure 2-6: Published multibeam ship-tracks and survey areas on GEBCO2020 grid
DSDP/ODP/IODP drilling sites are included for completeness and only referred to in Chapter 3 along with the 12 kHz MBES.

2.3.2 Processing

The GEBCO bathymetric grids were processed into 100 m contour maps and colour gradient maps for use in GIS (Geosoft, ArcGIS and qGIS were all used). The 2020 grid benefits from finer resolution (15 arc seconds versus 30 for the 2014), although this finer point resolution means increased ‘contour noise’ with regards to ship-tracks. Also integrated is 12 kHz multibeam survey area from the Belgian sponsored ISA contractor GSR. The published 12 kHz bathymetric images were georeferenced and included into the GIS projects as needed using grid data, contract vertices or natural features. These images are not levelled in terms of depth-colour classification, but are often fairly similar.

The contour data was analysed visually, and after some experimentation with different depth intervals a set of primary contours at 400 or 500 m depth intervals selected for their ability to elucidate discrete units within the CCZ (both 2014 and 2020 GEBCO grids). The specific contours selected for the final interpretation are:

- 4,000 m;
- 4,500 m;
- 4,900 m; and
- 5,400 m.

The colour gradient maps helped more with picking boundaries as well as other lineaments. The gradients were also sectioned (e.g., Figure 2-9) to support the interpretation further. The area of each unit was measured in GIS using a Goode homolosine projection.

CCZ wide interpretation was then made using the GEBCO grids with occasional reference to the 12 kHz images. Boundaries between features and domains as well as other structural features (lineaments and potential faults) were interpreted directly into the GIS package and the final maps thus are principally qualitative. Interpretation is generally completed at screen-scales³ of between 1:1,000,000 and 1:2,000,000 and the final map is at 1:4,000,000 (Section 10.1 in Maps and cross-sections). Comparison of some of the interpreted units was also made using hypsometric curves (50 m steps) from the GEBCO 2020 grid (9.5 Appendix 2B: Hypsometric Analysis).

To consider nodule quality, summary grade and abundance data was sourced from International Seabed Authority, (2010a), as well as the location of exploration contracts and reserved areas from the ISA (International Seabed Authority, 2020a) and exploration licenses issued by the United States (which has yet to ratify UNCLOS) from National Oceanic and Atmospheric Administration (2016). While the summary grade and abundance data are useful, it has problems in that sample coverage across the CCZ is incomplete and sample spacing is often highly irregular and sample bias for abundance may be significant e.g. (Lee et al., 2008). Ultimately, with a few exceptions, the ISA exploration contracts and reserved areas⁴ and US

³ All of the digitizing for this chapter used a 24" 1980 x 1080p display at 1:1,000,000 scale 10 km on the map was about 0.9 cm on the screen

⁴ Reserved areas result from the activity of the so-called “pioneer investors” that applied for a contract of exploration under the ISA regulations for exploration for polymetallic nodules. Contract areas and returned Reserved areas are initially of equal value in terms of nodule prospectivity. Developing States may sponsor applicants that then apply for (parts of the) Reserved areas for nodules exploration. These applicants can select sub-areas based on quality, and therefore the average of the remaining Reserved areas (after several rounds of applications) are very likely to be of lower quality relative to the average of the ISA Exploration Contract areas.

exploration licenses are comparable with parts of the CCZ with high grade and/or high abundance (see Figure 2-27, Figure 2-28). In the figures below this combined domain is shown as a simple single outline. Within the context of this discussion, all three types of license/contract area effectively reflect the same thing – a defined priority area for the deposit.

2.3.3 Classification

The interpretation in this chapter, and in Chapter 3, can be classified within the Coastal and Marine Ecological Classification Standard (CMECS (US Federal Geographic Data Committee, 2012)). In theory, this allows work being done at a variety of scales, on a variety of themes (e.g., towed photo profile-based habitat mapping), to be integrated into the same management system. The CCZ wide interpretation presented in this chapter is mostly of geomorphological units that extend at the scale of thousands of square kilometres with some features at the hundreds of square kilometres scale. Within CMECS, these equate to the “Tectonic Setting” scale and “Physiographic Setting” scales per Table 2-1. There is overlap with the 1:250,000 local scale maps in Chapter 3 that also have units at the “Physiographic Setting” scale as well as at the “Geoform Level 1” scale, which is at the square kilometres to tens of square kilometres scale.

Table 2-1: Coastal and Marine Ecological Classification Standard adapted and applied to the CCZ

Tectonic Setting Subcomponent (1,000s km²)	Physiographic Setting Subcomponent (100s km²)	Geoform Level 1 (10s–1 km²)	Geoform Level 2 (100s m²)
Abyssal Plain (AP)	(*) Abyssal Hills (incl subtypes)	Slope (incl subtypes)	Simple clay-ooze
Transition	Flatter area	Shoaling carbonate	Rippled clay-ooze
AP Low	Sediment drifts	Pot-hole	Mega-ripples
AP Rise – crust	(*) Knolls/seamounts chains	Single or composite knoll/seamount subtypes	Slumps
AP Rise - volcanic		Volcanic talus slope	Carbonate domes
AP Step		Fissure lavas/dykes	Shoaling carbonate
AP Trough			Escarpments
			Volcanic outcrop
			Depressions
<i>Mapped for the entire CCZ using GEBCO grids (this chapter)</i>	<i>(*) Mapped in part for the entire CCZ using GEBCO grids and published 12 kHz MBES images (this chapter)</i> <i>Mapped in more detail for the NORI, TOML and Marawa Areas covered by 12 kHz MBES (Chapter 3)</i>	<i>Mapped for NORI, TOML and Marawa Areas covered by 12kHz MBES (Chapter 3)</i>	<i>Mapped for limited areas covered by towed side-scan sonar (Chapter 3)</i>

Note each column above is independent of each other. Units do not relate along rows.

2.3.4 Summary of software used

For the map: GEBCO grids were clipped and contoured in (gdal_contour) in qGIS 3.10.7. Testing via hypsometric curves was done using native installed process in qGIS 3.10.7 and via bathymetric position in index using SAGA GIS Hill climbing clustering algorithm (courtesy Alex Fejer of Fathom Pacific). Interpretation and map compilation was done in ArcGIS 10.4.1. Terrain profiles for the cross-sections were derived using (Profile Tool 4.1.8) in qGIS 3.10.7, and assembled/interpreted in Inkscape 0.92.3. Map was compiled and set in ArcGIS 10.4.1.

For the figures: in addition to the above, raster processing used native installed Raster Calculator in qGIS 3.10.7. Data preparation for the rose diagrams and segment speed estimates used Microsoft Excel (version 16.0). Rose diagrams were prepared using GeoRose 0.5.1. Figures were drafted either in ArcGIS 10.4.1, qGIS 3.10.7 or Inkscape 0.92.3.

2.4 Results

Seven types of tectonic setting geomorphological units are defined. The terms used are somewhat specific to the setting and scale of the mapped area (Figure 2-2), so for example differ from the terms used at the global scale by Harris et al., (2014):

1. Plains – i.e. of abyssal hills that comprise most of the seafloor;
2. Transition - a plain with an overall west facing slope that in effect separates the eastern and central parts of the CCZ;
3. Lows - diffuse to distinct areas of abyssal hills at slightly greater depths, some associated with seamount chains;
4. Rises (Crust) - diffuse to distinct areas of variably defined abyssal hills at slightly shallower depths;
5. Rises (Volcanic) – areas of volcanic seamounts/knolls associated with slightly elevated abyssal hills;
6. Steps - slightly shallower blocks aligned along the main fracture zones;
7. Trough – narrow, slightly deeper area aligned along part of one of the main fracture zones.

Each of the above units are often defined by depths relative to each other, or by the presence of a major natural feature such as a fault. This is primarily because the CCZ seafloor as a whole deepens westwards to about 128 °W (Figure 2-2). The boundary between, for example a “low” and a “plain” in the Eastern CCZ may be some 500 m shallower than the same type of boundary in the western, older and deeper part of the CCZ. The visual interpretation used local contour intervals as a guide as well as lineaments. Knolls and seamounts are typically several hundred to thousand m shallower than their host units.

While the figures below aim to illustrate some key points in the interpretation, it is recommended to the reader to quickly review the full 1:4,000,000 scale map in Section 10.1 as this better illustrates the interpretation of each of the geomorphological units against its neighbours.

The newly defined tectonic setting geomorphological units (subcomponent level per Table 2-1) are mostly named after the International Radiotelephony Spelling Alphabet, for example, Alpha, Bravo, Charlie etc.

Features with existing names are maintained (e.g. GEBCO, 2020; International Hydrographic Organization, 2008; International Seabed Authority, 2010a). As the interpretation evolved some interim units were changed or removed (i.e., merged with a neighbouring unit), thus there are some gaps in the alphabet-name sequence. All names are informal per International Hydrographic Organization (2008) unless indicated in the text or figures below as being gazetted.

Most of the seabed is composed of the twelve discrete Plains and Transition, which as mentioned above deepen from the eastern end of the CCZ towards the central-western part of the CCZ, but then shallow again in the south towards the Line Islands Rise. The Transition also marks a key change from the eastern to central CCZ. These units are dominated by abyssal hills but also include the above-mentioned smaller features such as volcanic cones, deeper trough grabens, and potholes.

The Plains are crosscut by Rises and Lows which respectively comprise shallower and deeper seabed regions of abyssal hills. Both rises and lows may have knoll/seamount chains associated with them. Conditions relating to a given unit are often more complex or specific; for example, the Cooper Rise is distinctly different to the other rises, including numerous seamount chains striking at a high angle to the rise itself.

Adjacent to the main fracture zones are Steps and a Trough. These narrow blocks typically have an interpreted smaller bounding fault inside the CCZ, that reflect local vertical displacement related to the dominantly transform fracture zones. The occurrence and form of the steps and the trough are influenced by changes in the strike of the fracture zones and with the contact of rises and lows with the fracture zones.

The accuracy of the interpretation based solely on the GEBCO grid, can be tested by comparing the cases where 12 kHz MBES is also available, i.e. in terms of continuity of units over and across the edge of the 12 kHz coverage. While the interpretation process was iterative between the datasets in some areas, normally this was not needed (the GEBCO grid alone was clear enough). An example of this correlation is provided below where east-west trending ridges formed at the north-western end of the Cooper Rise (Figure 2-7) were interpreted from GEBCO grid. When the boundaries are overlain on higher resolution multibeam data, the correlation between the ridges and the interpreted boundaries shows good visual corroboration. Similarly, the central part of Hotel Low is clearly expressed in both data sets. This supports the proposed suitability of the GEBCO grid for interpreting seafloor features and accurately distinguishing between morphotectonic zones at the scales considered here.

In association with the above-mentioned interpreted tectonic setting geomorphological units, the following structural element types were also defined and interpreted (Figure 2-2):

1. Major transform fractures– the Clarion and Clipperton Fracture Zones that bound the plate segment;
2. Fault zones –smaller clear breaks in the seafloor fabric, the most significant being the Mahi Mahi Fault zone;
3. Axes of the above defined geomorphological Lows;
4. Axes of the above defined geomorphological Rises;
5. Major volcanic chains – includes numerous seamounts (>1,000 m above the adjacent seafloor) as well as single and composite knolls. Some associated with the Lows;
6. Volcanic chains – single and composite knolls, and occasional seamounts. Some associated with the Lows and others with the former spreading centre at the Mathematician Seamounts, and;
7. Small rift– high angle tear-apart like structures. So far all found near the Clipperton Fracture Zone or subparallel to the Mathematician Seamounts.

Example abyssal hill strikes were also highlighted where possible (i.e., where there was 12 kHz bathymetry or clear ship-track bathymetric data), and the traces show a general change in abyssal hill strike along the CCZ (Figure 2-8). This helps inform an interpretation of the CCZ plate segment towards the end of this chapter.

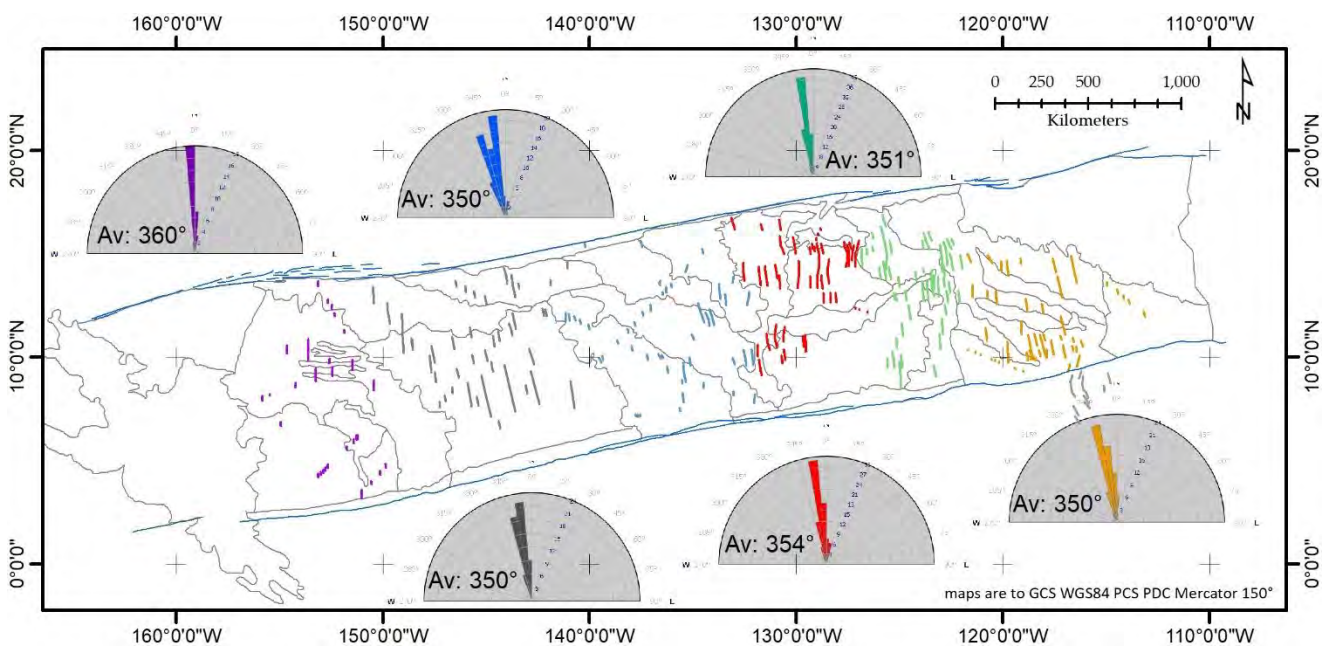


Figure 2-8. Trends of abyssal hill traces

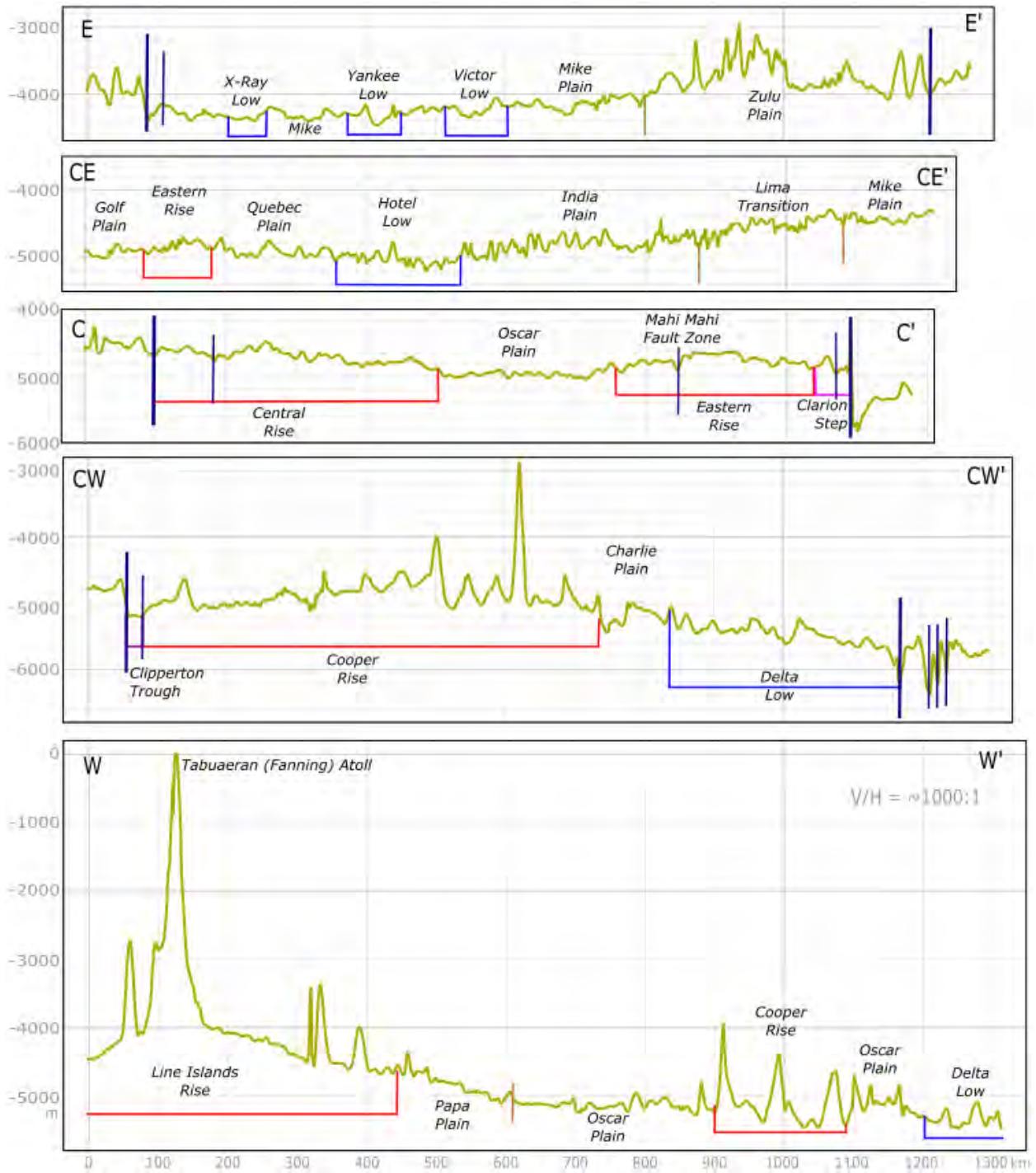


Figure 2-9. Cross-sections of GEBCO 2020 grid

Refer to Figure 2-10, Figure 2-14, Figure 2-17 below for their location as well as the 1:4,000,000 scale map in Section 10

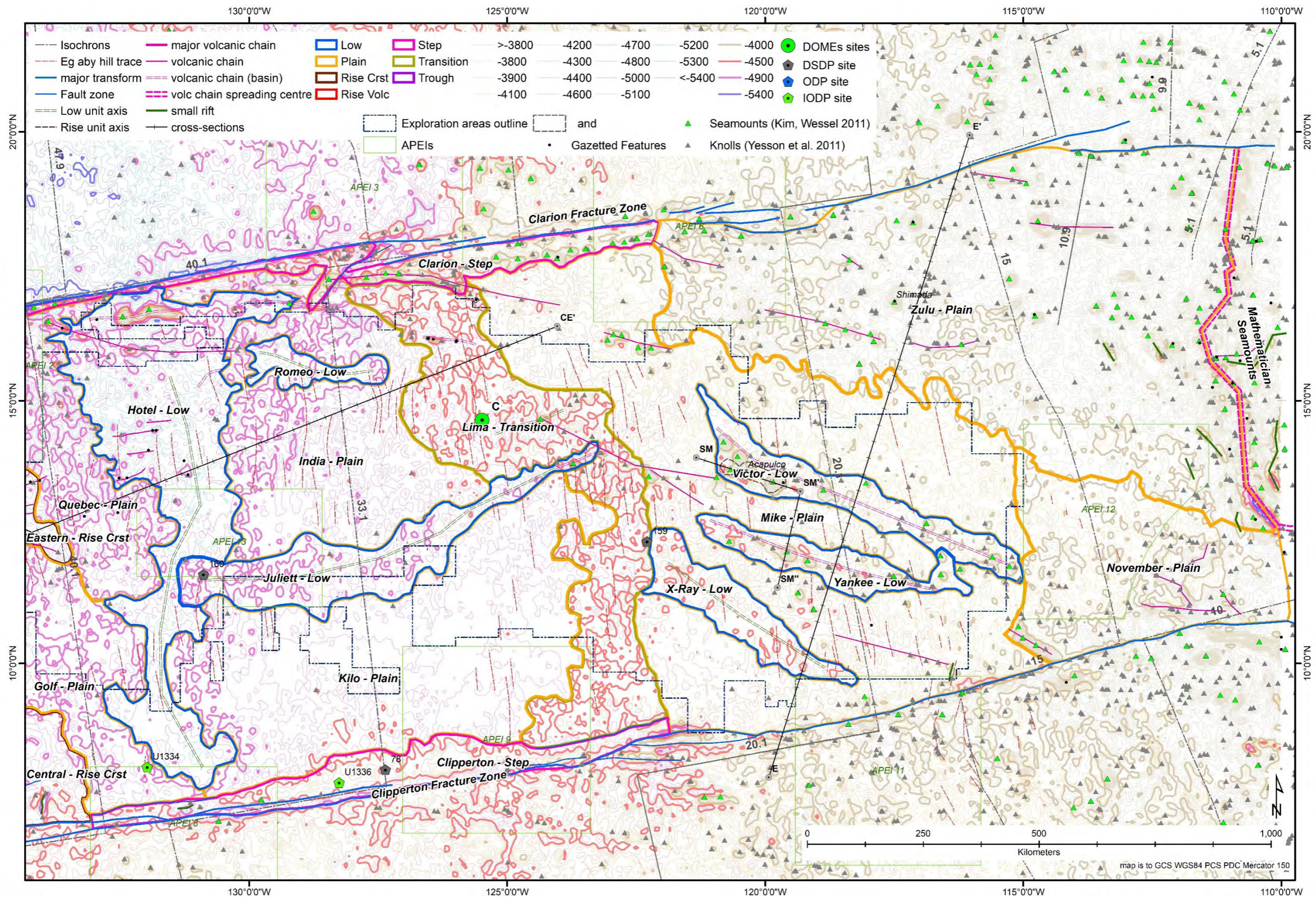


Figure 2-10. Eastern end of the Clarion Clipperton Zone

2.4.1 Defined Plains

Plains are the most common tectono-morphological unit, comprising the majority of the seafloor of the CCZ (~56% by area, or excluding the extensive Line Island rise, ~63%).

2.4.1.1 Mike Plain

An irregular shaped area a little over 529,000 km² located in the eastern side of the CCZ. Mike Plain is a relatively shallow part of the seafloor defined as between 4,000 and 4,500 m water depth (Figure 2-10). It encompasses the Victor, Yankee and X-Ray Lows which strike several hundred kilometres in a broadly WNW orientation. Abyssal hills strike to about 350° throughout the unit with some local secondary orientations tens of degrees to the east and west. The bulk of the seafloor basement formed between 30 and 15 Ma (mid Oligocene to mid Miocene; Figure 2-1).

The northern edge of Mike Plain contacts Clarion Step adjacent to the Clarion Fracture Zone which is a common arrangement for contacts between plains and the fracture zones. The southern edge of Mike Plain is however more unusual. Firstly, the plain is broader to the south along the Clipperton Fracture Zone (i.e. the shallower seabed to the east wedges out) which is at odds with the Clipperton-Galapagos plate segment being shallower (Figure 2-1). Secondly, there is also no southern marginal step or trough present, rather abyssal hills on either side of the fracture zone swing east from 350° to as far as about 030° across the Clipperton Fracture Zone (Figure 2-11) in some kind of drag arrangement (*cf* the southern end of Central Rise). Thirdly there is the abovementioned positioning of X-ray, Yankee and Victor Lows.

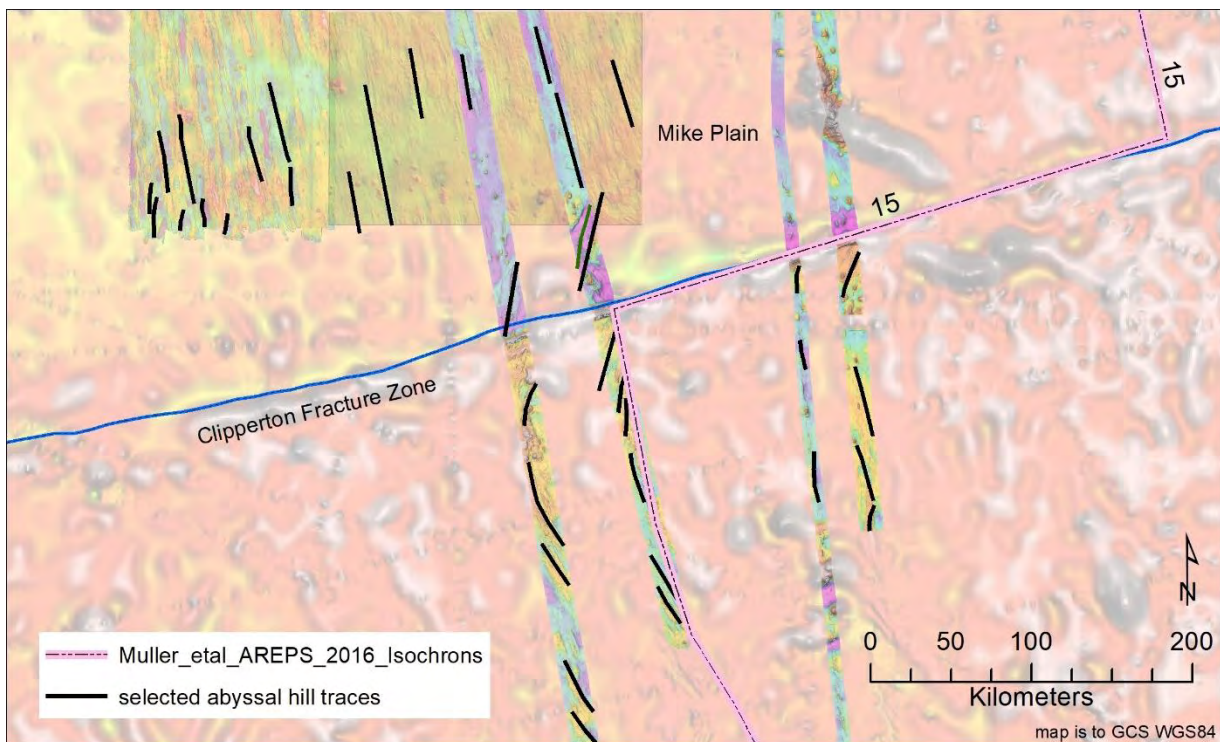


Figure 2-11. Selected abyssal hill traces across the Clipperton Fracture Zone at Mike Plain

Overall comparison between the geomorphological units and polymetallic nodule prospectivity is covered in section 2.5.2, but Mike Plain contains some of the highest grade and highest abundance nodule fields of the CCZ (Lipton et al., 2016). This has been long recognised, i.e. the pioneering KCON consortia's Frigate Bird area included parts of Mike Plain and today several groups have exploration contracts in the central and

southern parts of Mike Plain. The north-easternmost part of Mike and adjacent Zulu Plain are covered by APEI 6 and the southernmost edge of Mike by newly established APEI 11.

Figure 2-12 uses hypsometric curves to compare Mike Plain with the three Lows (Victor, Yankee and X-ray) embedded within Mike Plain as well as the adjacent Lima Transition (9.5 Appendix 2B: Hypsometric Analysis). While hypsometric curves typically cumulatively add the area of an elevated area (i.e. proportion of a domain (interpreted unit) above or below a given altitude/depth) in Figure 2-12 there is also a non-cumulative curve which highlights other aspects of the units. In this case, the non-cumulative curves show that Mike Plain has a much broader range of depths than the other units due to its greater area and scope across the CCZ. Mike Plain is generally shallower than X-ray or Yankee lows, but the contribution from the shallower parts of Mike coupled, with seamount contributions within Victor Low (highest 20% of the cumulative curve) mean that overall Victor Low is shallower than Mike Plain. Mike Plain is clearly shallower than Lima Transition which is located further west.

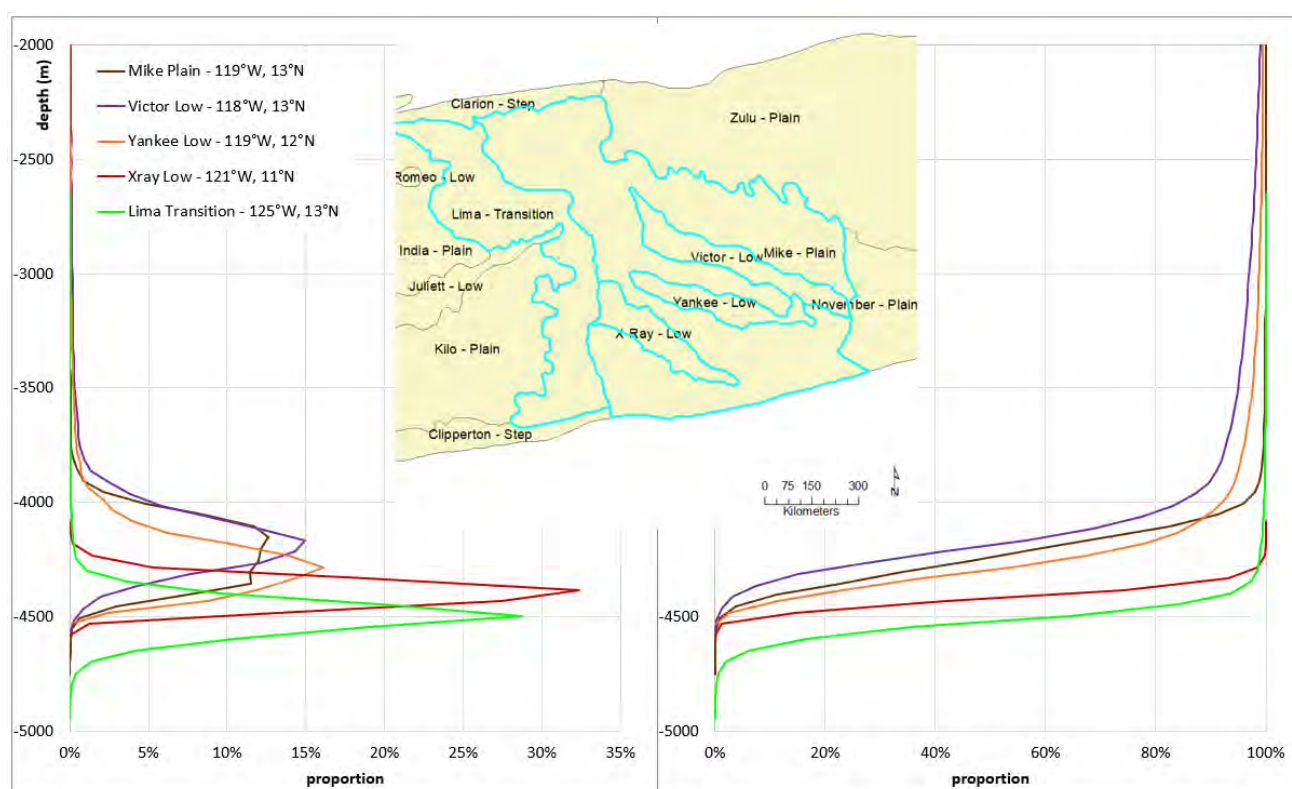


Figure 2-12: Hypsometric curves for Mike Plain, Victor, Yankee and X-ray Lows and the Lima Transition

2.4.1.2 November Plain

This small (169,000 km²) triangular plain to the east of Mike Plain is mostly at a similar or slightly shallower depth (4,000-4,200 mbsl; Figure 2-10) and is also prospective for nodules. The seabed is the youngest in the CCZ at around 5-15 Ma (mid to end Miocene). November Plain's eastern limit is adjacent to the Mathematician Seamounts (failed spreading arm off the East Pacific Rise (Mammerickx et al., 1988)). ODP site 854 is located just outside November Plain near the seamounts (Mayer et al., 1991). The site returned 50 m of Late Miocene to recent, dominantly calcareous to subordinate siliceous clays and oozes, as well as unusual Mn-Fe rich clays towards the base.

There are no contract areas or known exploration over November Plain, although Kennecott are thought to have sampled at least part of the region in the early 1970s (Lipton et al., 2016). (Morgan, 2017) makes the

case for an additional APEI (recently defined APEI 12; Figure 2-3) which overlaps with the northern-eastern part of November and adjacent Zulu Plain. To support this, he notes that the area is representative of existing areas under exploration contracts, namely in terms geomorphology, densities of benthic life, mineral resource abundance and metal content (of nodules). The eastern third of November Plain is shallower (<4000 m) and lies within the exclusive economic zone (EEZ) of Clipperton Island (Figure 2-2).

2.4.1.3 Zulu Plain

This extensive (586,000 km²) triangular plain to the east of Mike Plain and north of November Plain is at 3,000 – 4,000 mbsl (Figure 2-10) and is not thought to be prospective for nodules due to its relatively shallow depths. The northern limits at Clarion Fracture Zone show little depth change to the adjacent plate segment. The seabed age varies from about 5 Ma to around 15 Ma (mid Miocene). Zulu Plain's eastern limit is defined by the Mathematician Seamounts, and the north-eastern 40% of Zulu Plain lies within the EEZ of Clarion Island (Mexico). There are some tall seamounts within Zulu including the 16-17 Ma Shimada Seamount, whose summit is only about 30 m below sea level (Gardner et al., 1984).

The southern and central part of APEI 6 lies within this plain and there has been some AUV and box-core based reference environmental surveys (e.g. Durden *et al.*, 2017; Taboada *et al.*, 2018). There is little else known about Zulu Plain.

2.4.1.4 Lima Transition

Lima Transition spans the CCZ north-south as an irregular strip and marks the change from the eastern part of the CCZ to the central part (e.g. India, Kilo, Quebec and Golf Plains). It is an area of 209,000 km² at around 4,400-4,600 mbsl, i.e. it drops ~200 m over ~200 km from east to west (Figure 2-10).

The seabed is around 27 Ma to 30 Ma in age (Oligocene). DSDP site 159 (far eastern transect 16A in section 9.7) is located on the eastern edge of Lima Transition near X-ray Low. The site returned a 110 m thick sedimentary profile bottoming in fine grained altered basalt with ~80 m of late Oligocene to mid Miocene calcareous clays, ooze and marls covered with 18 m of silicious oozes of upper Miocene to Pleistocene age (van Andel et al., 1973a).

The unit is slightly better defined in the south where adjacent Kilo and Mike Plains are flatter. In the north it is generally more diffuse and gradational with similar slopes to India plain and northern part of Mike Plain. Abyssal hill traces are similar to the adjacent plains i.e. trending $\pm 350^\circ$. Larger seamounts seem to be restricted to the northern and central parts of the unit and mostly part of WNW trending chains. Both ends of the transition have step-type units with tectonic features: there is a distinctive offset fault in the Clarion Fracture Zone at the northern boundary and a curve in the Clipperton Fracture Zone at the southern boundary (Figure 2-10).

The northern part of Lima contains nodule exploration contract areas. The DOMES C site is located here as well (Deep Ocean Mining Environmental Study, 1981). Part of the southern part is covered by ISA reserved areas and APEI 9.

2.4.1.5 India Plain

The southern-central part of the roughly square India Plain (200,000 km² at 4,600-4,900 mbsl) has been identified as one of the most prospective locations for nodules in the CCZ (Figure 2-27, Figure 2-28). This plain is located just north of the centre of the CCZ and is bounded to the south by Juliette Low, to the west by Hotel Low and to the east by Lima Transition (Figure 2-10). The southern-central part of the plain is partly

separated to the northern part by Romeo Low. The northern part is complex with numerous knolls and seamounts. The crustal age is 30-35 Ma (latest Eocene to mid Oligocene).

Some published 12 kHz bathymetry and ship-tracks shows that in NW India Plain, abyssal hills trend 350°, but that locally they do swing up to $\pm 30^\circ$.

With consistently high abundance of nodules (Figure 2-27), the southern-central part of India Plain is covered with exploration contracts/licenses and is thought to have been fiercely negotiated as part of the Reciprocating States Agreement of the 1980s (Lipton et al., 2016). KCON's priority Albatross area included the SE majority of the plain. At least two ISA Contractors have stated priority development areas in India Plain (Melnik and Lygina, 2010; Fouquet et al., 2014). Recently defined APEI 13 (Figure 2-3) covers the southwestern corner of India as well as adjacent Hotel and Juliatt Lows (and also happens to overlap the eastern side of the USA1-1 exploration license not recognised by the ISA).

Figure 2-13 uses hypsometric curves to compare India Plain with adjacent and nearby units (Kilo Plain and Romeo and Juliatt Lows). From south to north the units generally get deeper with a significant portion of Juliatt Low clearly deeper than the plains. Romeo Low is lower and less variable than India Plain (which encompasses it) albeit with about 15% overlap.

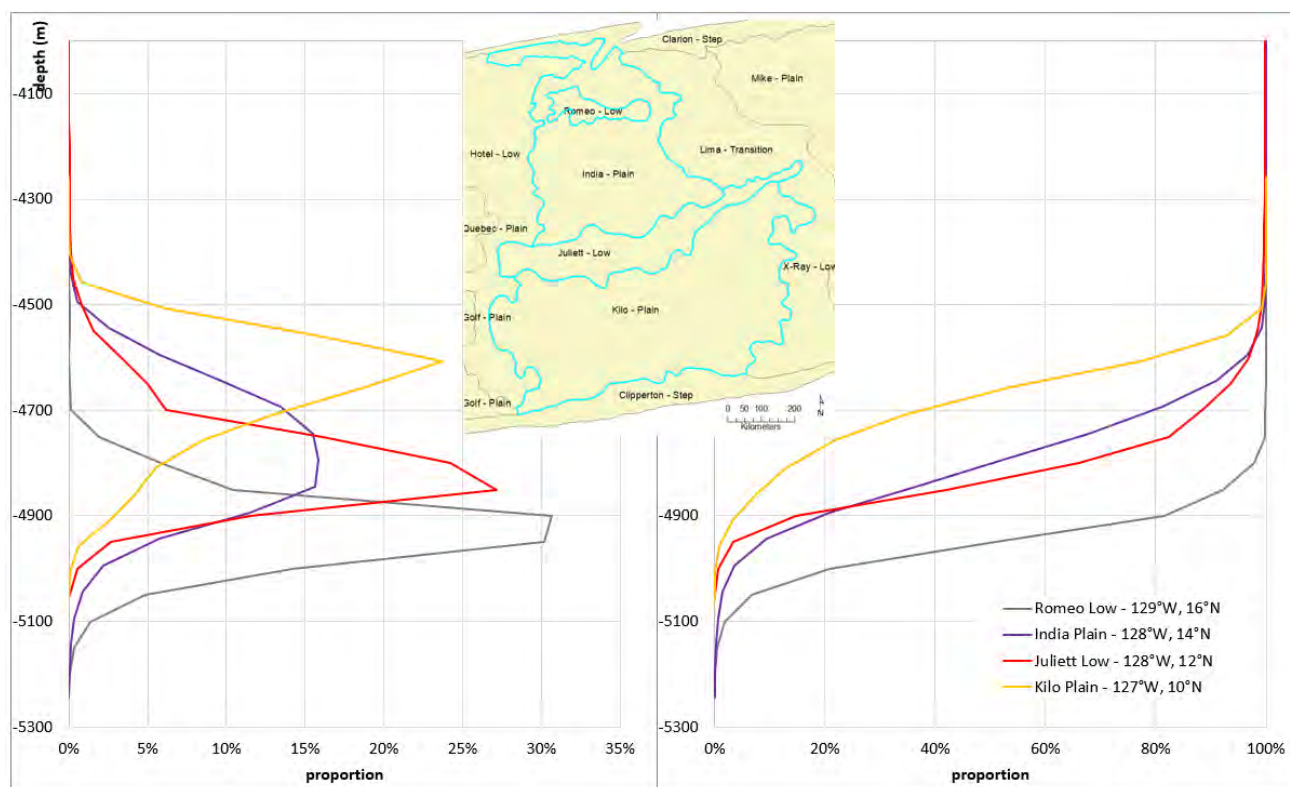


Figure 2-13: Hypsometric curves for India and Kilo Plains and Romeo and Juliatt Lows

2.4.1.6 Kilo Plain

Kilo Plain is larger than India Plain (322,000 km²) and has similar water depths (~4,700 mbsl), crustal age (33 Ma ± 5 Ma) and longitude, but is about 3° further south (Figure 2-10) and does not have the same nodule prospectivity.

The unit extends over 800 km WSW and 300 km N-S; mapped abyssal hill traces are rare but from the limited coverage they seem to trend consistently to 350°. The plain is bounded by the Clipperton Step to the south, Juliatt and Hotel Lows to north and west respectively and the Lima transition to the east.

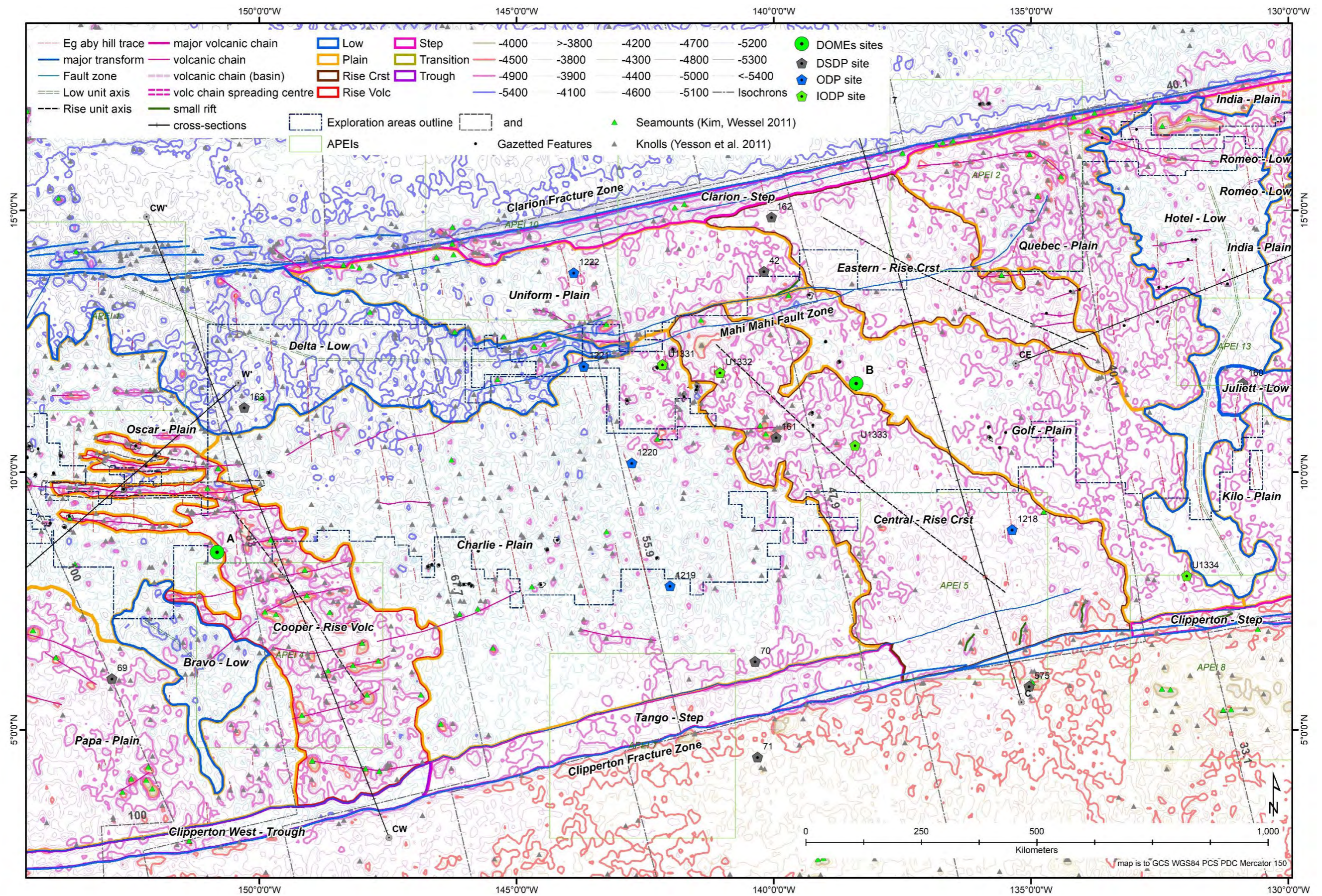


Figure 2-14: Central section of the CCZ

The northern part of Kilo is covered by returned areas and some parts of exploration contracts, but it is noteworthy that Korea Institute of Ocean Science and Technology, (2014) indicate that their priority area at more or less the same latitude, but further west and within Hotel Low at about 5,100 mbsl or about 400 m deeper (Figure 2-23).

APEI 9 covers the south-eastern corner of Kilo as well as the adjacent Clipperton Step.

2.4.1.7 Quebec Plain

Quebec Plain is roughly rectangular, trending NW between Eastern Rise and the western side of Hotel Low. It covers approximately 171,000 km² at around 4,900 mbsl (Figure 2-14, Figure 2-15). Crustal age is ±40 Ma (late Eocene). While the regional abyssal hills trend is still to 350°, some areas of hills in Quebec strike ±10° off north (Figure 2-8).

The north western parts of the plain include the likely termination of the Mahi-Mahi Fault zone. Associated with a bend in this fault, near the eastern termination, is a mapped area of calcareous seabed muds (Figure 2-15), with the bathymetry southeast of the fault suggesting the possibility of an uplifted block (i.e., shoaling Marquesas Formation chalk).

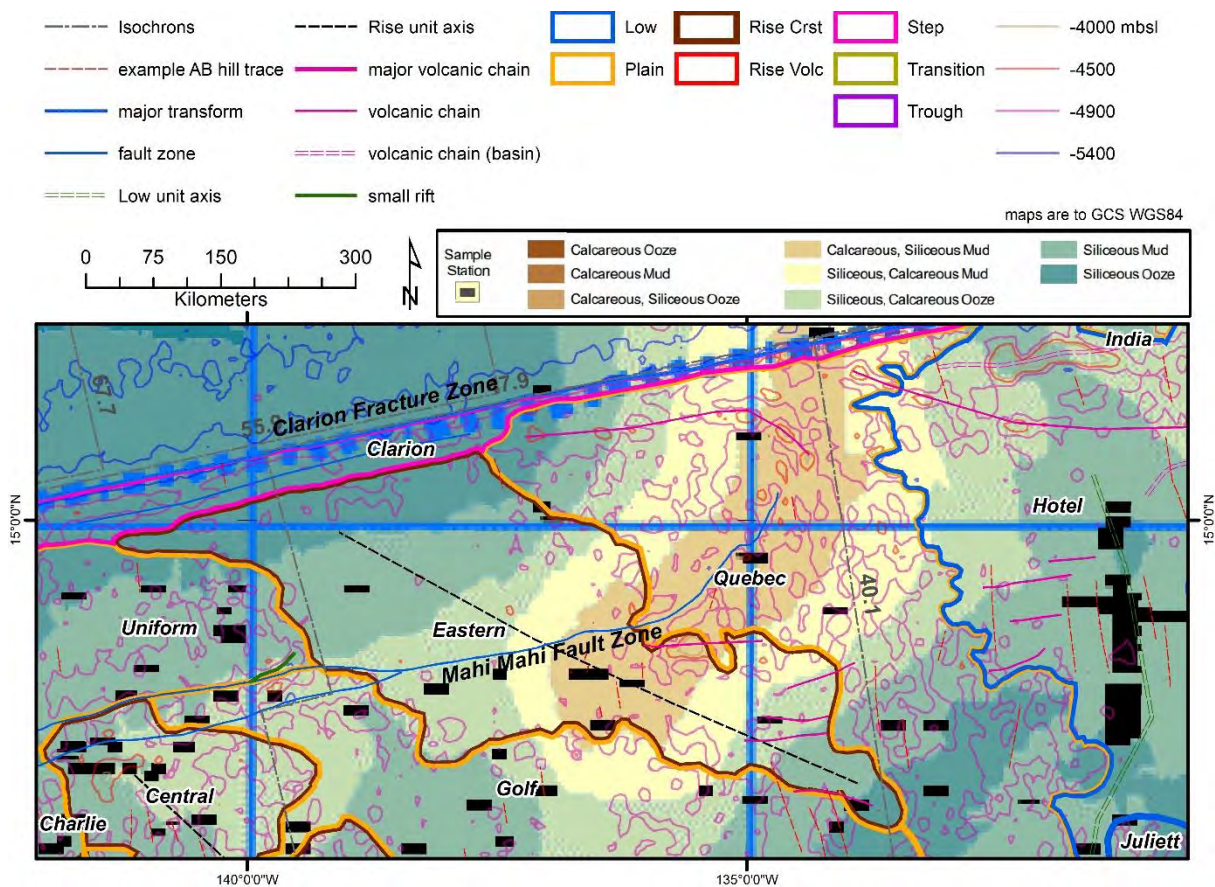


Figure 2-15: Features in Quebec Plain and Eastern Rise

Sediment map after International Seabed Authority, (2010a), black rectangles are sample stations.

The southern part of Quebec, with mapped surficial siliceous mud and ooze, is prospective for nodules as can be interpreted from the coverage of exploration contracts/licenses. The northern part of Quebec is covered by APEI 2.

Figure 2-16 uses hypsometric curves to compare Quebec Plain with some nearby units (Golf Plain, Eastern and Central Rises and Hotel Low. The two rises are overall significantly shallower than the plains and the low significantly deeper. Central Rise shows greater variability including some deeper parts than Eastern Rise. Hotel Low is quite consistent considering it spans the width of the CCZ. Golf and Quebec Plains have similar profiles, Golf Plain being a little deeper overall.

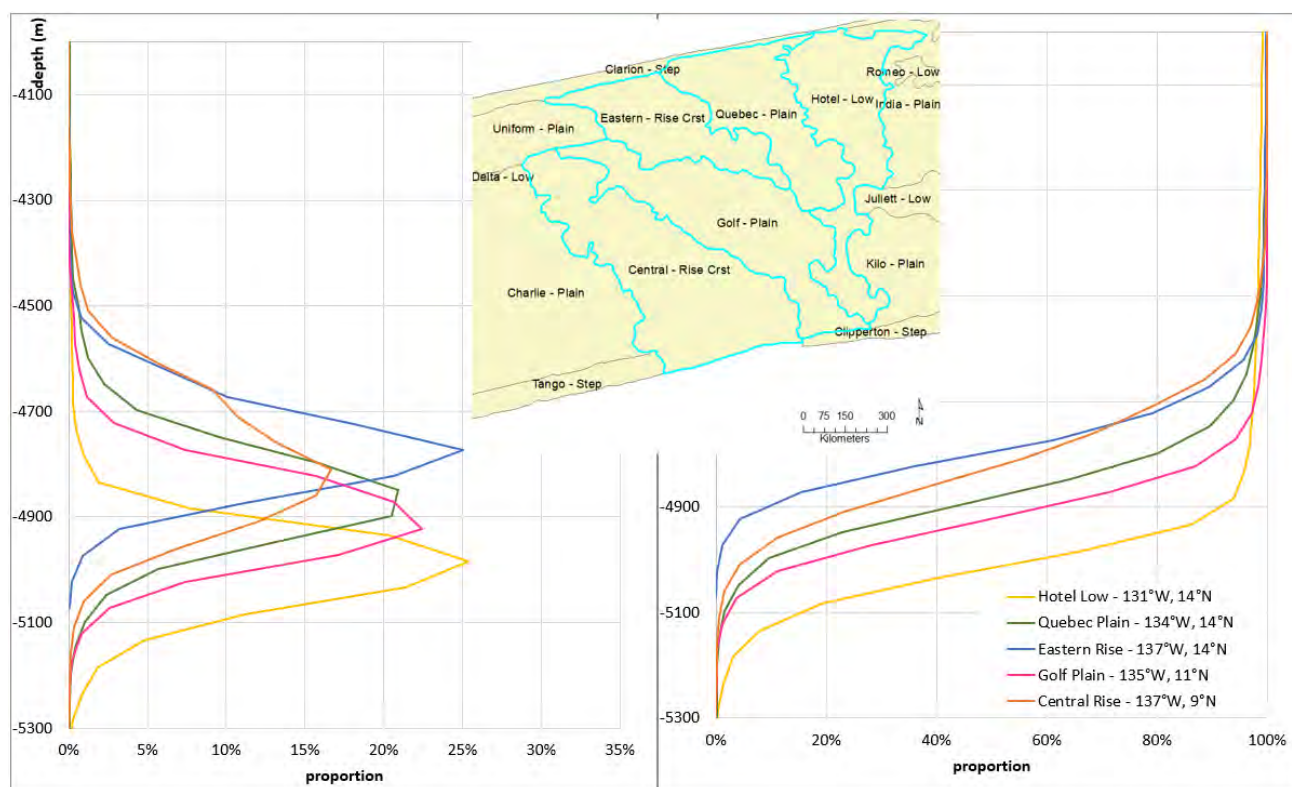


Figure 2-16: Hypsometric curves for Quebec and Golf Plains Eastern and Central Rises and Hotel Low

2.4.1.8 Golf Plain

This NW-SE elongate (800 x 290 km) plain is nestled between Central and Eastern Rises to the SW and NE respectively (Figure 2-14). Its south-eastern edge contacts Hotel Low, while to the NW it contacts Uniform Plain at the Mahi-Mahi Fault Zone. The plain is approximately 246,000 km² in area, at 4,900 to 5,000 mbsl. Abyssal hills seem to trend consistently to 350°.

The bulk of the seafloor basement formed between 50 and 40 Ma (Mid Eocene). IODP site U1334 (transect 320 in section 9.7) lies in the southern end of Golf Plain near Hotel Low. Pälike et al., (2009a) report a 285 m section ending in basalt, overlain by mid Eocene to early Miocene calcareous oozes, with the uppermost 50 m mostly comprising mid Miocene siliceous and calcareous clays and oozes.

Prospectivity for nodules is thought to be moderate to good in the northern part of Golf. This was a focus area for Ocean Management Inc in the 1980s (Lipton et al., 2016), and today is covered by exploration contracts.

2.4.1.9 Uniform Plain

This relatively small (162,000 km²) E-W elongate plain lies mostly at 5,100-5,300 mbsl (Figure 2-14) at the northern edge of the CCZ. It shallows to about 5,000 mbsl in the east. It is bounded by the Clarion Step to the north, Eastern Rise to the east, and Delta Low, Charlie Plain, Central Rise and Golf Plain to the south (in part along the Mahi-Mahi Fault Zone).

Crustal ages are from ~70 to 47 Ma (Paleocene to mid Eocene). DSP site 42 near the eastern end of the plain returned 100 m (un-bottomed) of mid Eocene to late Oligocene mixed subordinate calcareous and dominant siliceous oozes (The Shipboard Scientific Party, 1970). ODP site 1222 in the central part of the plain returned a broadly similar 100 m (un-bottomed) of ~30 m of mid to late Eocene siliceous cherts (likely Line Islands Oceanic Formation) directly overlain by ~70 m of Oligocene to recent siliceous ooze/clay (likely Clipperton Oceanic Formation; per transect 199 in Section 9.7).

There are no contract or reserved areas on Uniform Plain (all end at its southern margin, Figure 2-3), and very little more is known about it. Much like its neighbours, abyssal hills (seen only a few ship-tracks) strike $\pm 350^\circ$. The southern part of recently defined APEI 10 covers central Uniform Plain.

2.4.1.10 Charlie Plain

Charlie Plain is the largest single tectono-geomorphic unit in the CCZ covering 707,000 km² and spanning ~800 x 700 km (Figure 2-2, Figure 2-14). It mostly lies at 5,100-5,200 mbsl sloping very gently from south to north (an ~300 m drop over ~700 km). Part of the unit is covered by 12 kHz bathymetry survey areas (International Seabed Authority, 2010b; Deep Ocean Resources Development Co Ltd, 2014a). Abyssal hills consistently strike 350° and there are several distinct west to WSW trending volcanic chains extending from a bend in the Mahi Mahi fracture zone (*cf* also the orientation of those in Cooper Rise). A distinctive N-S positive relief feature at 140° W looks to be an artefact in the Gebco grid, but it does weakly align with seamounts and embayments in Central Rise.

The bulk of the seafloor basement formed between 80 and 50 Ma (latest Cretaceous to early Eocene). There are five DSDP/ODP/IODP drill sites in Charlie with transects 16B, 199 and to a limited extent 320 all crossing the unit (Section 9.7) on its eastern side. From south to north the drill sites show up to 120 m of calcareous oozes of early to mid Oligocene age (likely Marquesas Formation) lensing out against 70-100 m of underlying siliceous clayey ooze and cherts of early to mid Eocene age (likely Line Islands Formation), these being overlain by up to 30 m of siliceous oozes and clays of Mid Miocene to current age (likely Clipperton Formation). To the south, sites (1219,70) also contain basal units of mid Eocene calcareous or mixed units.

Charlie Plain is bounded by Rises to the east (Central) and west (Cooper), to the north by the western limits of the Mahi-Mahi Fault Zone and Delta Low, and to the south by Tango Step.

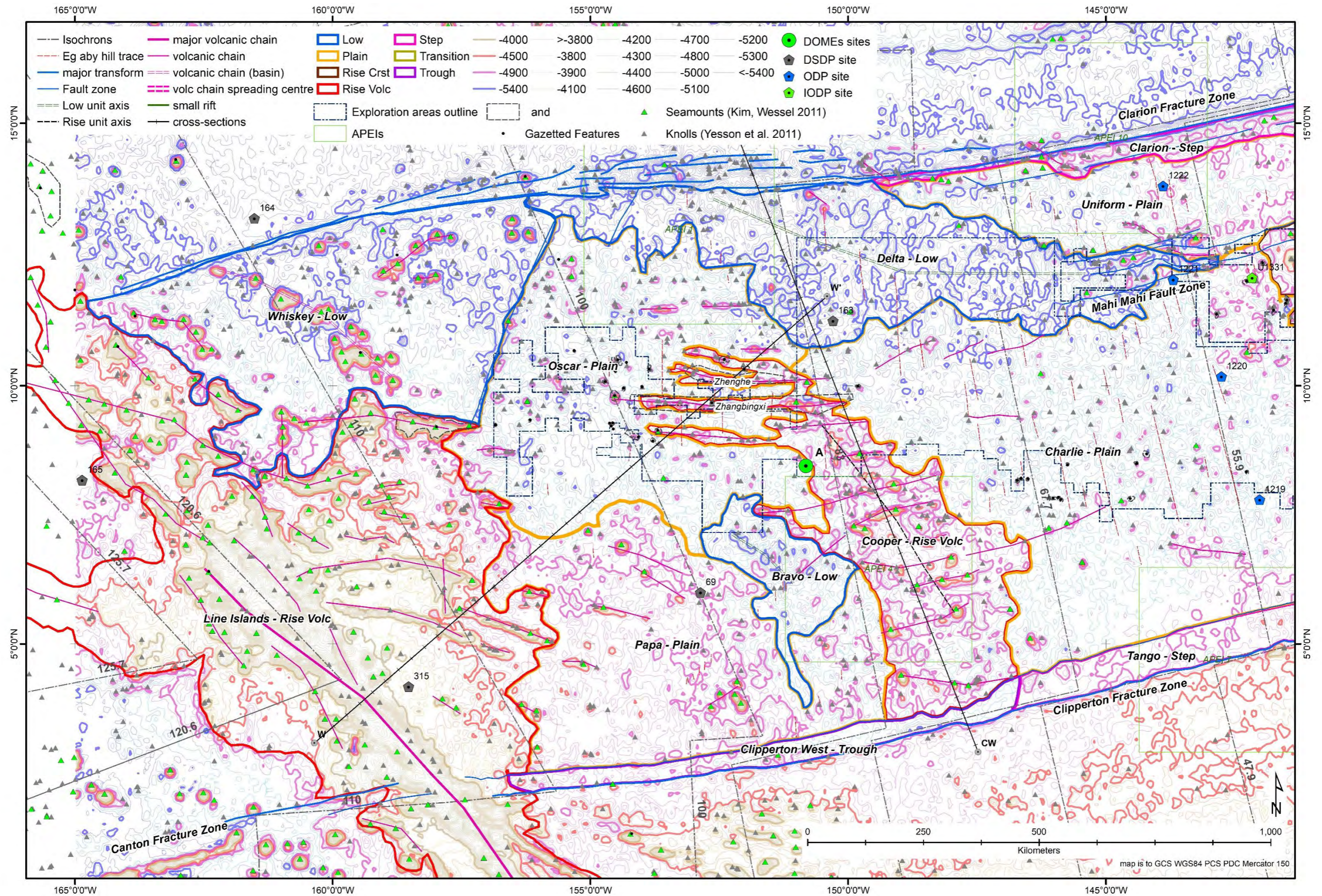


Figure 2-17: Western end of the CCZ

The northern and central parts of Charlie Plain are covered with exploration areas. The priority area of Deep Ocean Resources Development Co Ltd (2014a) is located on slightly elevated plateaux on the northern limit of Charlie Plain. Northern APEI 7 spans the Clipperton fracture zone, the bounding Tango Step and part of the southernmost part of Charlie Plain.

Figure 2-18 uses hypsometric curves to compare Charlie Plain other units to the west (Papa Plain, Cooper Rise and Bravo Low). While Bravo Low is significantly deeper than adjacent Cooper Rise and Papa Plain it has a similar only slightly deeper profile to Charlie Plain but with a larger proportion of the deepest portion. Papa has a very broad profile due to it shallowing slightly against the Clipperton fractures zone and Line Islands Rise. Cooper Rise also has a broad profile, but a much higher proportion of shallower areas related to the common seamounts within the rise.

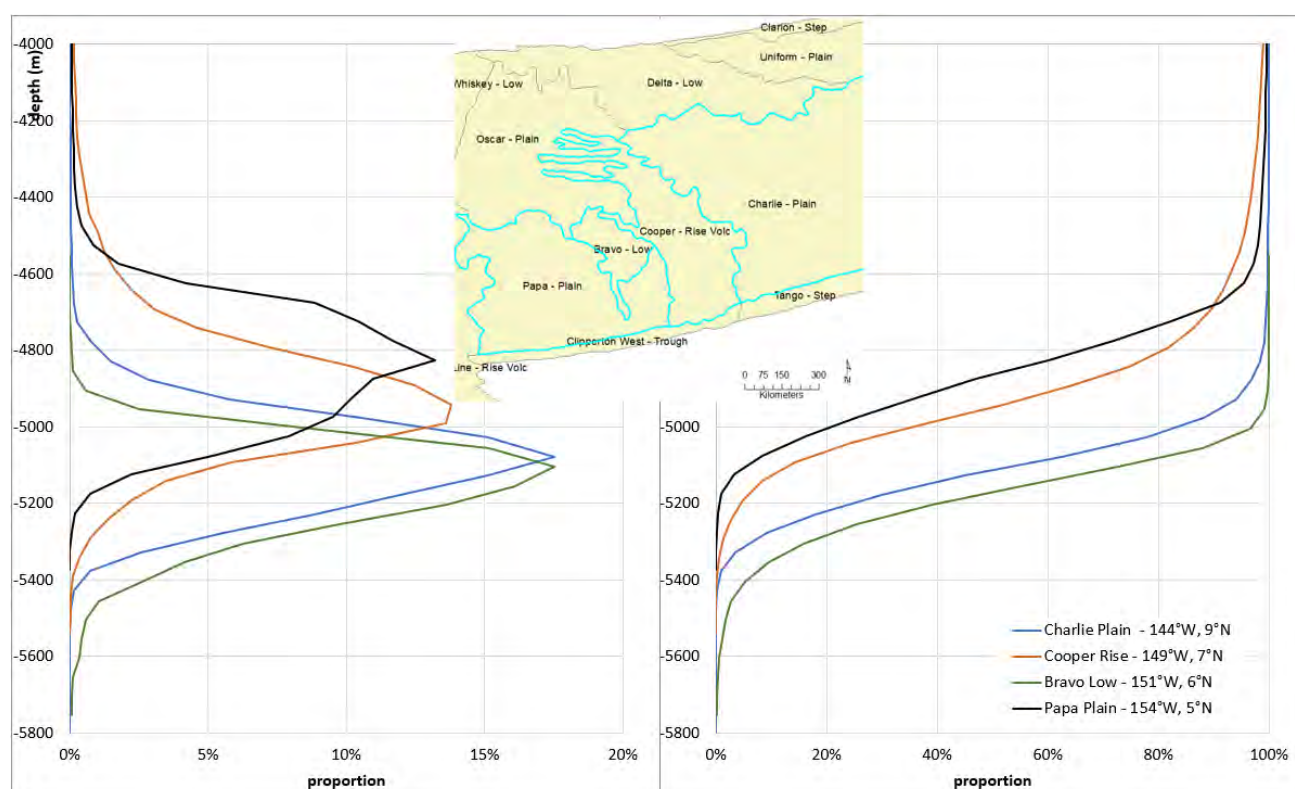


Figure 2-18: Hypsometric curves for Charlie and Papa Plains, Cooper Rise and Bravo Lows

2.4.1.11 Oscar Plain

Oscar Plain covers approximately 336,000 km² at 5,100 to 5,200 mbsl (i.e., it has similar depths to Charlie Plain despite being located ~1,000 km to the west). It is, in effect, the area between the north-western end of Cooper Rise and Line Rise (Figure 2-17), and like these units it also contains numerous seamounts. The bulk of the seafloor basement formed between 110 and 80 Ma (mid to Late Cretaceous). Abyssal hills at this end of the CCZ (i.e., Oscar and Papa Plains) have a different trend i.e. $\pm 360^\circ$. This change in angle suggests that the spreading direction turned about 10° from slightly north of west to slightly south of west at ± 80 Ma which is broadly consistent with the isochron pattern (Figure 2-1, Figure 2-17, (Müller et al., 2016)) and which in turn suggests that spreading accelerated at the northern side of the plate segment relative to the southern side between 80-100 Ma (Section 2.5.1 **Error! Reference source not found.**). Note however, that the 100 Ma isochron itself is at a markedly highly angle to the abyssal hill traces (Figure 2-17) which is

inconsistent with these observations. There is a distinct 450 km long NNE trending fracture defining the NW side of Oscar Plain and the neighbouring Whiskey Low. In the southeast, the Bravo Low is a gradational contact between Cooper Rise and Papa Plain.

Nodule potential in central-southern Oscar is thought to be modest but includes locally good abundances between the seamount chains (e.g., Figure 2-27); several exploration contracts and reserved areas are located here. APEI 1 covers most of northern Oscar Plain as well as the adjacent western part of Delta Low.

2.4.1.12 Papa Plain

This complex 319,000 km² plain extends from the Line Islands Rise east to Bravo Low and Cooper Rise. Most of the plain is a 4700-4800 mbsl (i.e., ~500 m shallower than Oscar Plain), but it is as shallow as 4500 mbsl adjacent to Line Islands Rise and deepens to 5200 m in the east (Figure 2-17). There are ESE trending seamount chains extending from the rise. As for Oscar Plain, the bulk of the seafloor basement formed between 110 and 80 Ma (Mid to Late Cretaceous) and rare coverage in ship-tracks shows abyssal hills traces trending $\pm 360^\circ$. DSDP site 69 had some recovery problems but found an upper layer (minimum 32 m) of silicious ooze of up to Early Miocene age (likely Clipperton Formation) over calcareous ooze of about 90 m (likely Marquesas Formation) over another minimum 90 m of siliceous ooze and cherts (Line Island Formation; Tracey et al., 1971).

There are no contract areas or APEI over Papa apart from the SW corner of APEI 4 and so very little is known about it. Papa Plain is close to Kiritimati Island (<500-1,000 km) and is thought to contain a full spectrum of calcareous to siliceous sediment (International Seabed Authority, 2010a).

2.4.2 Defined Rises

Rises are found in the central and western CCZ, comprising ~20% by area. There are two types:

1. Raised Crust type in the central CCZ (Eastern and Central Rises); and
2. Volcanic Chain type in the western CCZ (Cooper and Line Islands Rises).

Raised crust type rises are fairly subtle areas of seafloor that are typically only 300 to 500 m higher than adjacent Plains. Like the Plains they are typically composed of abyssal hills, with some rarer plateaux, although in some cases abyssal hills are either subtle or even absent. Volcanic Chain type Rises also include discrete to composite or amalgamated knolls and seamounts, these typically rise 500 m to 2,000 m above the surrounding seafloor.

The rises in the CCZ all trend between 300° and 340° , which is distinctly different to the abyssal hill trends. While the abyssal hills strike more or less perpendicular to the plate segment extension direction (which is WSW) the rises are oblique by 20° to 80° suggesting that their origin is possibly due to differential transform stresses relating to overall Pacific plate motion, and the differential speed of the plate segments (Figure 2-1, discussion section below).

Most of the rises have one end terminating at a (subvertical) fracture zone and tend to be broader at this end, suggesting that their formation relates to accommodation via buckling at depth (refer also to section 2.5.1).

2.4.2.1 Central Rise

This is the largest (~328,000 km²) rise in the CCZ and trends to the NW (~315°; Figure 2-14). Seamounts are relatively uncommon with only a few clusters in evidence (much like those also found on most of the plains). Abyssal hill traces are more common at the northern and middle parts of the rise and strike 350° and parallel to the traces seen in adjacent plains.

The crust was formed between 40 (SE end) and 50 Ma (NE end), i.e. early to mid-Eocene. There are four IODP/ODP/DSDP drilling sites on Central with transect 320 running partly along the ridge axis towards its eastern edge (Section 9.7). From NW to SE the transect shows a slightly younging basal sequence of sedimentary cover with mid to late Eocene siliceous ooze (possible Line Islands Formation) grading into Eocene to Oligocene chinks (Marquesas Formation) and then, in the case of site 1218, Miocene siliceous oozes or, at other sites, a hiatus to Pleistocene to recent siliceous oozes (all Clipperton Formation).

The southern broader edge of the rise ends at the Clipperton Fracture Zone, with Central Rise rising from about 4900 to 4700 mbsl at the fracture zone where it meets Tango and Clipperton Steps (Figure 2-14, Figure 2-19). The rise also intersects the fracture zone at a point where the fracture zone's trend swings slightly more southerly (Figure 2-2, Figure 2-8). There are three small (~50 x 10 x 0.5 km), but distinctive NNE en-echelon oriented rifts in the southern end of the rise. These presumably relate to local structural accommodation (Figure 2-19). Abyssal hills at the SE end of the rise seem less well defined (Figure 2-21).

The northern end of Central is truncated by the Mahi-Mahi Fault Zone, a distinctive zone of faulting extending from Delta Low, sub-parallel to the Clarion Fracture Zone for most of its length and terminating in Quebec Plain. There are several known seafloor hydrothermal systems nearby, located along the Mahi-Mahi Fault Zone (International Seabed Authority, 2010b).

Only the northern part of Central contains exploration areas, and APEI 5 covers the southern end.

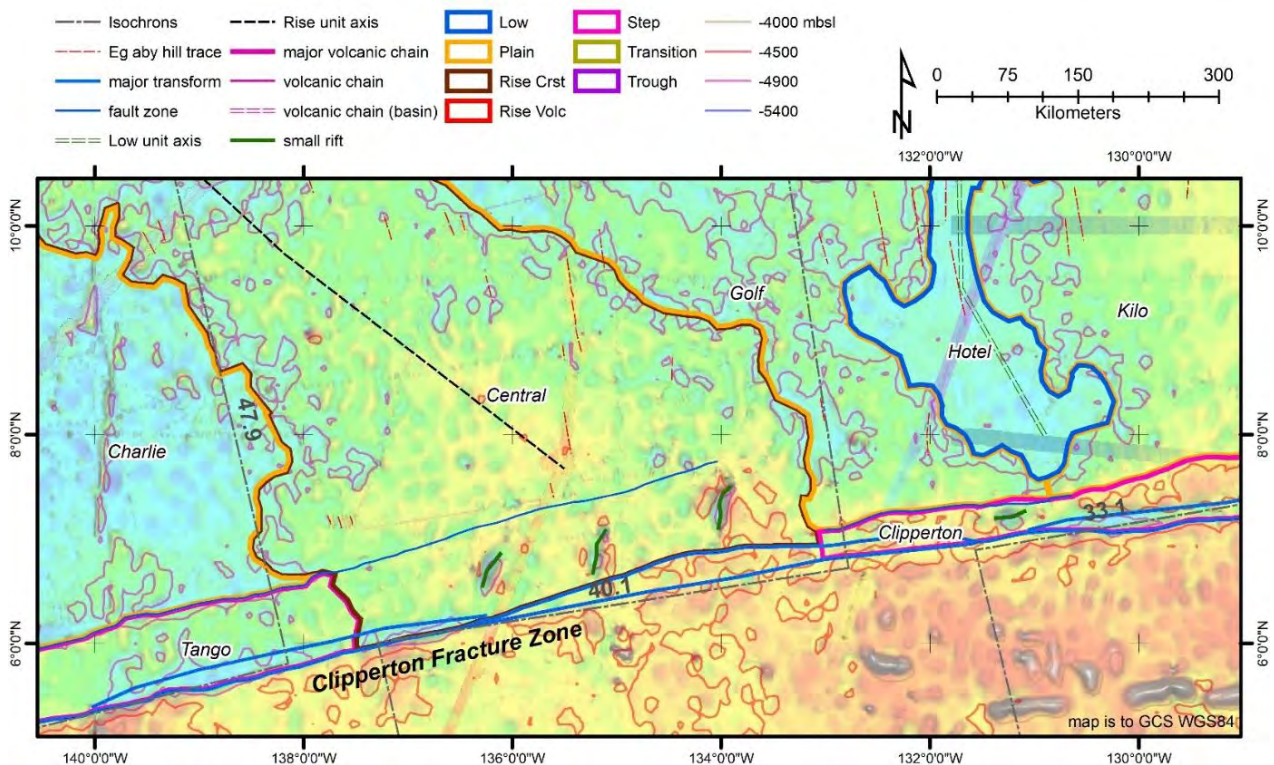


Figure 2-19: Structural features at the SE end of Central Rise

2.4.2.2 Eastern Rise

This ‘small’ rise (~142,000 km² at about 4,800 mbsl) trends ~120° from a wider than normal Clarion Step/Fracture zone (Figure 2-2, Figure 2-14), and lies between Uniform and Quebec Plains. It is crosscut by the eastern extents of Mahi-Mahi Fault Zone, expressing here as a relatively minor lineament. There is no clear sign of throw within the rise itself, although the 47.5 Ma Chron is offset dextrally ~75 km across the Mahi-Mahi Fault Zone immediately to the west.

Like Central Rise, the crust in Eastern Rise mostly formed between ~40-50 Ma (early to mid-Eocene). DSDP site 162 is located at the north-eastern corner of the rise (van Andel et al., 1973c). Drilling at the site ended in weathered basalt and several metres of ashy mixed sediments, overlain by ~150 m of predominantly silicious and minor calcareous oozes of mid-Eocene to early Oligocene age.

Abyssal hill traces are rarely seen on Eastern Rise due to paucity of 12 kHz or ship-track data. However, along the north-eastern edge of Eastern Rise, a single ship-track suggests they might be absent (Figure 2-21). Bathymetry at the southeast tip (Melnik and Lygina, 2010), shows the presence of relatively extensive flat areas in their “I2 area” that are thought to have extensive deposits of nodules (so called “Cloak Type”; Figure 2-20). 12 kHz bathymetry in the SE part of the rise indicates several seamount chains. A seabed sediment composition map from International Seabed Authority (2010b) indicates that more calcareous sediments are found in the centre of the rise and to the NE in Quebec Plain (Figure 2-15).

Like nearby parts of Golf and Quebec Plains and Hotel Low, the south-eastern end of Eastern is thought to be quite prospective as it is covered with exploration areas.

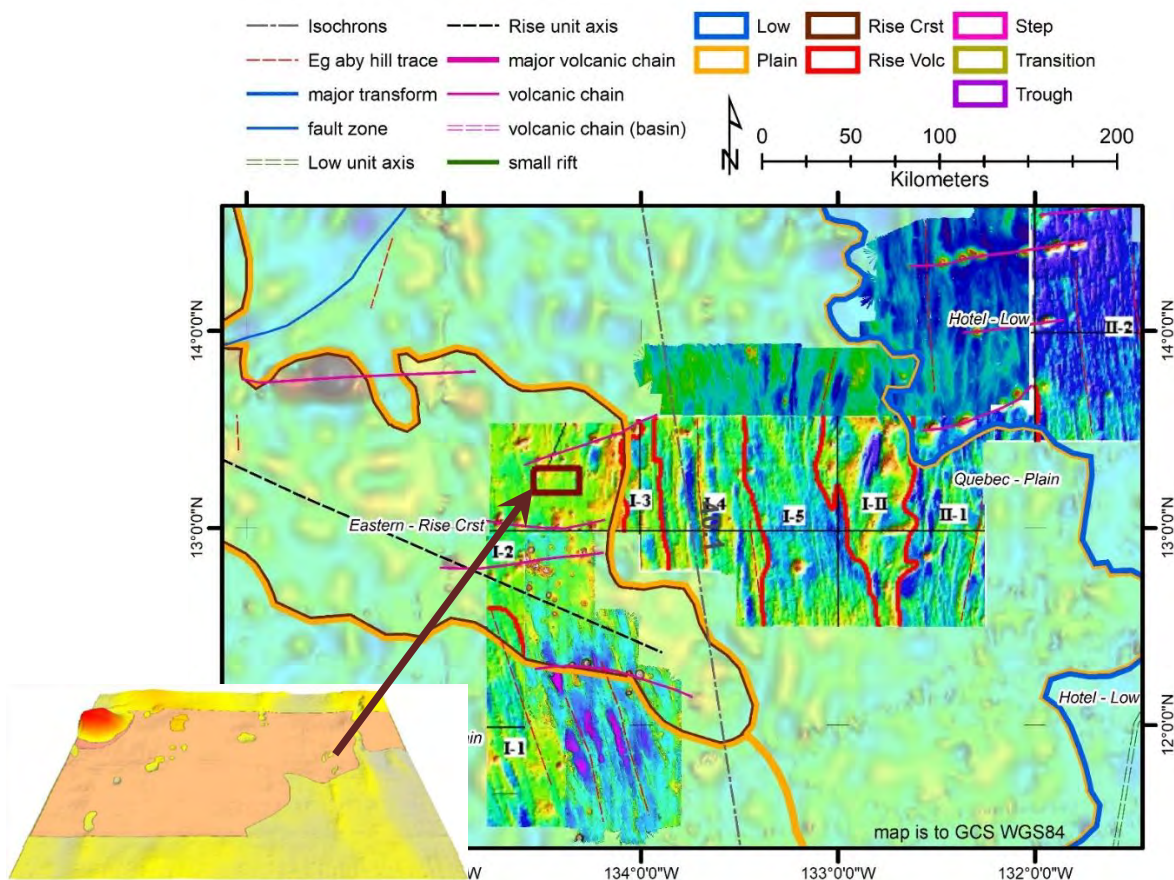


Figure 2-20: Bathymetry on and near the south-eastern end of Eastern Rise

Note relatively flat seafloor on 12 kHz MBES and in inset from Melnik and Lygina, (2010)

2.4.2.3 Cooper Rise

Cooper Rise covers approximately 214,000 km² at 4,900-5,000 mbsl and has an overall curving trend from 350° in the south to ± 315° in the north (Figure 2-8, Figure 2-17). It is distinctive for having numerous small to large seamounts both along the rise and also forming finger like seamount chains (e.g., the Zhangbingxi and Zhenghe seamounts) that extend west to WNW from its northern end (a similar trend seen in seamount chains in intervening units up to the northern end of the Line Islands Rise). These seamounts can rise several thousand m above the rise itself. The seamounts likely relate to local N-S extension related to a slightly northerly divergence in the Clarion Fracture Zone relative to Clipperton Fracture Zone (and associated formation of the Delta Low and Mahi-Mahi Fault Zone; Figure 2-17).

At its southern end, Cooper Rise contacts the eastern end of Clipperton West Trough immediately north of the Clipperton Fracture Zone. There is a paucity of ship-track or other 12 kHz data, but abyssal hills seem restricted to the northern parts of the rise and may be trending due north (as in west-adjacent Oscar Plain) rather than to 350° (as in east-adjacent Charlie Plain).

The crustal age of the rise is mostly between 70 and 90 Ma (Late Cretaceous). The age of the seamounts is unknown, but isochrons suggest that the timing of much of the movement along the Mahi-Mahi Fault Zone is between 40 and 47 Ma (mid to late Eocene).

APEI 4 covers the central and southern part of Cooper Rise, exploration contracts being restricted to the northern-most end. The western COMRA exploration contract area overlaps from Oscar Plain to Cooper Rise and has an intricate boundary to try and avoid the Cooper seamounts (Figure 2-3).

2.4.2.4 Line Islands Rise

This very significant volcanic chain is the western limit of the CCZ; further to the west lies the central Pacific Basin. The Clarion Fracture Zone terminates against the rise, and evidence for Clipperton Fracture Zone continuing through is limited, although the Canton Fracture Zone continues on the same trend (with perhaps a slight right lateral offset; Figure 2-17). Considering only the portion of the rise that lies between a hypothetical extrapolation of the CC fracture zones, the Line Islands Rise is large (~680,000 km² or about ½ of the total surface area of all the rises) and complex in form. The central-southern core of the rise is a massive volcanic edifice that in places almost reaches the sea-surface (e.g., Teraina, and Tabuaeran Coral Atolls; Figure 2-9). To the north, the Line Islands Rise comprises irregular massifs and discrete seamounts, to the east (and a lesser extent the west) there are seamount chains and volcanic ridges up to several kilometres high and several hundreds of kilometres long. Many of these seamount chains extend into adjacent Papa Plain and Whiskey Low (Figure 2-17). Orientations are predominantly WNW or NNW.

Original crustal ages were likely early Cretaceous, but there is evidence for multiple volcanic events (Ballmer et al., 2009; Storm et al., 2011; Pockalny et al., 2015), and it is noted that the isochrons of Müller et al., (2016) change direction significantly on or near the rise (in the Central Pacific Basin they generally age south to north and are in effect the south-east corner of the Pacific Triangle (Boschman and van Hinsbergen, 2016)).

Sediment cover on the rise can be very significant. DSDP site 315 (Figure 2-17) found about 700 m of cyclical to variegated dominantly calcareous (50->95% CaCO₃) ooze and chalk over about 300 m of transported intercalated volcanoclastics and claystones, that in turn rest on basalt basement (The Shipboard Scientific Party, 1976). At site 316 they found about 600 m of mostly carbonate dominated ooze and chalk over about 200 m of mixed carbonate and volcanoclastics.

There are no ISA exploration contracts or reserved areas on the Line Islands Rise. Much of the Rise lies within the EEZs of Kiribati and the United States (Figure 2-2), and past exploration in the area found that carbonate sediments predominate, with few or no nodules (International Seabed Authority, 2010a).

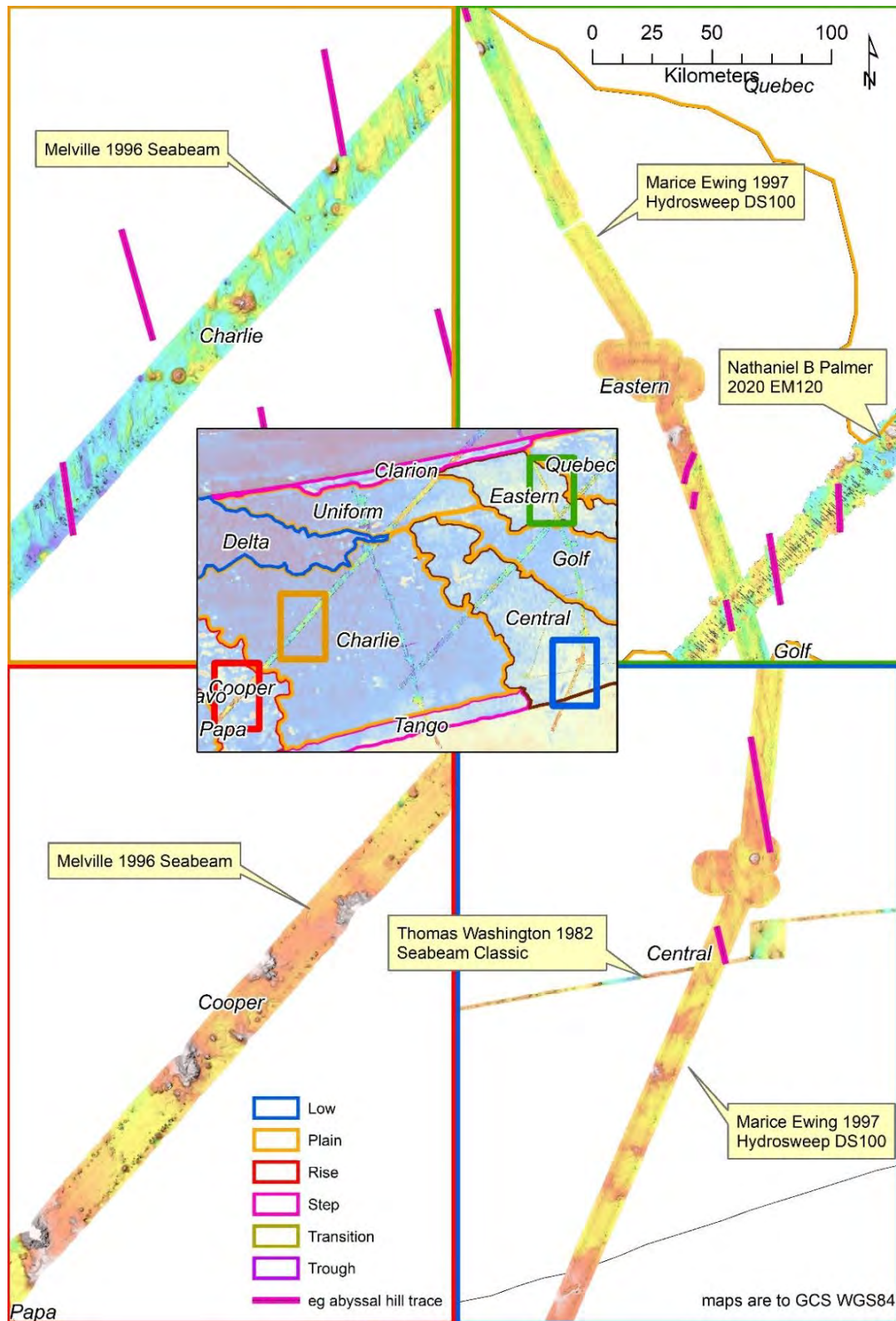


Figure 2-21: Seabed with subdued or absent abyssal hills on some of the rises
Ship-track through Charlie Plain shown to contrast with the other areas.

2.4.3 Defined Lows

Lows are areas that are typically several hundred metres lower than adjacent plains. They comprise ~15% of the area of the CCZ (~17% if the Line Islands rise is not included). Unlike the rises they are oriented in a variety of directions. Some of the lows have chains of volcanoes (knolls and seamounts) along their axes (Figure 2-22). The abyssal hills within the lows are often muted in terms of relief or even absent.

Parts of Hotel, Delta, Bravo and Whiskey Lows, as defined here, correspond with the “basins” unit of Harris et al., (2014); Figure 2-4).

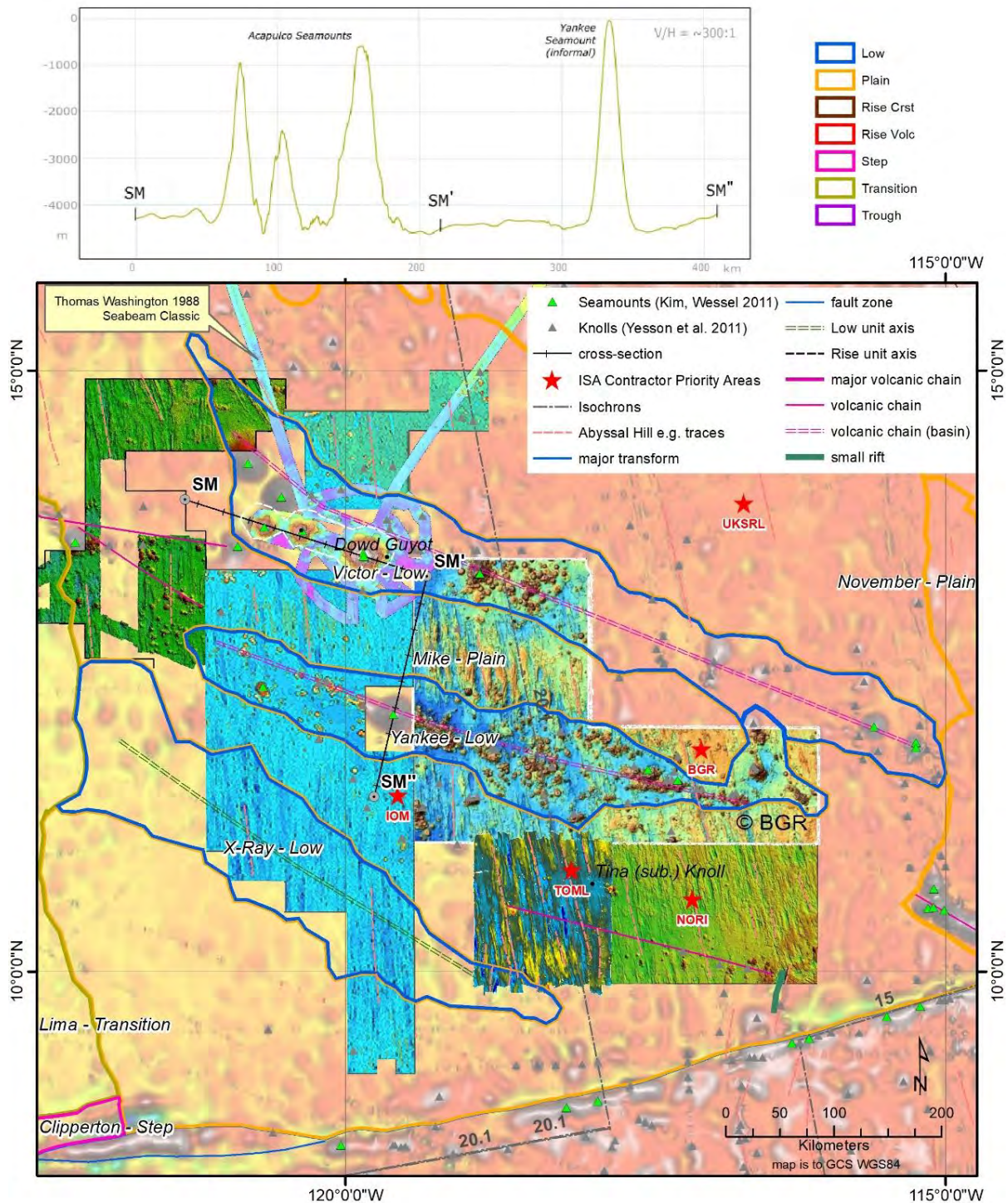


Figure 2-22: Features in and around X-ray, Victor and Yankee lows

2.4.3.1 Victor Low

Victor Low strikes $\sim 295^\circ$ over 600 km, and covers approximately 55,000 km². It has a floor at around 4,500 mbsl (or ~ 300 m below the adjacent Mike Plain, Figure 2-9, Figure 2-10), with subdued to absent abyssal hill traces and common seamounts, including Dowd Guyot within the Acapulco Chain (Figure 2-22). Within the NORI C area the northernmost seamount shows clear evidence for recent effusive lava flows from vents at the northern base (Figure 3-51 in Chapter 3). Isochrons indicate crustal formation at 20 Ma \pm 3 Ma (early Miocene). Victor Low crosses a range of exploration contract areas focused on the high potential of nearby Mike Plain.

Like X-ray and Yankee Lows, Victor is broadly parallel to the overall direction of plate motion i.e. the Hawaiian – Emperor trend, and as such a small hot-spot origin for the seamounts in Victor and Yankee might be considered. Arguments against such an origin include that the lows are not actually perfectly parallel (heading 154° 162° and 146° , from NE to SW respectively) and recently emergent volcanism at the NW end of the chain (section 3.3.4.2) is opposite to where it would be expected, if there was a discrete hot spot origin.

2.4.3.2 Yankee Low

Yankee strikes ~ 400 km towards 285° and covers approximately 36,000 km². Like Victor it has a floor at around 4,500 mbsl (or ~ 300 m below the adjacent Mike Plain), but with very common seamounts that can be over 1,000 m high (Figure 2-10, Figure 2-22). Abyssal hill traces are subdued relative to the adjacent plain. Crustal ages are similar to those of Victor Low.

Despite common seamounts, Yankee is contained within ISA exploration contract areas (Figure 2-22), with the occlusion of one large seamount (“Yankee Seamount”) whose summit appears to be just below sea level (-21 m from the GEBCO 2020 grid). Yankee Seamount is identified in the classification of (Kim and Wessel, 2011) (unnamed; Peak ID = 3606273), but they indicate a depth of 460 m below sea-level. This may be an issue of resolution, as (Kim and Wessel, 2011) used utilized the 1-min Mercator VGG grid (version 16.1) while this interpretation relies on the 15 arc second resolution of GEBCO 2020 grid.

Note that priority areas of Interoceanmetal Joint Organization, (2014) and Lipton et al., (2016, 2019) are located in Mike Plain between Yankee and X-Ray Lows, and the priority nodule resource area of (Vink et al., 2017) on Mike Plain also, but on the northern side and eastern end of Yankee Low.

2.4.3.3 X-Ray Low

X-Ray Low lies 100-300 m below Mike Plain (i.e. at around 4,500 mbsl) covering about 43,000 km². It strikes 305° , i.e. sub-parallel to the more northerly located Yankee and Victor Lows (Figure 2-10, Figure 2-22) but unlike them it does not contain discernible seamounts or even large knolls. While fairly subtle on the GEBCO grid (section 10.1); it is slightly more apparent on the published 12 kHz multibeam bathymetry, and there are relatively strong model currents along its axis (Figure 2-4).

The low transects the southern part of a single ISA exploration contract area and has well defined abyssal hills (Figure 2-10) striking to about 350° , i.e. similar to those in Mike Plain. The seabed crust formed between 20 and ~ 25 Ma (early Miocene).

2.4.3.4 Hotel Low

Hotel Low trends N-S over almost the entire width of the CCZ ($\pm 1,000$ km) and covers 199,000 km² at depths of around 5,100 mbsl. While the main trend of the low is N-S, at several points there are E-W or NW-SE trending embayments (Figure 2-10). Abyssal hill traces are often well defined (again striking 350°) and volcanic chains relatively small and often striking E-W. Isochron ages for the crust are around 37 Ma \pm 2 Ma (latest Eocene). The abyssal hills within the low, within TOML areas B and C show generally broader wavelengths and deeper amplitudes than those in other areas outside the low (Figure 3-17 in Chapter 3).

The central-northern part of Hotel Low is prospective for nodules with total coverage of ISA exploration contracts and licenses. There is a notable step south in the northern boundary of exploration areas along the border between Hotel Low and Quebec Plain (especially if some reserved areas are not considered). There is only one significant contract area in the south parts of the low. This includes the priority area of Korea Institute of Ocean Science and Technology (2014), on the eastern edge of the low (Figure 2-23).

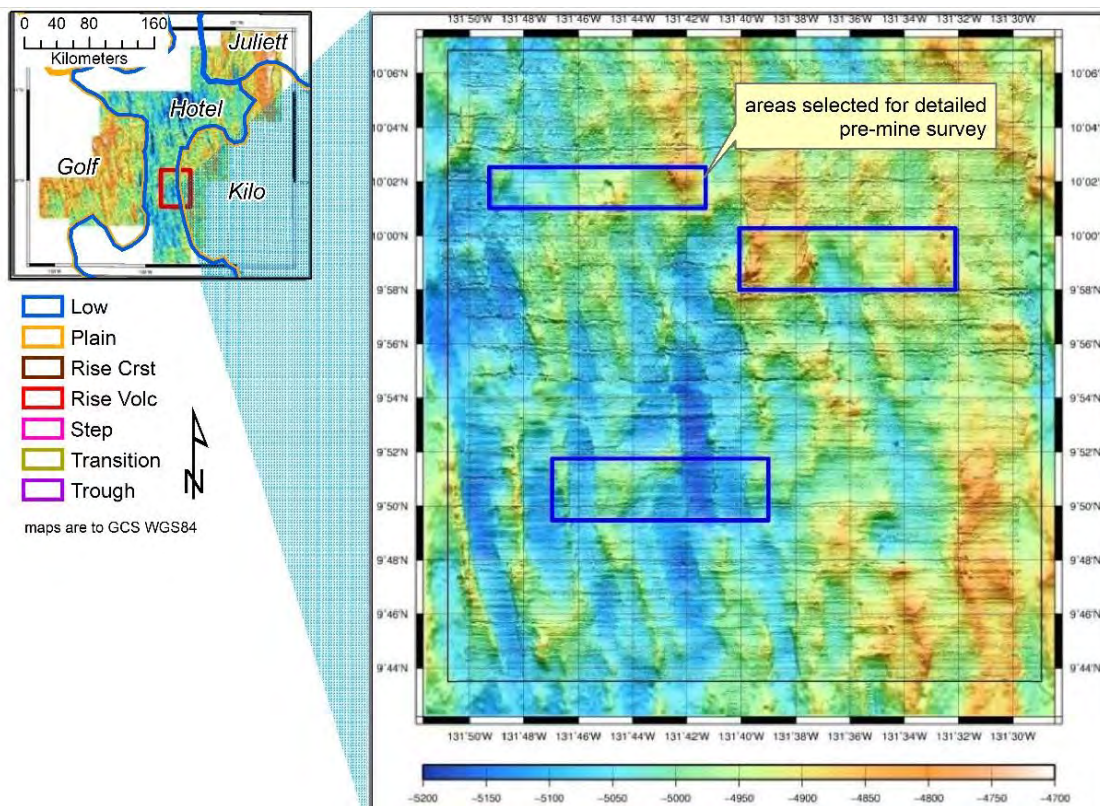


Figure 2-23: Priority Area within southern Hotel
after (Korea Institute of Ocean Science and Technology, 2014)

2.4.3.5 Romeo Low

This small E-W trending Low covers approximately 16,000 km² at 5,100 to 5,200 mbsl. It is encompassed by India Plain (Figure 2-10) and is 100-200 m deeper. Romeo Low's western end is only 12-50 km from northern Hotel Low. There is a little 12 kHz MBES coverage and abyssal hills are relatively well developed (traces trend 350°). Isochron ages for the crust are ~32-35 Ma (latest Eocene to early Oligocene).

While volcanic chains do not seem common within Romeo Low, there is a E-W trending volcanic chain along strike within northern Juliett Low (Figure 2-14).

While much of the low is covered in reserved areas, it is more notable how many exploration contract areas end at its southern and western limits (Figure 2-3).

2.4.3.6 *Juliatt Low*

Juliatt Low trends WSW to west over 1,000 km covering about 80,000 km² at 4,800 to 4,900 mbsl (Figure 2-10). Its boundaries are fairly diffuse but there is a continuous zone of seafloor about 100-200 m below India and Kilo Plains which lie to the north and south respectively. The western end protrudes about 80 km into Hotel Low at slightly higher depths (~100-200 m). 12 kHz MBES cover in Juliatt Low is limited but abyssal hills seem well developed and some seamounts/knolls are present.

Isochron ages for the crust are ~27-38 Ma (late Eocene to early Oligocene). A DSDP site in the far western end of Juliatt ended in basalt overlain by ~80 m of Oligocene to early Miocene chinks then grading into ~30 m of more siliceous oozes of largely indeterminate age (van Andel et al., 1973b).

Juliatt Low is covered in places by exploration contracts, but these are the southern limits of contacts centred on India Plain (Figure 2-3).

2.4.3.7 *Bravo Low*

This small low (~55,000 km² at 5,100-5,500 mbsl) lies at the junction of Papa Plain and Oscar Plain and Cooper Rise (Figure 2-17). A distinctive feature is that the depth of the low goes against the shallowing trend from north to south seen for Papa Plain. A single ship-track suggests that abyssal hill traces trend due north so similar to hills to the west (e.g. Papa Plain). There also appear to be few seamounts in Bravo contrasting with the units on either side. Isochron ages for the crust are 83-95 Ma (Late Cretaceous).

Most of the low is free of exploration contracts/reserved areas (Figure 2-3). APEI 4 covers much of the central-eastern side and its contact with Cooper Rise.

2.4.3.8 *Delta Low*

Delta Low includes the deepest part of the CCZ. It covers approximately 268,000 km² at depths of 5,300 mbsl in the east to over 5,700 mbsl in the west (Figure 2-17). The low strikes roughly WNW over 1,200 km, and is wedge shaped being widest against the Clipperton Fracture Zone narrowest where the Mahi-Mahi Fault Zone enters from between Charlie and Uniform Plains (Figure 2-2, Figure 2-17). At the point where Delta contacts Clarion Fracture Zone, the fracture zone curves from WSW-ENE in the east to due E-W in the west, and splits (ramifies) into numerous subparallel short fractures (Figure 2-8).

Abyssal hill trends in central and eastern Delta Low are parallel to those in Charlie Plain (adjacent to the south) and trend to 350°. There are a few seamounts visible on the GEBCO grid specifically at the eastern end in association with the Mahi-Mahi Fault Zone and adjacent to Clarion Fracture Zone. Isochron ages for the crust are 55-100 Ma (mid Cretaceous to end Paleocene). DSDP site 163 is located at the southern end of the low near Cooper Rise and Charlie Plain. It forms the western limit of transect 16A in Section 9.7. Core recovery was very patchy (between two holes) with basalt basement overlain by 25-125 m of mid Campanian to early Maestrichtian calcareous sediment then ~150 m of silicious sediments of early Maestrichtian age to Tertiary age.

There are no exploration contracts over Delta Low, but the ISA reserved areas include a returned area of relatively low grade and abundance (Figure 2-27, Figure 2-28). APEI 1 covers the western end of Delta Low and adjacent northern Oscar Plain.

2.4.3.9 Whiskey Low

Whiskey Low is a complex area of lows and seamount chains between the northern end of the Line Island Rise and Oscar Plain in the western CCZ (Figure 2-17). It is bounded on the north side by the Clarion Fracture Zone. It covers approximately 321,000 km² at 5,200 to 5,500 mbsl. It includes abundant large seamounts that are probably related to the nearby Line Islands chain/Rise although within this unit apparent trends vary widely. Four lines of 12 kHz survey along the SW edge of Whiskey do not show any clear development of abyssal hills (Calder and Masetti, 2015).

Isochrons indicates that the bulk of the seafloor basement formed between 100 and 120 Ma (mid Cretaceous). DSDP drill site 164 located nearby to the north on similar aged crust (far side of Clarion Fracture Zone), found basalt basement overlain by about 200 m of cretaceous aged siliceous clays and cherts, in turn overlain by about 70 m of similar rocks of mid to late tertiary age (Winterer et al., 1973).

There are no contract areas or reserved areas in Whiskey Low, and little else is known about the area. The eastern contact with Oscar Plain is a sharp step interpreted to be fault, its orientation is at odds with the other fracture zones, and suspiciously parallel to nearby ship-tracks (Figure 2-17), even though no specific ship-track is known at this location.

2.4.4 Defined Steps and Trough

Steps and a trough are tectono-geomorphic units within the CCZ found adjacent to parts of the Clarion and Clipperton Fracture Zones, where the contact is not a simple break, but rather involves a discrete, usually narrow, unit running parallel to the fracture zone. They comprise ~8% of the area of the CCZ (~9% if the Line Islands Rise is not included).

Typically, the southern edge of the Clarion-Clipperton plate segment is depressed relative to the south adjacent Clipperton-Galapagos segment while its northern edge is elevated relative to the north adjacent Molokai-Clarion segment (Figure 2-1). But this is not always the case and varies along the fracture zone's strike i.e., probably in association with the specific development of these segments over time.

There is no known 12 kHz multibeam coverage outside of occasional ship-tracks over the steps and trough, but it is likely that their internal structure is complex including fractures and more recent volcanic units such as seamounts.

Nodule potential of the steps or troughs is unknown, but they are covered by parts of some of the APEIs.

2.4.4.1 Clarion Step

On the north side of the CCZ is Clarion Step, which extends 2,900 km, almost the entire length of the CCZ from Mike Plain in the east to the eastern contact with of Delta Low in the west. The step is typically about 20 km wide but can be as little as 7 km and as much as 60 km wide, and the unit totals approximately 112,000 km² (Figure 2-2).

The step has the main Clarion Fracture bounding its northern side and often a second bounding fault to the south along much of its western and central length. This bounding fault (and the Step) terminates at a ~100 km long offset at the eastern end of the Lima Transition. The offset is oblique to the orientation of the Clarion fracture at some ~45° relative (Figure 2-14). From east to west Clarion Step is covered in part by APEIs 6, 3 and 2.

2.4.4.2 Clipperton Step

Extending 1,200 km between the Clipperton Fracture, and Lima Transition and Kilo and Golf plains, the Clipperton step varies widely in width from 10 -120 km. In area it totals approximately 76,000 km². The step includes narrow valleys associated with the fracture zone and starts and ends at changes in the fracture zone's strike, with a splay at the eastern end, and a possible bifurcation where it ends against the southern end of Central Rise (Figure 2-8, Figure 2-14).

IODP site U1336 (Heiko Pälike et al., 2009; transect 320 in section 9.6) and DSDP site 78 (Hays et al., 1972) are located about 100 km apart in the central part of the Clipperton Step. They have near identical ~300 m thick sections with site 78 bottoming in basalt with an overlying sequence of ~150 m of Oligocene chalks and cherts and then mid Miocene calcareous oozes. Site U1335, within the Clipperton - Galapagos plate segment and ~300 km to the SE, has a similar sedimentary sequence again albeit with a thickness slightly over 400 m (Pälike et al., 2009a).

Clipperton Step is covered in part by APEIs 8 and 9.

2.4.4.3 Tango Step

Tango Step extends from the western side of Central Rise to Cooper Rise over 1,000 km (Figure 2-14). It is typically 80-90 km wide, and its area is approximately 85,000 km².

Tango Step has a well-defined bounding fault along its northern edge, but this extends into the western and central base of Central Rise with a distinct offset to the north of the eastern termination of Clipperton Step (Figure 2-14). Parts of Charlie Plain rise to similar depths to Tango Step against this northern bounding fault.

Tango Step is covered in part by APEI's 5 and 7.

2.4.4.4 Clipperton West Trough

The western end of Tango Step transitions into the relatively diffuse 1,100 km long Clipperton West Trough at the eastern end of the southern end of Cooper Rise (Figure 2-17). The Trough is best defined at its eastern end where it is ~200 m deeper than Cooper Rise and becomes less distinct as it approaches the Line Island Rise. In total the trough covers 49,000 km².

This trough has developed at a point where the CCZ widens, *cf* Cooper Rise and Delta Low.

2.5 Discussion

2.5.1 Structural setting

The morphological structure of the CCZ as described here is primarily defined by the tectonic adjustment of the basaltic upper oceanic crust. It is worth recalling that the geomorphological units defined and described above have vertical resolution generally of the scale of several hundreds of metres, while oceanic crust is typically 6 km thick e.g. (Minshull, 2002) and oceanic lithosphere below the CCZ, 50- 100 km thick (Maggi et al., 2006; Isse et al., 2019). The ~100 m thick sedimentation record (Figure 3-2, Figure 2-25) is not thought to play a significant role in the CCZ's structural development, except perhaps at the local scale e.g. near-shoaling of preserved carbonate platforms (e.g. Figure 2-15).

There are in effect three mechanisms of lithospheric plate motion to consider:

1. the overall Pacific Plate motion to the NW (Hawaiian trend). This happens to also be the axial direction of the geomorphological rises in the CCZ.

2. the generally WSW-ENE extension (spreading) within the CCZ plate segment. This is as evidenced by the generally perpendicular (NNW-SSE) strike of abyssal hills.
3. the speeds of spreading of the CCZ plate segment relative to its adjacent plate segments (Figure 2-24). The three segments have similar speeds up to Chron 21 (47.9 Ma). However, at this time spreading speeds increase generally, but also change between the segments, with Clipperton - Galapagos (CG) spreading faster than Clarion - Clipperton (CC), and Molokai - Clarion (MC) spreading the slowest of the three. Some aspects of these changes in relative speed are expressed in changes in the orientation of the Clarion and Clipperton transforms along strike.

It is also worth noting from Figure 2-25, that each plate segment progressively shallows by roughly 500 m, north to south, once sediment cover is accounted for (as best as is currently possible).

It is reasonable to expect that the far-field stress associated with these three interplaying motions propagate through the plate (Figure 2-26), and thus a number of observations are made here, from west to east along the CCZ.

1. Study of the Cretaceous to Tertiary Line Island volcanic rocks indicates a complex history with multiple volcanic events, likely including transform hosted volcanism and perhaps also hot-spot or smaller scale sub-lithospheric convection influences in some areas (Ballmer et al., 2009; Storm et al., 2011; Pockalny et al., 2015).
2. At approximately 100-67 Ma more rapid spreading in the MC segment is associated with the divergence of the Clarion transform from the Clipperton transform in the current day western CCZ. This leads to a N-S spreading component (resulting in the Delta Low) and formation of seamount-knoll chains in the Cooper Rise. This change also relates to a $\pm 10^\circ$ change in direction of spreading, as reflected in the abyssal hills either side of Cooper Rise. The divergence between the transforms is also linked to a slowing of the northern-most part of the following portion of the CCZ (expressing through the synthetically oriented Mahi-Mahi Fault Zone), with the fault zone eventually being accommodated in Quebec Plain.
3. The distribution of the Eastern and Central Rises is interpreted in relation to a slight narrowing between the transforms at a time (55.9 - 40.1 Ma) when plate segment spreading rates and rate differentials increased significantly. Depths to these rises are correspondingly similar to the adjacent section of the CG segment. On these rises there is a telling absence of marginal troughs or development of steps, with effective "promotion" of adjacent seafloor. This is supported in some cases, by a lack of developed abyssal hills (lesser extension) and at the base of Central Rise, the development of small tear apart basins that might be related to drag forces from the plate segment to the south.
4. Intriguingly, if seamounts to the NW of the CCZ are also considered, the Central Rise might be part of a trend including the Hawaiian – Emperor volcanic chain (Figure 2-1). The age of seafloor formation in Central Rise includes Chron 21 (47.5 Ma) which is associated by Barckhausen et al., (2013) with a bend in the Hawaii-Emperor seamount chain and an associated plate tectonic reorganisation in the Central Pacific. Another event, that is at the very least temporally associated with the end of this period, is the opening of the Drake Passage at around 41 Ma after a change in related spreading at ~50 Ma (Scher and Martin, 2006).

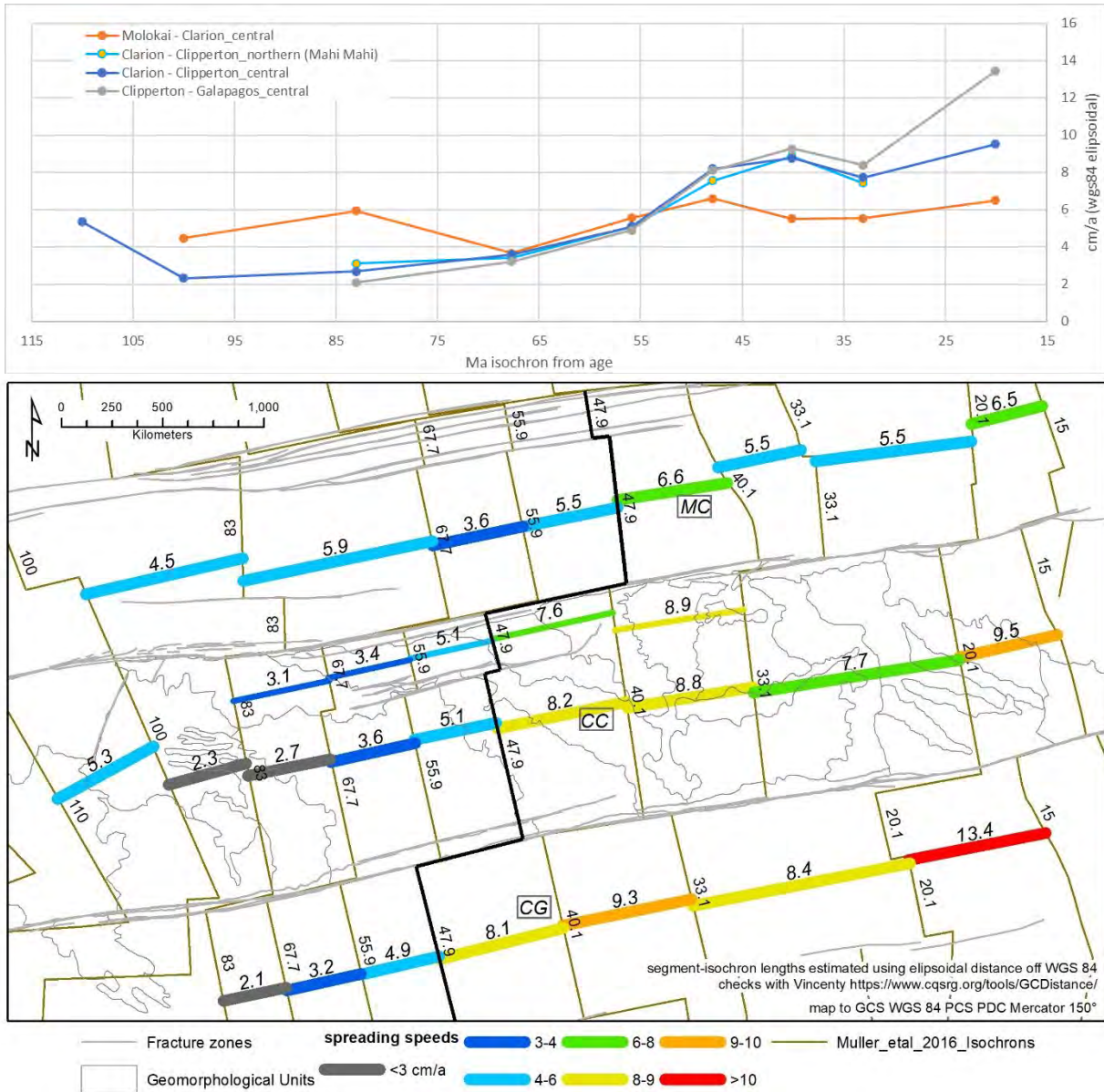


Figure 2-24: Plate segment speeds over time CCZ versus adjacent plate segments

MC is Molokai–Clarion plate segment; CC is Clarion–Clipperton and CG is Clipperton–Galapagos. Refer to section 9.6 for the measurements and calculations

5. Between 40 and 35 Ma, Hotel Low formed due to a period of slightly thinner crust formation resulting from faster spreading rates. This is supported by the orientation of this low across the CCZ and to it having relatively well-defined abyssal hills and no major volcanic chains. Depths are correspondingly similar to the north adjacent MC segment, even though the then average spreading rate was higher in the CCZ (at the present-day Hotel Low).
6. By about 20 Ma, the ongoing acceleration of the Clipperton–Galapagos segment (versus Clarion–Clipperton segment), along with the fracture zones turning more E–W, may explain the direct abutment of Mike Plain against the Clipperton transform and the development of Victor, Yankee and X-ray Lows in a roughly en-echelon arrangement. For these lows, a higher thermal gradient allowed for more ductile attenuation with lower rates of cooling and block faulting and in some cases extending to the formation of the volcanic seamount–knoll chains. Note that almost all of the

defined volcanic chains in the eastern CCZ (Figure 2-2) roughly follow the Hawaii-Emperor trend, but there is no other evidence for hotspot contributions.

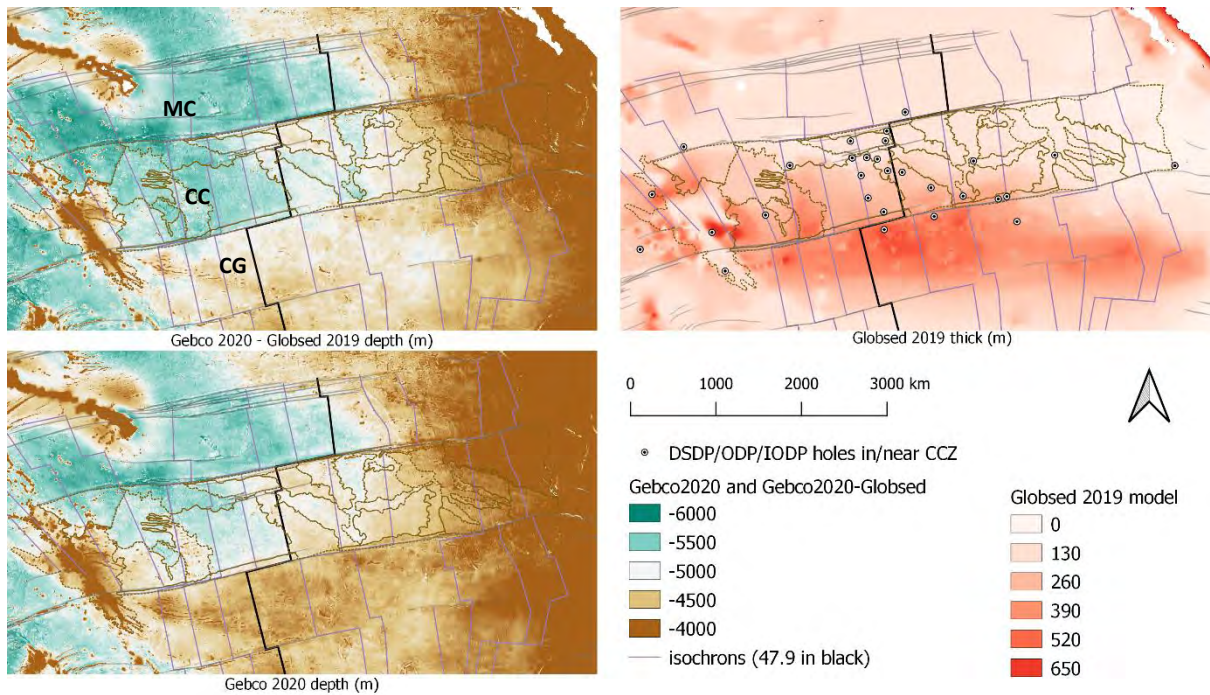


Figure 2-25: Plate segment depths accounting for sediment cover (Müller et al., 2016; Straume et al., 2019; British Oceanographic Data Centre, 2020)

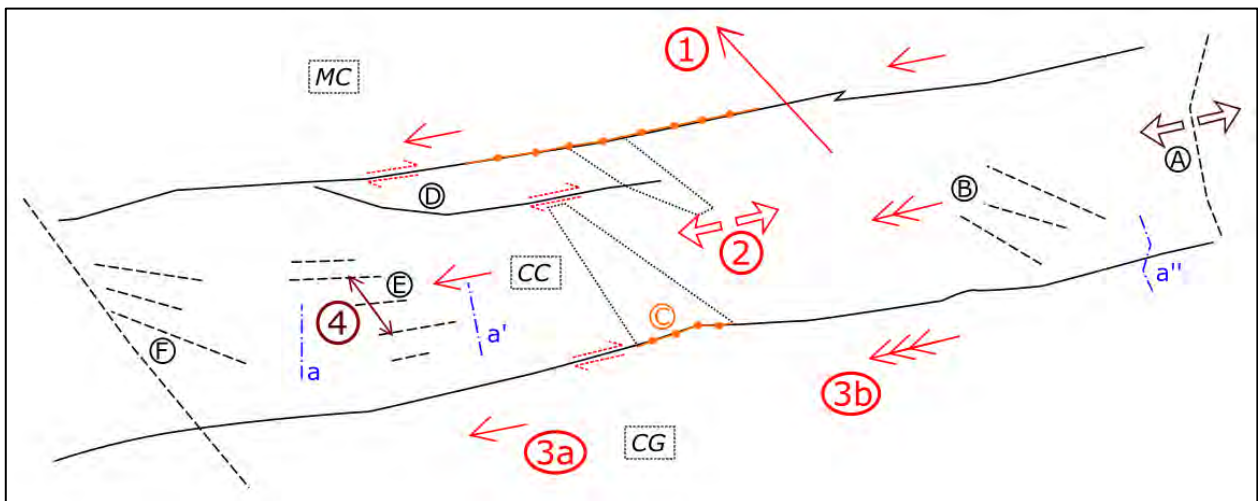


Figure 2-26: Schematic of structural drivers behind CCZ features

1: primary motion of the Pacific plate; 2: overall extension of upper crust; 3: variable speed of the three plate segments and relative motion along fracture zones (3a = plate segments extending at similar speeds, 3b = southern plate segments faster than northern); 4: local extension with divergence of fracture zones. A: spreading centre; B: eastern example lows; C: “pinch points” and preserved rises; D: synthetic fracture zone propagating from divergence of main fracture zones; E: seamount chains in extensional setting; F: ancient transform and seamount chains; a to a’ change in strike of abyssal hills along CCZ, a’’ change in strike of abyssal hill across Clipperton Fracture Zone at least at the eastern end. MC is Molokai Clarion plate segment; CC is Clarion Clipperton segment, CG is Clipperton Galapagos segment.

2.5.2 Nodule prospectivity

It has been observed that nodule grades within the CCZ relate to bathymetric conditions but also to the position of the lysocline; and flux-export of metal bearing organics (e.g. Morgan, 2003; International Seabed Authority, 2010a; Figure 7.1 in Lipton, Nimmo and Parianos, 2016). A key point is that within the CCZ, all three factors have a broad ENE-WSW trend and past research also shows a general east – west trend in abundance and grades (International Seabed Authority, 2010a).

Thus, it should not be expected that there is a simple correlation between nodule prospectivity and the (relative depth defined) geomorphological units, and this seems to be the case from the analysis here. However, some influence at the contacts (edges) to the geomorphological units might be expected for two possible reasons. Firstly, a depth change might bring an area of seabed into a more prospective setting *vis-à-vis* the lysocline. Secondly, seabed currents may often follow the contact between two geomorphological units (as supported to some extent by seabed current modelling; Figure 2-4). Changes at the contacts is seen, to some extent, in abundance and grade mineral inventory models from (International Seabed Authority, 2010a) (e.g. Figure 2-27 and Figure 2-28; 9.4 Appendix 2A Other supplementary figures), as well as with regards to the location of the priority development areas reported by various ISA exploration Contractors.

The abundance-grade models presented by International Seabed Authority (2010a) are limited in terms of extent of data coverage and spacing between data points, so care needs to be taken in interpretation, especially towards the edges of the models. Clearly additional analysis is warranted if better CCZ-wide abundance/grade data become available.

In terms of abundance, a strong correlation with India Plain stands out and this was a focus area in the 1970s (Lipton et al., 2016). Ifremer's priority area (Fouquet et al., 2014) is a legacy from those times. This high abundance area also extends into adjacent areas. GSR, whose contract is centred on the northern part of Lima transition, has their priority area near the contact with India (Global Sea Mineral Resources, 2018). Higher abundance is also found at the SE edge of Eastern Rise (YMG's priority area (Melnik and Lygina, 2010)), the northern part of Golf Plain, the north-western part of Charlie Plain (DORD priority area (Deep Ocean Resources Development Co Ltd, 2014b)) and central Oscar Plain extending into the inter-seamount areas of northern Cooper Rise (Jin, 2014). The abundance model of (International Seabed Authority, 2010a) does not extend into the eastern CCZ where there are several contractor priority areas in Mike Plain, and does not seem to capture the southern part of the Hotel Low where KIOST have chosen their priority area (reported abundances of 8-12 kg/m² in Korea Institute of Ocean Science and Technology, (2014) are much higher than shown in Figure 2-27).

In terms of grade, nickel, manganese and copper have similar trends although the highest grades of copper are offset about 250 km to the SSE (section 9.4). A relationship of copper grades with distance from the EPR might be a subject worth falsifying by future workers. Conversely cobalt is offset 300-700 km to NNW with an antithetic relationship to the other metals (section 9.4). This offset is well known, and work reported in section 4.5.2.3, attributes the change in Co to a change in the type of primary productivity (i.e., metal source). Apart from the offset to the north, higher cobalt and lower nickel is seen on parts of the rises, presumably where the seabed lies above the calcite lysocline and other (e.g., hydrogenetic) processes necessarily dominate. The most consistent and best supported regions for higher grades are the northern part of Golf Plain extending through southern Eastern Rise and Quebec Plain as well as across Hotel Low into western India Plain and central Charlie Plains.

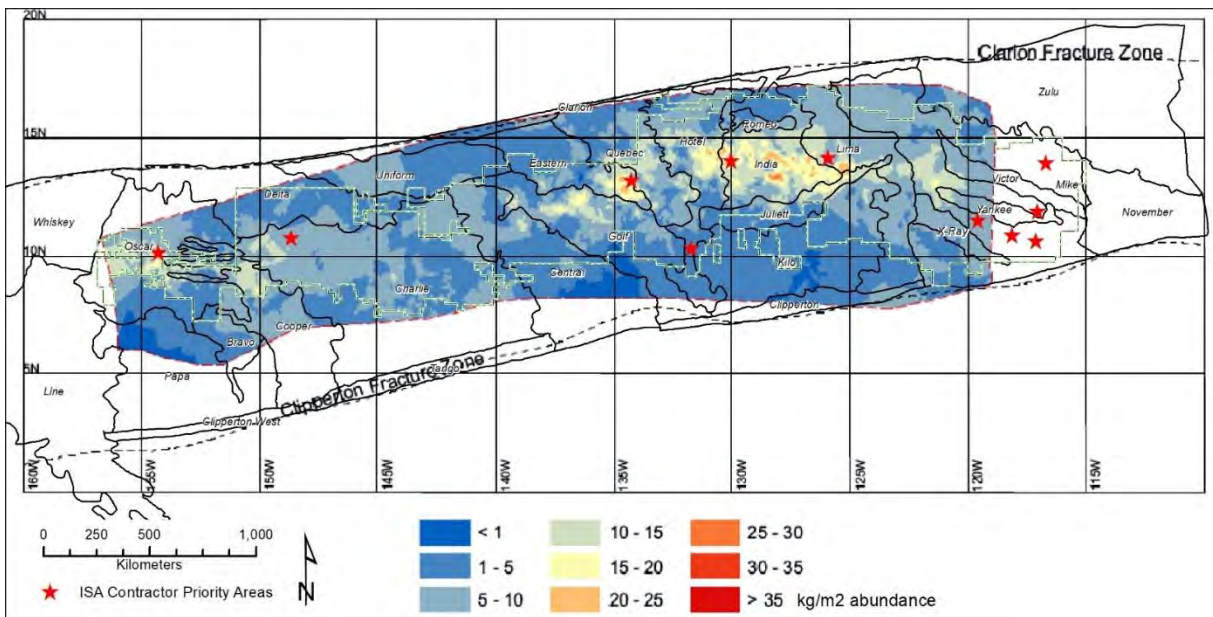


Figure 2-27: CCZ abundances and geomorphological units

Source of background map: (International Seabed Authority, 2010a). Map is to GCS WGS84 PCS PDC Mercator 150° .

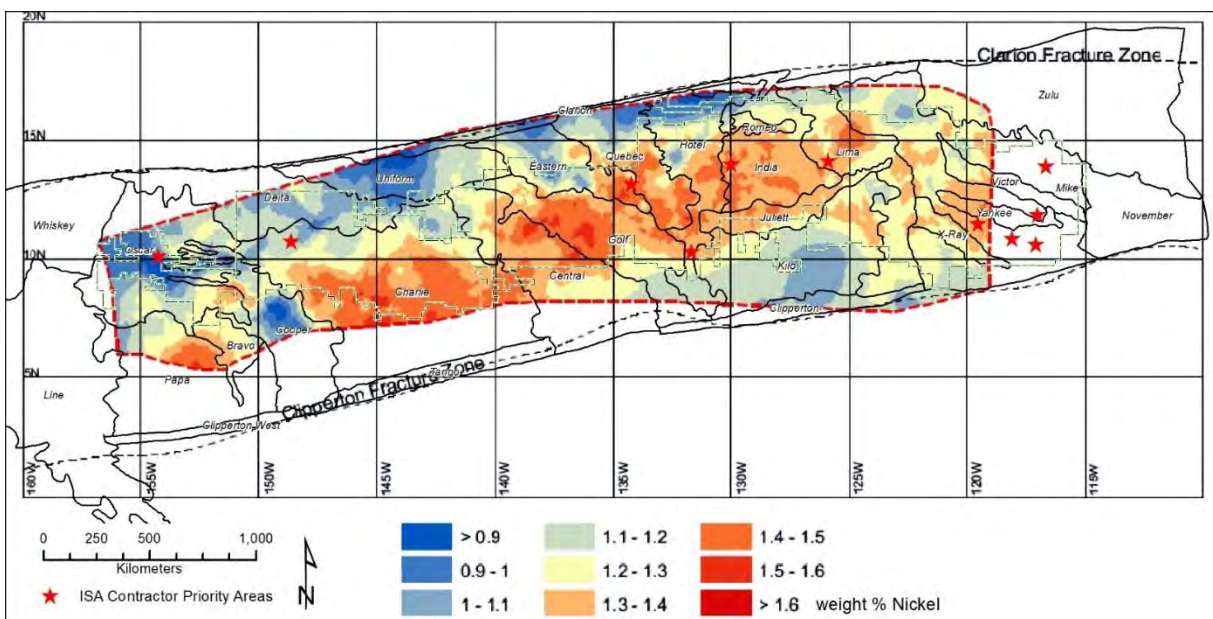


Figure 2-28: CCZ nickel grades and geomorphological units

Source of background map: (International Seabed Authority, 2010a) Map is to GCS WGS84 PCS PDC Mercator 150°. Cu, Co and Mn maps included in Section 9.4.

2.6 Conclusions and Recommendations arising from Chapter 2

Interpretation of the entire CCZ, based on the GEBCO grid, and with reference to areas with available 12 kHz MBES, results in:

- A complete and relatively comprehensive map of the seabed geomorphology. This includes distinct plains, rises and lows of abyssal hills, and steps and a trough along parts of the bounding fracture zone.

Observation that abyssal hills generally strike perpendicular to the direction of spreading but occasionally can also be influenced by other forces e.g., the direction of plate motion or to drag effects across tectonic boundaries.

Each geomorphological unit is described in as much detail as available information permits, with commentary as to how it may have been formed.

Definition of seamount chains and major internal fault zones and rifts.

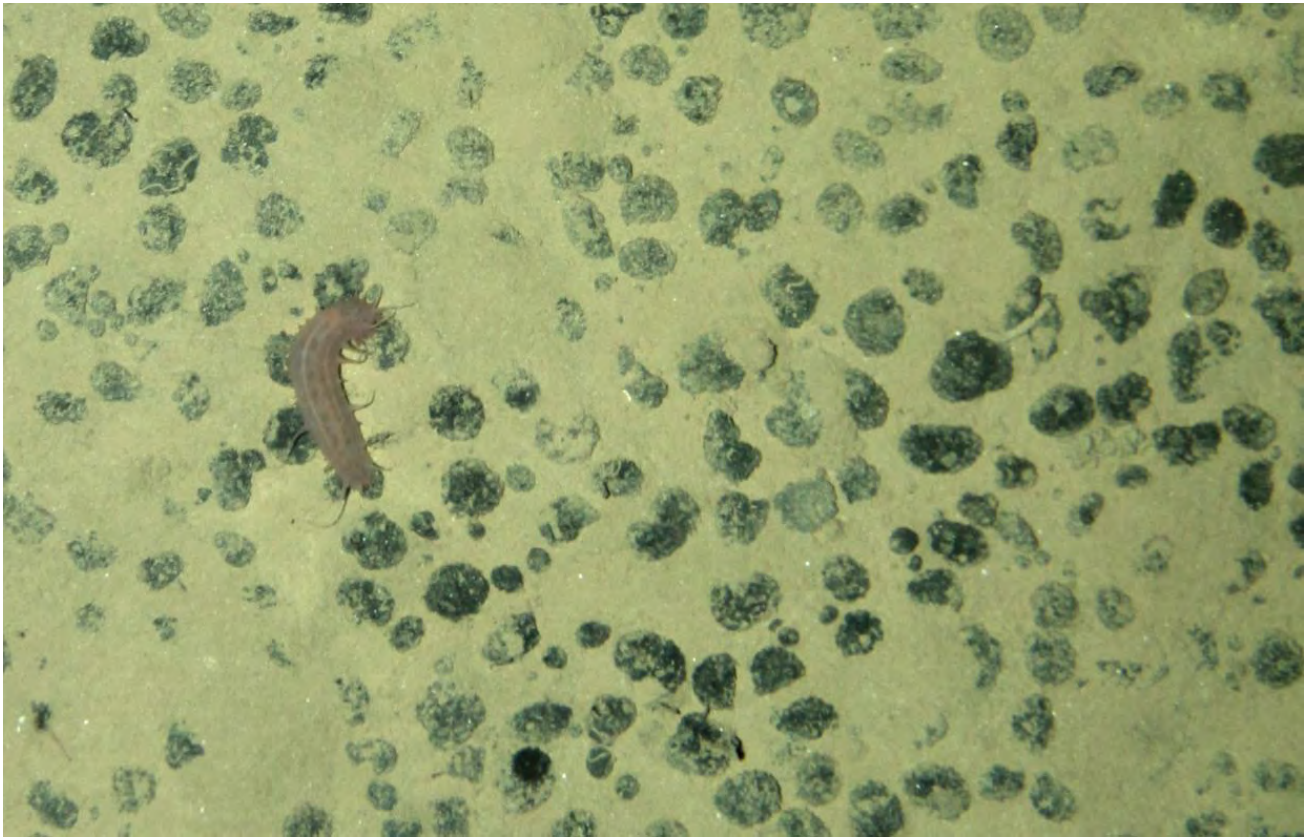
- A refined structural model, as orientation of the above-mentioned geomorphological units often relates to the geometry and history of the formation of the plate segment. That is, the interplay of three factors:
 1. Overall Pacific Plate motion to the northwest.
 2. General WSW-ENE extension (spreading) within the CCZ plate segment.
 3. Relative speeds of spreading between the CCZ plate segment and its adjacently neighbouring plate segments.

In this context, the location and orientation of the rises and some lows can be related to changes in relative plate segment speeds and associated widening or narrowing of the bounding fracture zones. The orientation of some of the other lows can be related to changes in spreading rates and propagating fault zones associated with plate segment speed changes. The rises are mostly sub-parallel to the Pacific plate motion direction but oblique to the bounding fracture zones, indicating north to south and west to east propagation of the formative stresses.

- A little additional commentary on the distribution of nodule mineralization, most notably a predisposition of priority areas for developers to be near unit contacts (and locally significant changes in depth).

Future work could look to:

- Refine the interpretation and understanding further, especially as/if improved data becomes available. Application of sophisticated statistics and/or artificial intelligence-based analysis might prove successful in building or improving a general model regarding nodule formation and especially grade endowment.
- Application of a similar approach external to the CCZ.



Grazing holothurian at ~4,800 mbsl August, 2015.

Captured using Yuzhmorgeologiya's Neptune towed camera system

3 Local scale geology

This chapter looks at the geology of areas covered by 12 kHz MBES survey (Figure 3-1). Specifically, surveyed parts of the exploration contract areas held by ISA contractors Tonga Offshore Mining Limited (TOML; sponsored by the Kingdom of Tonga), Nauru Ocean Resources Inc. (NORI; sponsored by Republic of Nauru) and Marawa Research and Exploration Limited (Marawa or MARA; sponsored by Republic of Kiribati). It also looks at several sub-areas covered with additional, more detailed, data (Figure 3-1).

There are four key products as follows:

- 1) A series of seven 1:250,000 scale surface geological maps (Section 10.2 in Maps and cross-sections; Figure 3-1), i.e.:
 - i) Sheet 1 (NORI contract area A)
 - ii) Sheet 2 (NORI B and TOML B)
 - iii) Sheet 3 (TOML C)
 - iv) Sheet 4 (TOML D and E)
 - v) Sheet 5 (Marawa 19. 20)
 - vi) Sheet 6 (NORI C)
 - vii) Sheet 7 (TOML F and NORI D)
- 2) A series of two side-scan sonar (SSS) maps and nine sub-bottom profiler (SBP) sections and SSS swath maps all at 1:25,000 scale (Section 10.3 in Maps and cross-sections; Figure 3-1, Figure 3-3), i.e.:
 - i) SSS Map for TOML B1 and C1;
 - ii) SSS Map for TOML D1 and D2;
 - iii) SBP section and SSS swath for CCZ15-M01, TOML B1;
 - iv) SBP section and SSS swath for CCZ15-M02, TOML B1;
 - v) SBP section and SSS swath for CCZ15-M03, TOML B1;
 - vi) SBP section and SSS swath for CCZ15-M04, TOML B1;
 - vii) SBP section and SSS swath for CCZ15-M05, TOML C1;
 - viii) SBP section and SSS swath for CCZ15-M06, TOML D21;
 - ix) SBP section and SSS swath for CCZ15-M07/7B, TOML D21;
 - x) SBP section and SSS swath for CCZ15-M08, TOML D2;
 - xi) SBP section and SSS swath for CCZ15-M09, TOML D1;
- 3) Commentary by geological unit including example (type) areas; and
- 4) Commentary by exploration contract sub-area.

The chapter aims to illustrate the diversity and often dynamic nature of the geology of the CCZ. It builds on the history and structure of the regional setting but at a local scale more familiar to most workers in the

area. This is ultimately the scale of mapping required to inform domaining for a polymetallic nodule Mineral Resource estimate (e.g. as covered in Chapter 5).

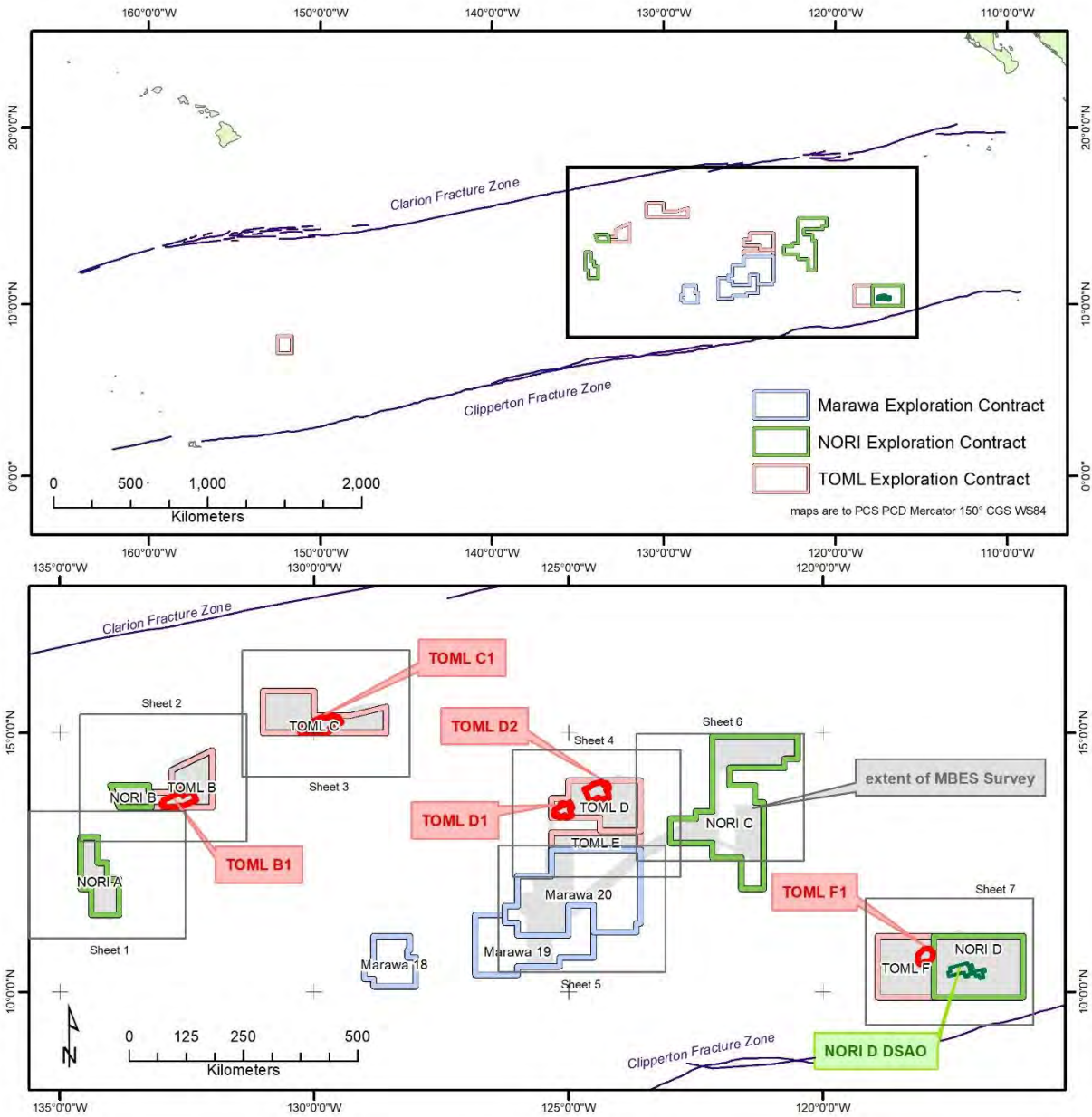


Figure 3-1: Survey areas, sub-areas and 1:250K map sheets

The NORI DSAO (Detailed Survey Area) is an area covered with AUV bathymetry, photographs and sonar surveys as reported in (Lipton et al., 2021).

3.1 Background

A time-space synthesis for the areas mapped and discussed here comprises Figure 3-2 and 9.9 Appendix 3A: Time-space worksheet. The areas mapped in this chapter represent a wide range of longitude (i.e. 19° of CCZ plate segment history) and latitude (i.e. 6°; from ~50 km north of Clipperton Fracture Zone to ~150 km south of Clarion Fracture Zone).

From west to east there is progressive younging of the basement volcanic abyssal hills (i.e., from mid-Eocene (~40 Ma) to early Miocene (~18 Ma). These are overlain by chalk and clay-ooze sediments. Details on the sedimentary sequences are sparse but bio-stratigraphic logging of two “nearby” (<500 km) DSDP holes indicate continuous sedimentation from the time of basement formation till the present, with a possible disconformity at the Oligocene-Miocene boundary; (van Andel et al., 1973a, 1973b). While stratigraphic constraints for the sequence in TOML F and NORI D are almost non-existent, for the other areas it is possible to extrapolate changes from a predominantly calcareous sedimentation regime to one that is predominantly siliceous. The change composition occurs between the early and late Miocene, albeit that this change relates to the plate movement with regards to latitude and lysocline position (Figure 3-2, Section 2.5.1). While the two DSDP drill holes indicate a continuous process of sedimentation, the sub-bottom profiles from TOML areas B, D and especially C indicate a frequently unconformable contact within the upper siliceous sediment. This may be due to the more diagenetically competent calcareous strata warping as the abyssal hills develop over geological time, while semi-consolidated siliceous sediments are more prone to slumping, especially off basement highs.

Mapping of the different areas also reveals varying occurrences of volcanic edifices (knolls, domes, seamounts, sheet flows, fissure lavas and dykes). Constraining the ages of these edifices is difficult and frequently impossible due to unit homogeneity and lack of stratigraphic indicators. There is no reason why many should not be coeval with the formation of the basement crust, and many of the knolls have sediment on their summits indicating that they are quite old. In at least one case the sediment is carbonate that must be of the order of at least 20 Ma, based on the stratigraphic constraints in Figure 3-2. Other volcanic edifices are clearly much younger, based on a near total lack of any clay-ooze cover, and in one case discovery of lava fragments on the clay-ooze seabed with minimal ferro-manganese coatings.

The age of the polymetallic nodules and other ferromanganese deposits can be constrained by their sizes vis a vis modelled growth rates of (0.5 to 3 cm per Ma; (Chang et al., 2005); Chapter 4). This indicates ages of 1 to 5 Ma or more. However, many polymetallic nodules from TOML B for example contain fragments of clearly older nodules encompassed with younger ferro-manganese growth. Cronan (1973) discusses nodules found at depths of up to 244 m within the cores of DSDP Leg 16. This includes two in early Miocene or late Oligocene sediments (± 23 Ma) at 101-105 m depth at site 159, near the NORI C area.

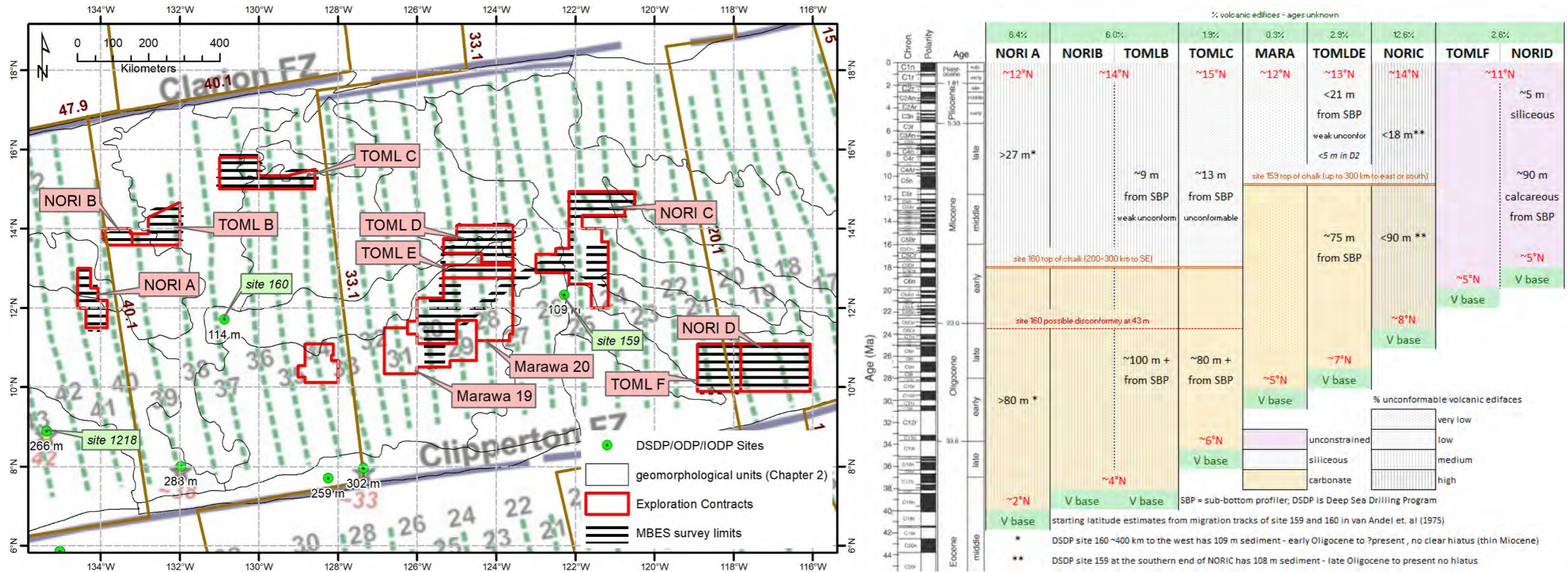


Figure 3-2: Deposit scale survey areas – basement ages and extrapolated stratigraphy

Green isochrons at left are from Barckhausen et al., (2013), while the brown isochrons are from Müller et al., (2016) DSDP site 159 information is from van Andel et al., (1973a), site 160 from van Andel et al., (1973b) and migration estimates based on the work of van Andel et al., (1975). Additional detail in section 9.6

3.2 Datasets and map products

Three key datasets were used in the deposit scale mapping and analysis:

1. 12 kHz Multibeam Echosounder (MBES) survey;
2. combination of towed sub-bottom profiler (SBP, 5 kHz) and side-scan sonar (SSS, 30 kHz);
3. seabed colour photographs (mostly deep towed 2.4 x 1.6 m at 3,456 by 2,304 pixels).

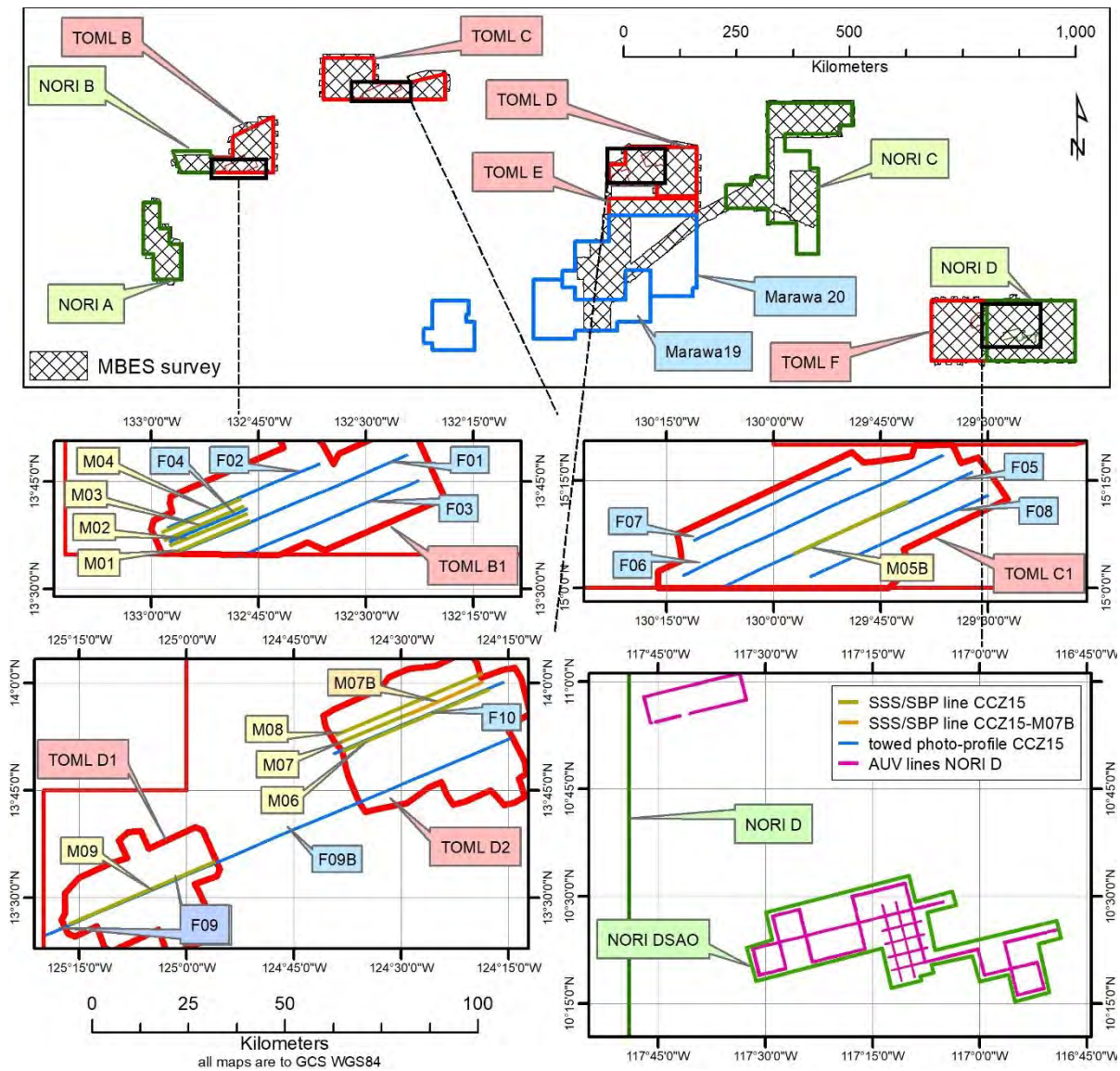


Figure 3-3: Location and extents of used MBES, SBP/SSS, AUV and photo-profile data

Reference is also occasionally made in the analysis below, to box-core samples of ferro-manganese nodules and host sediments.

Note that the acoustic data is proprietary information to Tonga Offshore Mining Limited, Nauru Offshore Resources Incorporated and Marawa Research and Exploration Limited, and is thus not included in the

Appendices to this study. The MBES bathymetry is however being contributed by Deep Green/The Metals Company to the Seabed 2030 initiative.

3.2.1 MBES dataset

All of the MBES data was collected using the same system (Kongsberg EM120, gondola mounted on the R/V Mt Mitchell), but over two expeditions. In 2012 Deep Green Resources contracted Williamson and Associates to supervise and process survey over part of NORI C, part of Marawa 19 and 20 and all of NORI D. All of this data was subsequently reprocessed by specialist consultants, Margin, in 2017. In 2013 Tonga Offshore Mining Limited conducted their own survey expedition (CCZ13), with the author acting as Chief Scientist. This 2013 expedition covered all of TOML B, C, D, E as well as part of NORI B and all of NORI A (the NORI areas under commercial contract to Deep Green for those areas that had not been surveyed the year before). The TOML data has only been processed by TOML staff and contractors, but the NORI A and B datasets were also included in the reprocessing done by Margin in 2017.

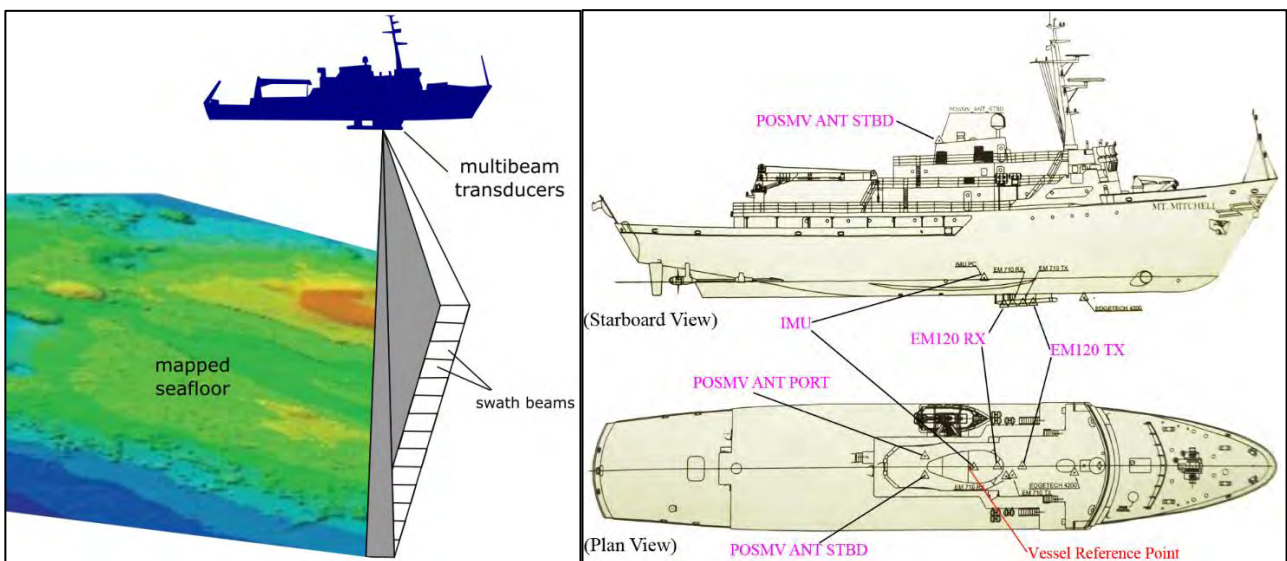


Figure 3-4: MBES survey schematic and layout

TX is transmit or projection array, RX is reception or hydrophone array, IMU is inertial motion unit offset to vessel reference point, POS MV ANT are differential GPS antennae.

MBES essentially works by a series of transmitter transducers (projector array) ensonifying the seafloor via constructive sonar interference signal (main lobe of a transmit fan). Though the system is nominally 12 kHz, the transmit fan is split into several individual sectors with independent active steering according to vessel roll, pitch and yaw. The sectors are frequency coded from 11.25 - 12.60 kHz and are transmitted sequentially and aimed and calibrated to comprise a ping with optimum coverage.

A series of receiving transducers (hydrophone array) is arranged at right angles such that short time delays to the hydrophones for the return signal intersecting the transmit pulse discriminate a series of returning beams. The timing of the return signal deduces water depth (bathymetry) while the reduction in strength of the return signal versus transmit signal, deduces sea-bottom absorption via composition and angle (backscatter).

Calibration of an MBES system (for latency, heading, roll and pitch biases) over a known point is normally done prior to each survey, and sound-velocity profiles measured via a casting at each survey block prior to data collection. Corrections are made for vessel orientation (constantly via inertial motion unit) and water

salinity (which can be assumed for these blue ocean surveys). While the MBES system creates a preliminary map immediately on signal return, post data collection processing (e.g., CCZ13) can include profile by profile review and occlusion of obvious false returns (either from the water column or stray seabed reflections).

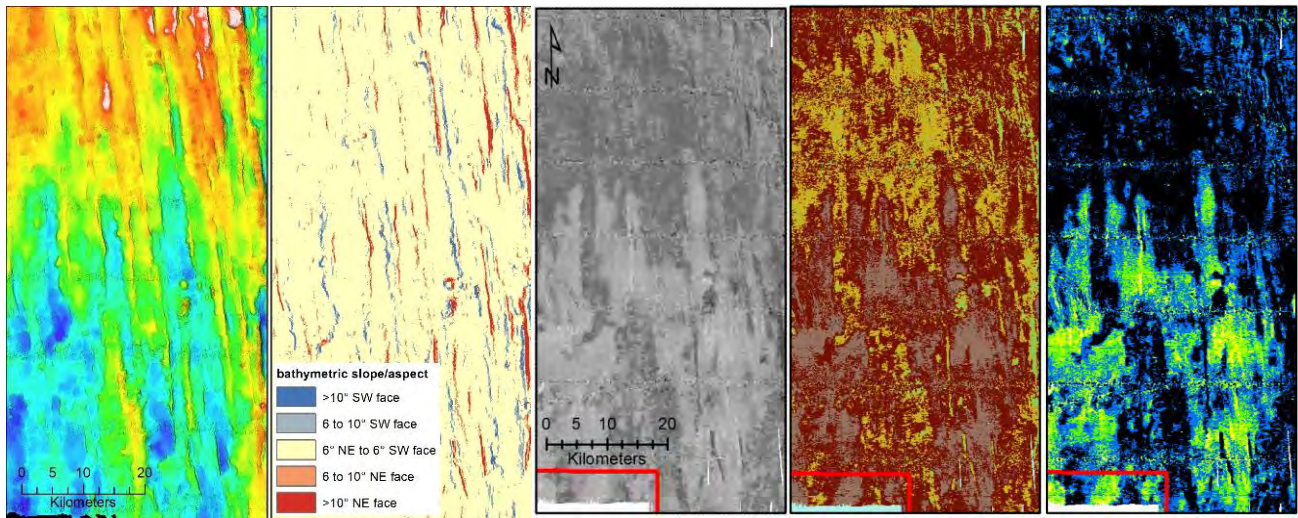


Figure 3-5: Example comparative bathymetric and backscatter images for part of TOML D

L to R bathymetry, bathymetric slope/aspect, backscatter as grey scale (dark grey ~ 5 dB to light grey ~ -40 dB), back scatter as "brown scale" and back scatter as green scale (see Figure 3-6).

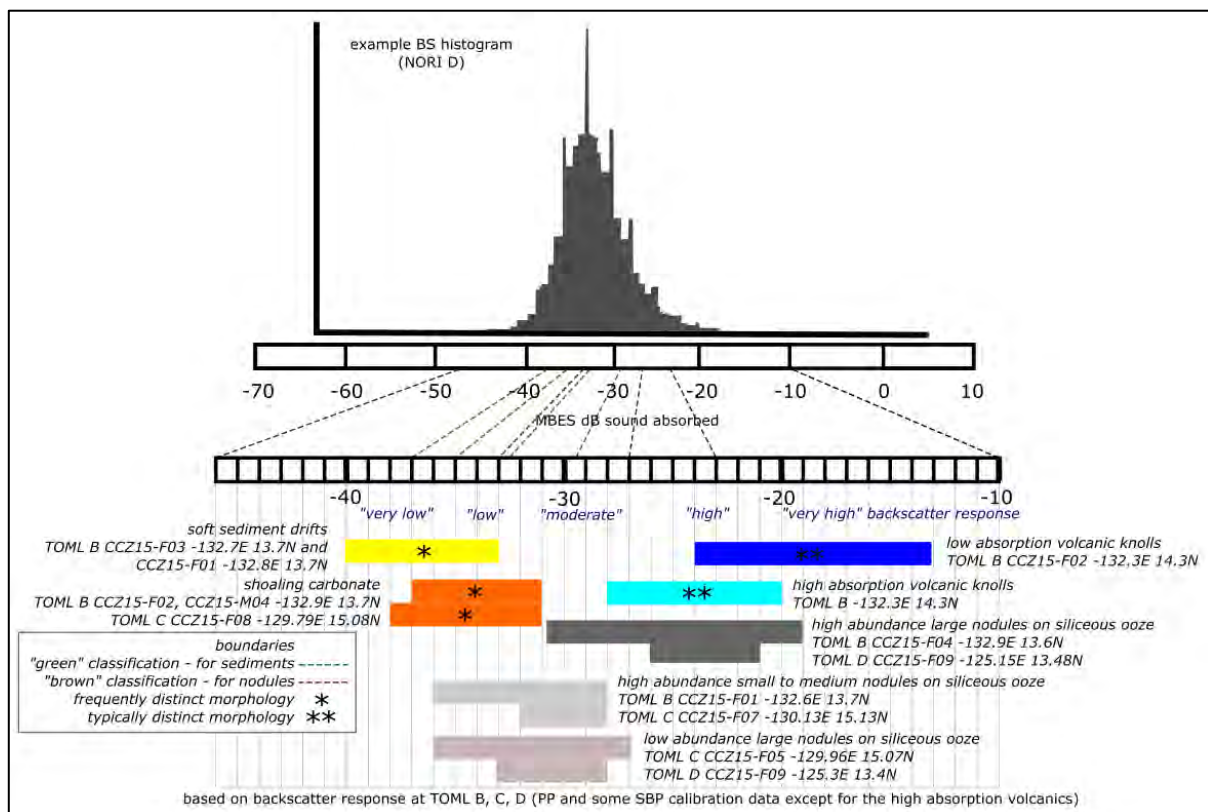


Figure 3-6: Photo and SBP correlation with the MBES BS brown and green scales

Photo lines are CCZ15-FXX and sub-bottom profile lines are CCZ15-MXX. These data were able to positively identify a rock-type which was then compared to its MBES BS response in 'native' grey scale and in the two colour scales.

The 231' R/V Mt Mitchell was first commissioned in 1967 and operated by NOAA until 1995, it boasts a quiet hull and propellers as well as motion compensation tanks port and starboard on the forward mezzanine decks. During the two multibeam surveys she was operated by the company Global Seas LLC in Seattle, Washington, USA. While no longer "state of the art", a Kongsberg EM120 MBES is notionally capable of operation in up to 11,000 m water depth (Kongsberg, 2005). The system aboard the R/V Mt. Mitchell is configured at 2°x2° angular resolution, yielding seafloor sounding resolution on the order of 3.5% of oblique range. During the 2013 expedition, data was processed into grids with lateral resolutions of 60 m and 30 m for bathymetry and backscatter respectively. The system's effective maximum swath is 6 times the water depth (specified swath is 5.5 times; (Kongsberg, 2005)), but the effective swath can be reduced to as little as 2 times the water depth depending on the depth (shallower is less), sea state (rougher is less) and heading related to prevailing sea-state (into result is best). For the two survey programs this equated to a line spacing of about 12 km to ensure complete coverage.

Three main Multibeam products were used in the interpretation:

1. **Bathymetric** images as TIFF format files and ASC grids in a variety of colour stretches (e.g. Figure 3-5). This data served to define the extents of volcanic rocks, basins and rises as well as the abyssal hills and valleys and collapse potholes. While the backscatter could discriminate well volcanic rocks and types of nodule bearing sediment units, the bathymetry often provided more accurate in locating their contacts.
2. **Bathymetric slope and slope aspect** as an ASC grid was used to define the steeper slopes ($\geq 6^\circ$) and helped discover collapse potholes and the more subtle volcanic mounds (Figure 3-5).
3. **Backscatter** as an ASC grid was used to interpret richer and poorer areas with respect to nodules and sediment cover and also to discriminate volcanic rock types and slope types. Unfortunately, due to unresolved issues with commercial implementations of Geocoder backscatter processing, along track smearing results in places, especially during periods of bad weather.

The backscatter was compared between areas using three standard stretches:

- a. A conventional grey scale stretch for volcanic rocks, scarps and to check the interpreted nodule and sediment units;
- b. A brown-yellow-green scale to discriminate nodule bearing areas and volcanic units, called the "brown" scale in (Figure 3-5, Figure 3-6);
- c. A black-blue-yellow scale to define drift sediments, called the "green" scale in (Figure 3-5, Figure 3-6).

It was apparent that backscatter response between the areas varies, likely due to differences in the sound velocity profiles that are not fully accounted for in the processing. Using type units such as sediment drifts and volcanic rock units as a guide, backscatter thresholds for the colour scales were thus varied slightly between some areas due to ensure consistency in the interpretation (Section 9.10).

Normally, during the process of interpretation, it proved best alternate between bathymetry and backscatter (BS) backdrops, but integration of bathymetry and backscatter was often useful to elucidate some features per the example in Figure 3-7.

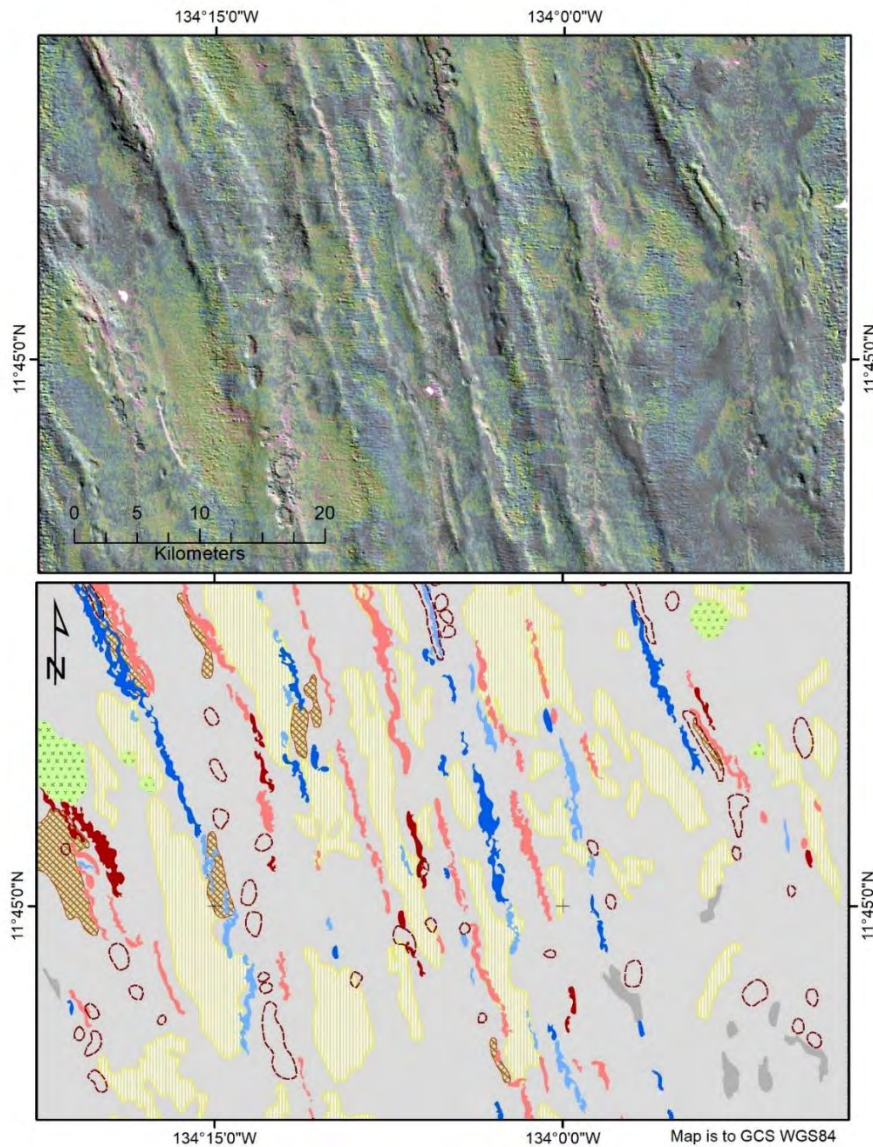


Figure 3-7: Southern NORI A example of bathymetric hillshade over 'greenscale' backscatter
 Refer to Table 3-1 for the interpretation legend and Figure 3-6 for the backscatter scale.

3.2.2 MBES Mapped units

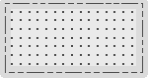
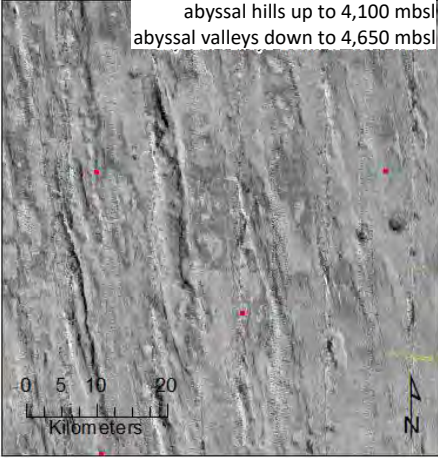
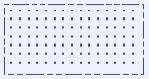
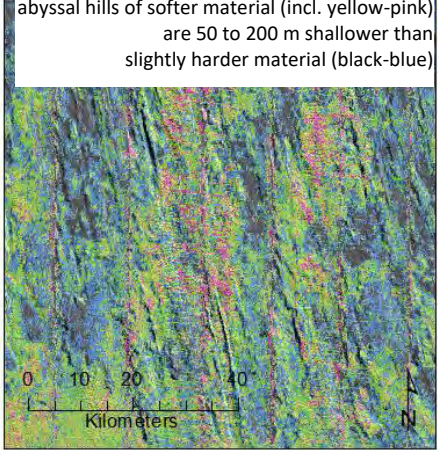
Examples of each mapped or identified unit are shown below. While MBES response was the predominant data source used in the mapping, case histories involving other data sets were key in helping define the units and these are included in the commentary by stratigraphy section further below. Feature terminology recommended by (International Hydrographic Organization, 2008) was used as appropriate, e.g. for volcanic seamounts versus knolls.


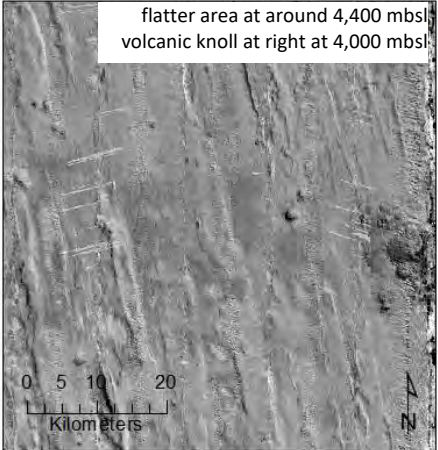

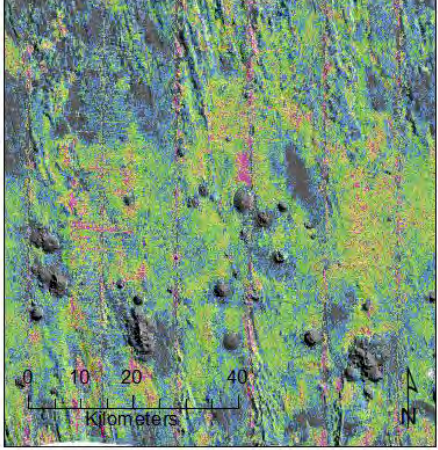

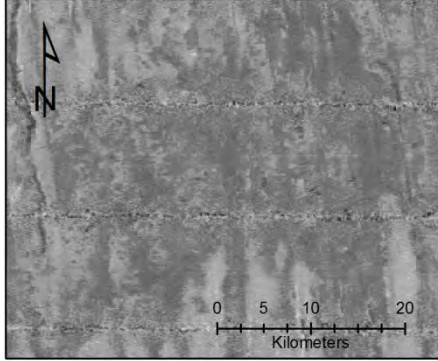
The map series in Section 10.2 Maps and cross-sections is presented at 1:250,000 scale. This scale was selected for reasons of practicality:


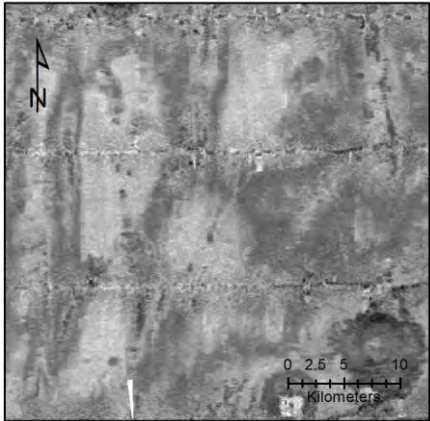

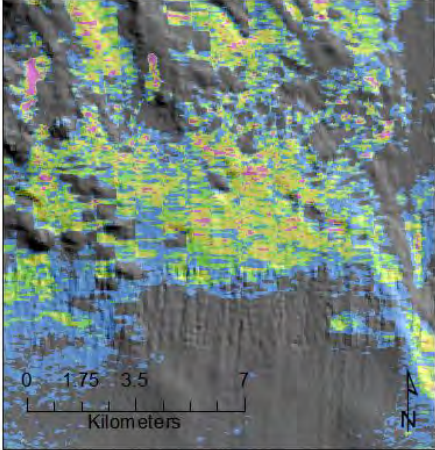
- 1:250,000 scale is a familiar common first pass mapping scale on land;
- at 1:250,000 scale, 100 m (2-3 times effective MBES resolution) is 2.5 mm;
- the area mapped totals some 173,000 km² (or almost double the area of mainland Portugal).



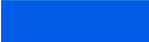





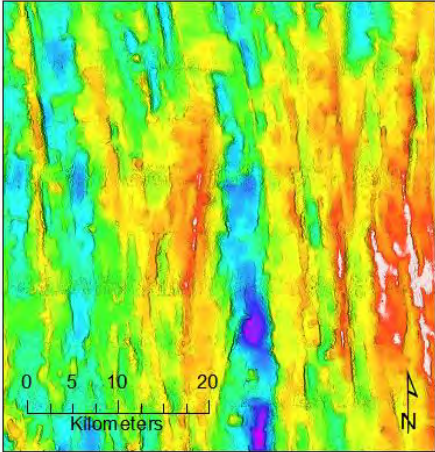


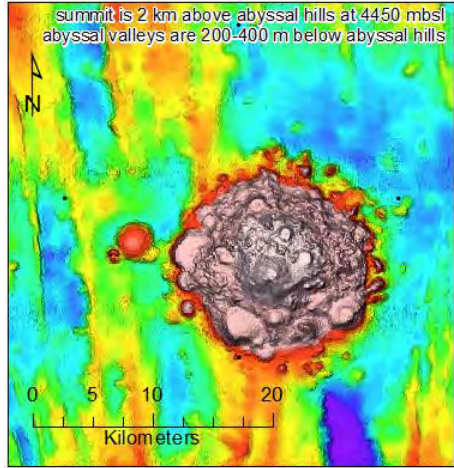
The map series was built up in GIS (either ArcMap v10.4.1 for desktop or qGIS v3.10 depending on the processing being employed; see also section 3.2.9). The bulk of the compilation was conducted at 1:100,000 scale, varying to capture detail or context. All of the digitizing for products in this chapter used a 27" 1920 x 1080p display. At 1:100,000 scale, 1 km on the map was about 1.2 cm on the screen. The map is assembled using a series of sequenced layers to improve flexibility in review and reduce the complexity associated with a single integrated polygonal product (for example the slopes layer alone comprises over 10,000 polygons).


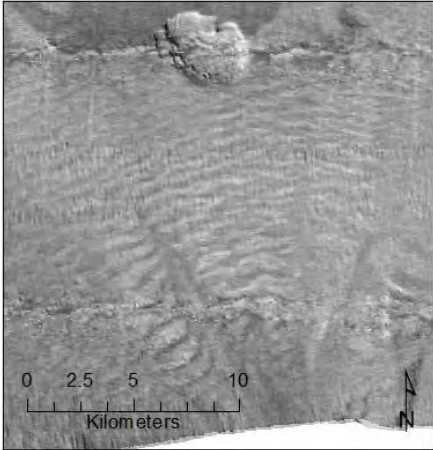

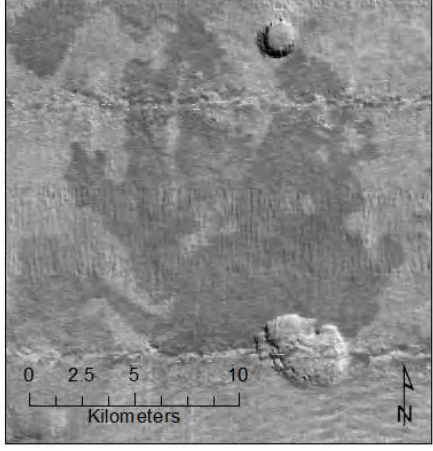

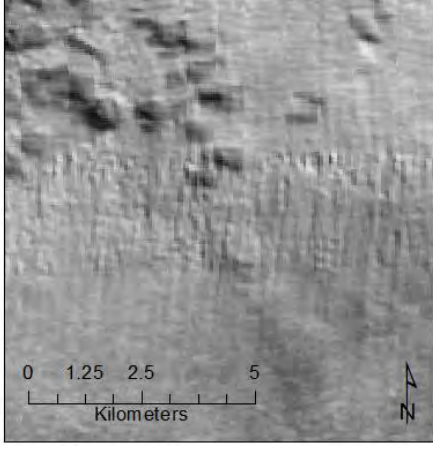
Table 3-1: MBES 1:250,000 Interpretation - Detailed Legend

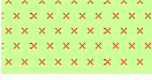
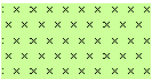
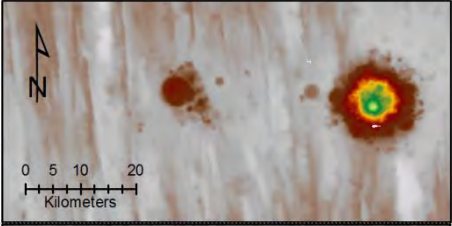
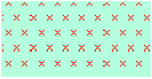
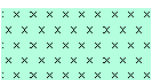
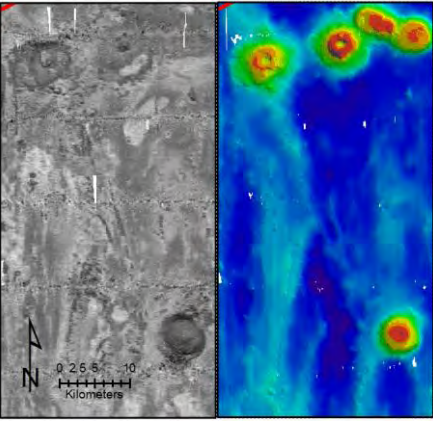

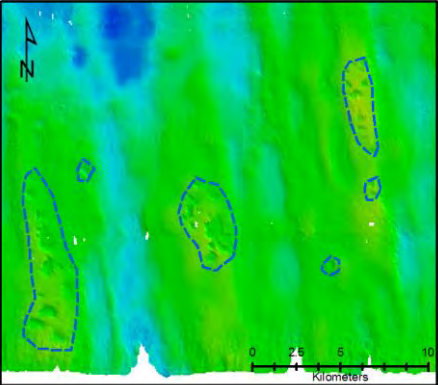
Unit/Code	Example	Description
<p>Abyssal hills likely nodule bearing</p> <p>Ab_s</p> 	 <p style="text-align: center;">SW TOML F</p>	<p>Abyssal hills with moderate backscatter (-27 to -36 dB). 6° taken as the slope margin for the hills. Effectively the default unit within the CCZ, seen to make way for Ab_c in SE NORI D and Ab_d in southern Marawa survey areas.</p> <p>Nodule abundance can be very high in this unit especially if the nodules are of smaller diameter</p> <p>Terrain ruggedness index generally > 2.3</p> <p>Red dots on the image are box-core sites</p>
<p>Abyssal hills likely nodule bearing - soft</p> <p>Ab_c</p> 	 <p style="text-align: center;">Central NORI D</p>	<p>Extensive areas of abyssal hills with more moderate-low backscatter than Ab_s (~ -5 dB). This might relate to a slightly higher carbonate content in the clay-ooze although samples show siliceous sediment within the top decimeters.</p> <p>Nodule abundance seems to be slightly lower on this unit relative to nearby Ab_s.</p> <p>Terrain ruggedness index generally > 2.3 but includes common areas <2.3 indicating a correlation with frequently fewer abyssal hills</p>


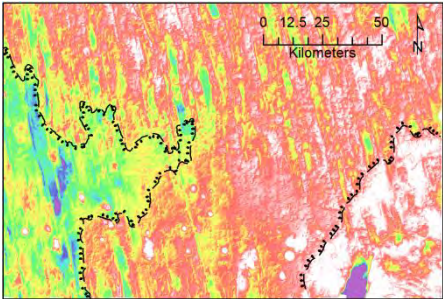
Unit/Code	Example	Description
<p>Flatter area of abyssal hills likely nodule bearing</p> <p>Abl_s</p> 	 <p>W TOML F (sub-area F1)</p>	<p>Subdued to absent abyssal hills with moderate backscatter and usually frequent volcanic knolls and mounds.</p> <p>Nodule abundance can be very high in this unit especially if the nodules are of smaller diameter.</p> <p>Terrain ruggedness index generally < 2.3</p>
<p>Flatter area of abyssal hills likely nodule bearing - soft</p> <p>Abl_c</p> 	 <p>Southern NORI D</p>	<p>As per Ab_c but with subdued to absent abyssal hills and usually frequent volcanic knolls and mounds.</p> <p>Nodule abundance varies but seems to be often slightly lower on this unit relative to nearby Abl_s.</p> <p>Terrain ruggedness index generally well < 2.3</p>
<p>high volume nodule bearing sediment</p> <p>hN</p> 	 <p>Northern TOML D</p>	<p>Discrete zones of frequently higher backscatter response (-20 to -30 dB) within Ab_s or Abl_s and rarely within Ab_c and Abl_c.</p> <p>In the northern part of the NORI A area this unit has distinctly very high reflectance and a dredged sample returned nodules up to 15 cm across. In TOML C this unit has abundant medium sized nodules ~ 5 cm across.</p> <p>Thought to correlate with abundant and/or larger nodules.</p>

Unit/Code	Example	Description
<p>Abyssal hills likely nodule poor or free</p> <p>Ab_d</p> 	 <p style="text-align: center;">South-eastern TOML B</p>	<p>Areas of very low acoustic return tend often form drift-like bodies in valleys and slopes to one side or around the base of seamounts.</p> <p>Nodule abundance thought to be very low to absent.</p>
<p>Chalk outcrop to subcrop</p> <p>Ab_k</p> 	 <p style="text-align: center;">Western TOML B</p>	<p>Areas with similarly low acoustic return to Ab_d thus often impossible to discriminate.</p> <p>Mapped where morphology is more indicative of outcropping or subcropping chalk i.e. on hill-tops and edges.</p> <p>Note that nodule abundance can be high in parts of this unit in areas where thin siliceous clay-ooze cover is present.</p>

Unit/Code	Example	Description
<p>Abyssal hill slopes</p> <p>S1_NE_h</p>  <p>S1_NE_s</p>  <p>S1_SW_h</p>  <p>S1_SW_s</p>  <p>S2_NE_h</p>  <p>S2_NE_s</p>  <p>S2_SW_h</p>  <p>S2_SW_s</p> 	 <p style="text-align: center;">Eastern TOML D</p>  <p style="text-align: center;">Eastern TOML D</p>	<p>Selected at $\geq 6^\circ$ as to more likely be associated with the graben and horst related normal faults associated with abyssal hills. Circular features are not included (volcanic rocks or potholes; section 3.3.2.3.1).</p> <p>S1 orientation is the most common regionally including irregular slopes often associated with offset faults and valley terminations.</p> <p>S2 orientation is a locally secondary orientation (i.e. not normally present)</p> <p>NE facing is net aspect between 315 and 135°</p> <p>SW facing is net aspect between 135 and 315°</p> <p>_s has less backscatter reflectance -30.5 dB or less – interpreted to be predominantly carbonate outcrop \pm sedimentary cover</p> <p>_h has more backscatter reflectance more than -30.5 dB – interpreted to include common volcanic outcrop</p> <p>Nodule abundance is generally very low to absent unless there is siliceous clay-ooze cover in flatter parts of the slope. Preservation of the semi-liquid layer is unlikely to be widespread at slopes $>6^\circ$</p>
<p>Seamount – coherent facies</p> <p>V1_m</p> 	 <p style="text-align: center;">Eastern TOML D</p>	<p>Bathymetry illustrates composite dome and mound formation; very high backscatter reflectance indicates all is lava. Slopes are around 20° but locally up to 30°.</p> <p>No significant nodules known.</p>

Unit/Code	Example	Description
<p>Seamount – talus V2_t</p> 	 <p style="text-align: center;">NW NORI C</p>	<p>Only one example; slopes are around 10° but locally as high as 20°.</p> <p>Nodule abundance potential likely to depend on cover e.g. per V1_k (three historical samples from near the base of the slope returned 10-13 kg/m² but 1-1.3% Ni and 24-31% Mn).</p>
<p>Sheet flows V1_s</p> 	 <p style="text-align: center;">NW NORI C</p>	<p>High reflectance indicates lava but very low aspect unit over long distances is problematic (slopes are often less than 2°). May be breaching sill? Else some type of high reflectance gravity density flow.</p> <p>Nodule abundance unknown (one historical sample on the edge of a unit returned low abundance and grade).</p>
<p>Fissure lavas/dyke V1_f</p> 	 <p style="text-align: center;">Western TOML B</p>	<p>Relatively uncommon linear high reflectance bodies and mounds.</p> <p>Nodule abundance potential expected to be the same as for V1_k/c.</p>

Unit/Code	Example	Description
<p>Knoll/mound – hard V1_k</p>  <p>Composite knolls - hard V1_c</p> 	 <p style="text-align: center;">North-eastern TOML Area D</p>	<p>Irregular of the ocean crust basalts that constitute the abyssal hills/valleys. Characterised by standing proud in the bathymetry and having very high backscatter reflectance (0 to -20dB).</p> <p>Variety of landforms not discriminated (e.g. pancakes, cones ridge complexes).</p> <p>Often associated with basins.</p> <p>Distal flows not seen larger edifices formed from compound short range flows (likely pillows).</p> <p>Origin is either off-axis during spreading or later (decompression or hot-spot related).</p> <p>Nodule abundance likely to be highly variable. In exposed volcanic areas will likely be patchy with some occurrences in areas where thin siliceous clay-ooze cover is present. In covered shallow mounds will likely be the same as Ab_s.</p>
<p>Knoll/mound – soft V2_k</p>  <p>Composite knolls - soft V2_c</p> 	 <p style="text-align: center;">Northern TOML B</p>	<p>Characterised by lower “moderate” backscatter than the V1 volcanic units (i.e. similar to that of high nodule abundance areas) despite often steep landforms.</p> <p>Seen only in TOML Area B and NORI Area A. These may represent more fragmental volcanic products (scoria or even covered by density current flows).</p> <p>Nodule abundance potential expected to be the same as for V1_k/c.</p>
<p>Pothole/trough zone PH</p> 	 <p style="text-align: center;">Southwestern TOML C</p>	<p>Groups of these indicated with a general outline on these preliminary maps as they are too small at this scale of interpretation.</p> <p>These small depressions commonly form in lines along ridge tops. They can grade into scarps. In NORI A they also grade into long trough structures parallel to the abyssal hills. Rare in the east (TOML Area F NORI Area D).</p>

Unit/Code	Example	Description
Tb 	 Eastern NORI D	Major topographic break-line separating distinct domains based on relative water depth.

Other features are marked as comments on the maps.

3.2.3 Sub-bottom profiler and side-scan sonar datasets

The MAK-1M deep-tow acoustic system (Figure 3-8) includes side-scan sonar (SSS) and a 5 kHz sub-bottom profiler (SBP). The system also measures tilt and heading and water pressure as well as location using a 12 kHz USBL system in responder mode. The system is rated to 6,000 m but was used only to ~4,800 m; tow speeds at that depth were of the order of 1 knot.

The SSS was used at 30 kHz giving a slant range of 1200 m from ~100 m above the seafloor (a shorter range 100 kHz option was not used). Penetration of the sub-bottom profiler into the sediments was ~100 m, coherent volcanic units reflecting the signal back almost immediately. The depth penetration is approximate based on an estimate of signal travel time through the sediment (e.g. 1600 m/s). As is apparent in the sections interpreted in this chapter, refraction of high reflectance bodies normally causes delayed returns and development of “shoulders” off the edges of these bodies. The system was held at about 100 m above the seafloor, but drape with changes in elevation of the seafloor was also limited by momentum related delays and associated response of the winch operator.

Note that for the figures and discussion below, unless specified otherwise:

- SBP (sub-bottom profile) data have vertical exaggeration $v/h=10$ and a profile thickness of ~100 m;
- SSS (side-scan sonar) data has a total swath width of about two kilometers.

The deep tow SSS/SBP was deployed along 9 lines over 4 sites per Table 3-2, Figure 3-3.

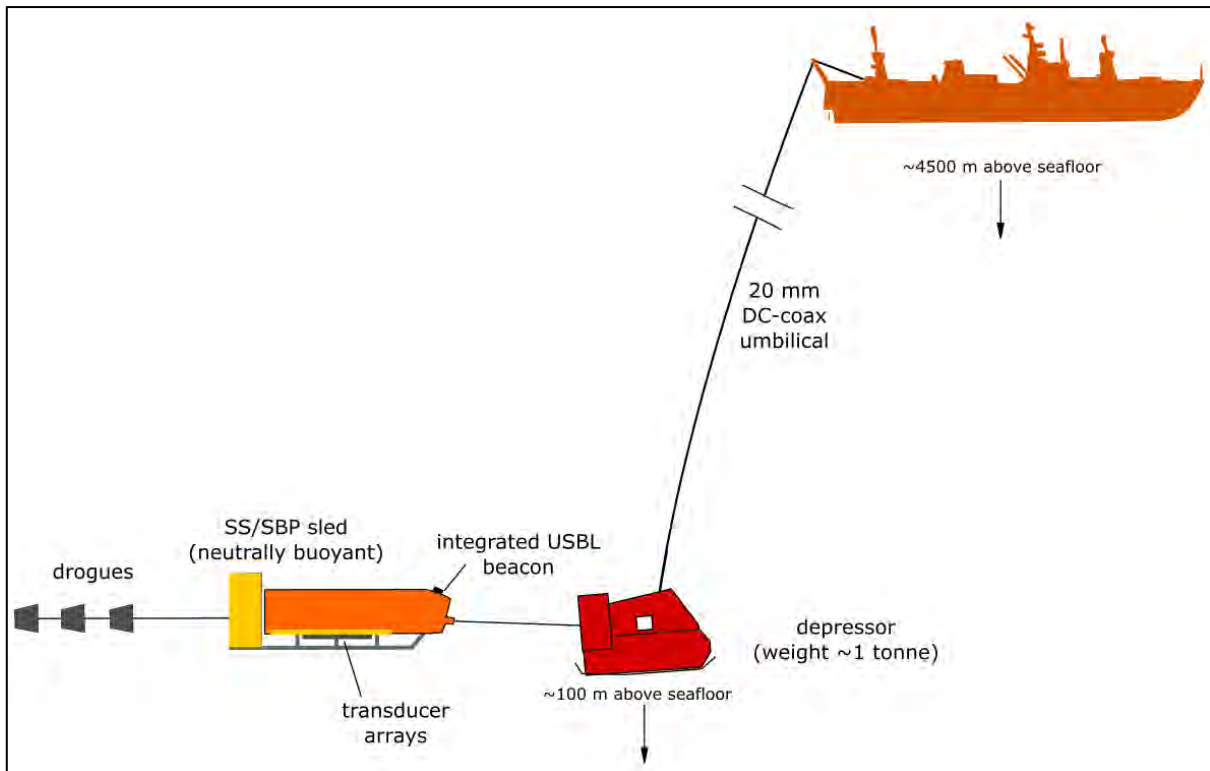


Figure 3-8: MAK1-M deep tow sidescan sonar (SSS)/ sub-bottom profiler (SBP)

3.2.4 Sub-bottom profiler mapped units

Examples of each mapped or identified unit are shown below in Table 3-3. While SBP response was the discriminant used for mapping, comparison with nearby towed photos and the SSS response were also used. The unit codes are distinct from the other datasets as the units are discriminated and evaluated differently; for example the abyssal hill units (Ab_s) from the MBES interpretation usually include at least basement volcanic rocks (G), overlying carbonate units (B) and surficial siliceous clay-ooze (A1 and A2).

The sections in section 10.3 are presented at 1:25,000 scale. They were built up in Inkscape (v0.92.3) to preserve image quality and so are not georeferenced. Each section comprises:

1. SBP response at 10 x vertical exaggeration with geological interpretation;
2. SBP response at 1 x vertical exaggeration for reference;
3. 12 kHz MBES profile over the line both as absolute depth and as degrees of slope with $\geq 6^\circ$ highlighted;
4. Associated SSS swath, interpreted as discussed further below.

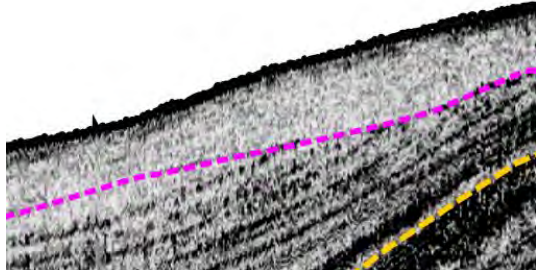
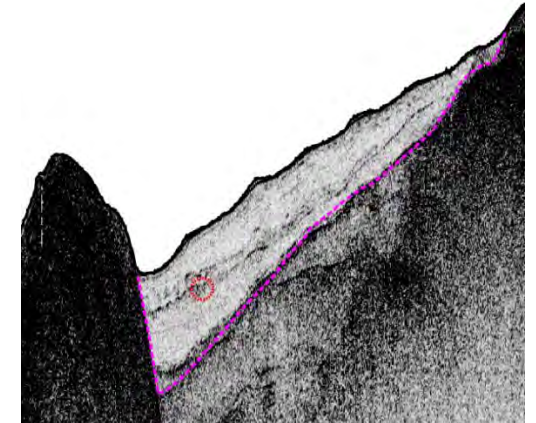
Table 3-2: MAK1M Deep-tow Sonar Lines in TOML Contract Area, CCZ

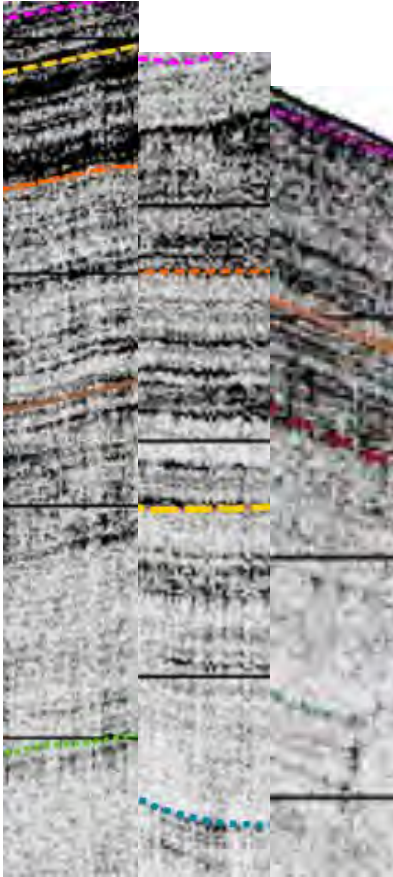
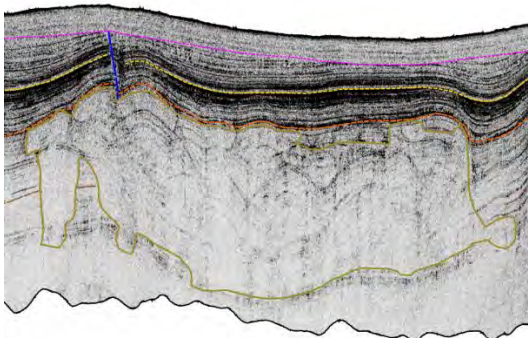
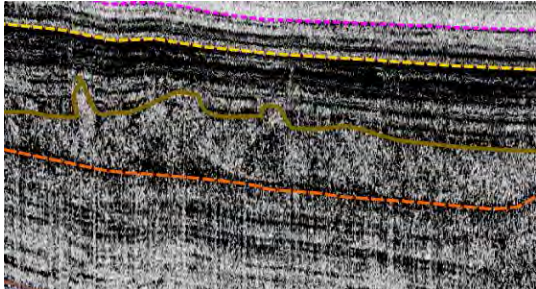
Line ID	Location	Date (UTC)	Start		End		Depth (m)	Length (km)
			Lat. (N)	Long. (W)	Lat. (N)	Long. (W)		
CCZ15-M01	Area B1	22/08/15	13°34.755'	132°57.584'	13°39.610'	132°46.160'	4750-5080	22.4
CCZ15-M02	Area B1	13/08/15	13°36.032'	132°57.504'	13°40.614'	132°46.544'	4780-4900	21.4
CCZ15-M03	Area B1	24/08/15	13°36.845'	132°58.217'	13°41.609'	132°47.031'	4800-5080	21.9
CCZ15-M04	Area B1	25/08/15	13°37.894'	132°58.592'	13°42.615'	132°47.427'	4780-5100	21.9
CCZ15-M05B	Area C1	11/09/15	15°05.396'	129°55.956'	15°12.999'	129°39.147'	4840-4980	31.6
CCZ15-M06	Area D2	23/09/15	13°50.487'	124°38.179'	13°59.118'	124°17.664'	4300-5300	40.2
CCZ15-M07	Area D2	23/09/15	13°51.614'	124°38.727'	13°55.832'	124°28.662'	4400-4500	19.7
CCZ15-M07B*	Area D2	26/09/15	13°55.716'	124°28.755'	13°59.798'	124°17.680'	4400-4480	20.16
CCZ15-M08	Area D2	25/09/15	13°52.661'	124°39.238'	14°01.398'	124°18.668'	4380-4510	40.4
CCZ15-M09	Area D1	27/09/15	13°26.293'	125°16.500'	13°35.019'	124°55.970'	3950-4660	40.4

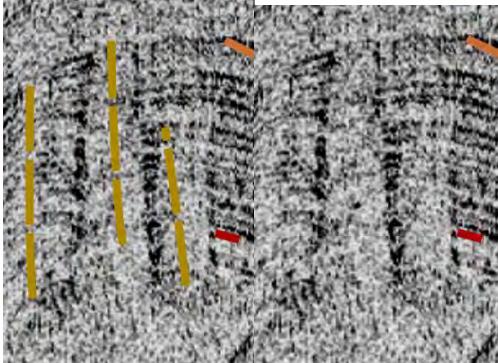
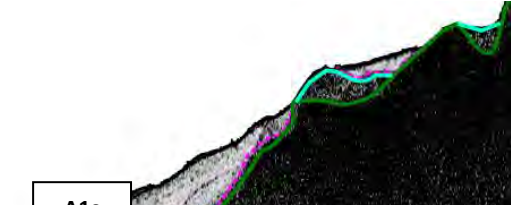
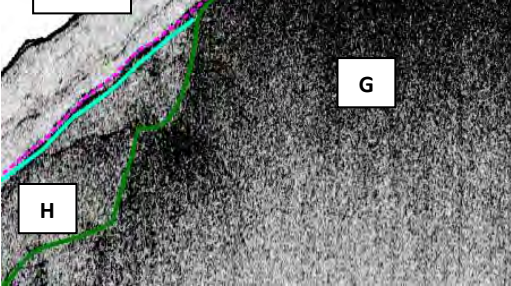
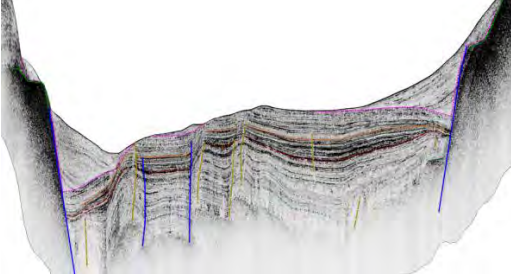
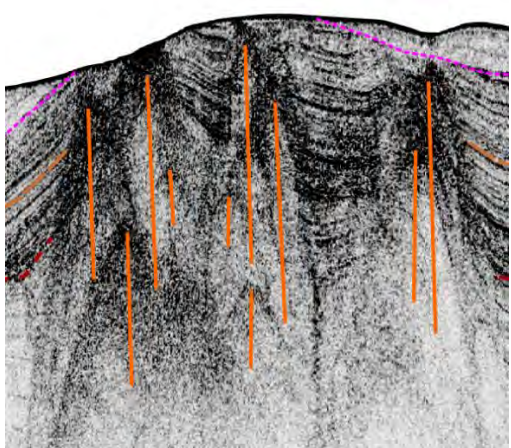
* Note CCZ15-M07B is an extension of M07 when that line was aborted due to a systems failure.

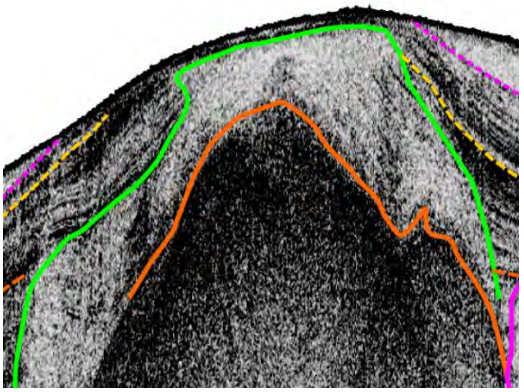
Importantly, comparison between the SBP profile and the 12 kHz MBES profile for the same areas shows that the MBES slopes are not especially smoothed (although they lack some detail), and that there are significant discrepancies between the absolute depths of the two surface profiles. While the differences cannot be fully explained, it is suspected that the MBES is more accurate than the SBP due to the draping limitations with the SBP mentioned above.

Table 3-3: Sub-bottom profiler units legend

Unit/Code	Example	Description
A1 <i>dashed magenta line</i>		Base of surficial acoustically translucent unit. Interpreted to be siliceous clay-ooze. Typically unconformable on underlying units. Underlying units may be: <ul style="list-style-type: none"> • an acoustically translucent unit (again siliceous clay-ooze but called unit A2); • B (see below) • G or rarely I or I' (see below)
A1s <i>dashed red circle above dashed magenta line</i>		Locally thickened surficial acoustically translucent unit on steeper slopes. Interpreted to be horizontally transported and gravity slumped siliceous clay-ooze. Invariably conformable on underlying unit B and not usually discriminated in the sections.

Unit/Code	Example	Description
<p>B Markers are variable yellow, orange, brown, blue, lines</p>	 <p style="text-align: center;">B_tb B_tc B_td</p>	<p>Acoustically layered unit (interpreted to be carbonate-chalk, called in aggregate B) Within the TOML areas surveyed three different stratigraphic variations called</p> <ul style="list-style-type: none"> • B_tb, B_tc and B_td • These all have different marker horizons. • B_tb is found in TOML Area B1 in lines CCZ15-M01 to M04 (basal marker not shown) • B_tc is found in TOML Area C1 in lines CCZ15-M05 • B_td is found in TOML Areas D1 and D2 in lines CCZ15-M06 to M09
<p>K solid khaki outline</p>		<p>Carbonate Strata Breccia – breakthrough subtype Mixed to domed, semi-stratabound superprint onto B, can form at any level. Occurs almost exclusively in grabens, but expansion causes slight doming of overlying strata. Interpreted to be result of subterranean karstic collapse.</p>
<p>Ksb solid khaki line</p>		<p>Carbonate Strata Breccia – stratabound subtype As above but only the top edge discernible as at depth or thin stratabound type expression.</p>

Unit/Code	Example	Description
<p>J <i>long dashed khaki line</i></p>		<p>Vertical to sub-vertical acoustically translucent blanking superprinted onto B. May be spatially associated with F or I or K. May have slightly down-warped strata on one or both sides. Found in both grabens and horsts. Interpreted to be carbonate dissolution channels.</p>
<p>G <i>solid dark green line</i></p>		<p>Acoustically highly reflective and masked unit interpreted to be volcanic basement – coherent facies such as basaltic lavas Likely to be easily confused with unit I Note acoustic refraction off edges of this and similar units makes the sides impossible to map accurately.</p>
<p>H <i>solid aqua line</i></p>		<p>Acoustically mixed unit without strata interpreted to be volcanic basement – uncoherent facies such as brecciated volcanic rocks</p>
<p>F <i>solid medium blue line</i></p>		<p>Interpreted normal fault based usually on offset in the acoustic strata within B</p>
<p>I <i>solid orange line</i></p>		<p>Acoustically highly reflective and masked unit interpreted to be an intrusion (dyke or sill) – coherent facies such as basaltic lava (see also below) In some cases, the unit is very narrow perhaps representing an intrusive vein Any mapped traces (usually from MBES but correlated with SBP) numbered as follows</p> <p style="text-align: center;">④</p>



Unit/Code	Example	Description
I' solid bright green line		Acoustically translucent to mixed unit adjacent to and interpreted to be alteration halo to I, i.e. peperite (White et al., 2000).


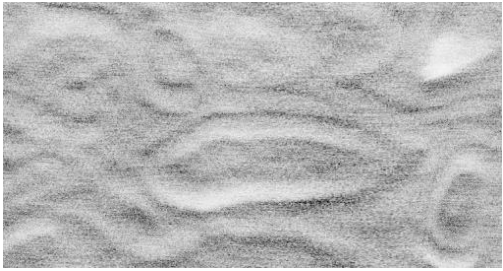

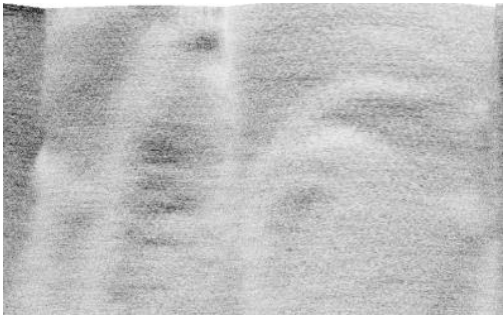
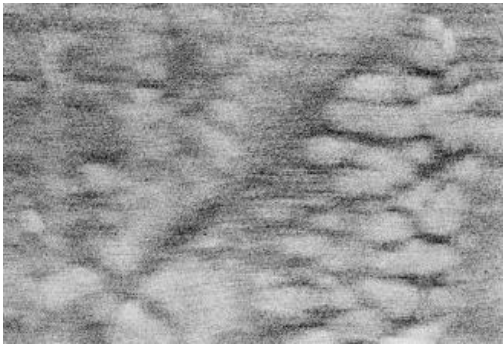
3.2.5 Side-scan sonar units




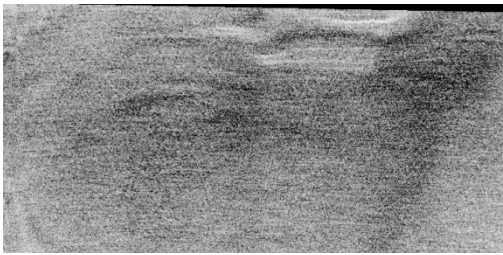






Unlike the SBP, these sidescan (SSS) defined units relate mostly to variants of Clipperton Formation silicious clay-ooze (A1 and A2 in Table 3-3; section 3.3.3) that may assist in understanding detailed nodule potential. The sidescan response also can express subsurface geology (often elucidated via comparison of the accompanying SBP data) and can help in mapping potential obstacles for any future mining operation.

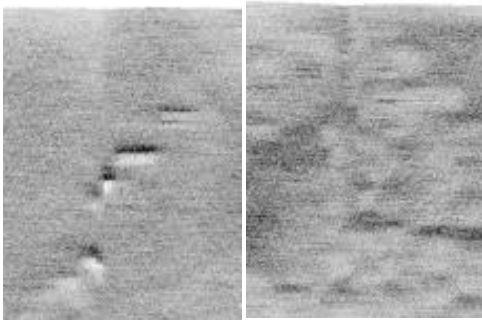

Examples of each mapped or identified unit are shown below. Note grey scale is linked to absorption (darker), not reflectance as used in MBES BS. Care also needs to be taken regarding effects from angle of ensonification and shadows (darker) from the two sides of the side-scan transducer arrays.

Table 3-4: Side-scan sonar units legend

Unit/Code	Example (all are approximately 1 km wide)	Description
co		Default unit of featureless plain of clay-ooze with variable amounts of nodules. Example here from CCZ15-M03 includes a black mark that is a dredge track from the CCZ13 expedition
co_sl --- ●		Clay-ooze that is slumping

Unit/Code	Example (all are approximately 1 km wide)	Description
co_r -----		Clay-ooze with subtle ripples or hummocks
co_mr -----		Clay-ooze with striking mega-ripples and hummocks (10-20 m wavelength)
co_dp ----- ▼ (co_md ▲)		Depression in the clay ooze – variable size. Often but not always in the centre of valleys. co_md ▲ are the contrary (mounds) but these are always small ~<100 m)
co_cm ----- ●		Clay-ooze with large (500-1km) mounds and basins over near surface warped carbonate strata
co_cb		Almost non-existent clay-ooze with a blocky appearance over slightly irregular near surface carbonate strata

Unit/Code	Example (all are approximately 1 km wide)	Description
co_ph 		Pothole in exposed carbonate - the example here (CCZ15-M01) is of small incipient pothole over a near surface dyke
kco 		shoaling carbonate, tends to absorb sound but depends on angle of seafloor
Scr 		Escarpment break-line – position on the scarp unspecified (i.e. if top bottom or at a mid point)
k_s 		Escarpment with exposed carbonate strata
v_s 		Escarpment with exposed basement volcanic

Unit/Code	Example (all are approximately 1 km wide)	Description
co_Vd — — — — —		Clay-ooze with texture imposed by near surface dyke swarm TOML D2 CCZ15-M06
Vd — ●		Breached dyke (unit V1_f per the 1:250,000 scale MBES interpretation) TOML D2 CCZ15-M06

3.2.6 Towed camera dataset

Three types of seabed image data are nominally available (Figure 3-9):

1. YMG Neptune system, deep towed photos profiles for TOML (PP; Figure 3-10).

The system uses a 5 mega pixel sensor and 4 x 70 watt lamps from a 3 m altitude, a altimeter triggers the camera at minimum 15 second intervals with manual motion compensation and altitude adjustment from the winch operator. Twin red laser pointers in the central part of the image are 30 cm apart and can only be seen, when contacting the sediment, in the photos after processing.

Navigation was via a 12 kHz USBL transponder beacon mounted above the camera sled transponding to a flush mounted Posidonia 6000 transceiver mounted near the centre of the ship's hull. Claimed accuracy is 0.2% of slant range (i.e. ~13 m if towing ~6,000 m astern in 4,500 m of water), but correlation between MBES and photos ranges up to 10 times this.

2. Box-core bottom photos, by TOML (others by NORI and Marawa were not sighted);
3. Fugro Hugins AUV bottom photos for NORI;

Almost all of the work reported here is based on the Neptune towed photo data set as these are of the best available quality (Figure 3-9), and comprise numerous transects (Table 3-5) over numerous geological features of interest.

Information on the AUV survey is included in Item 9 of Lipton et al., (2019).

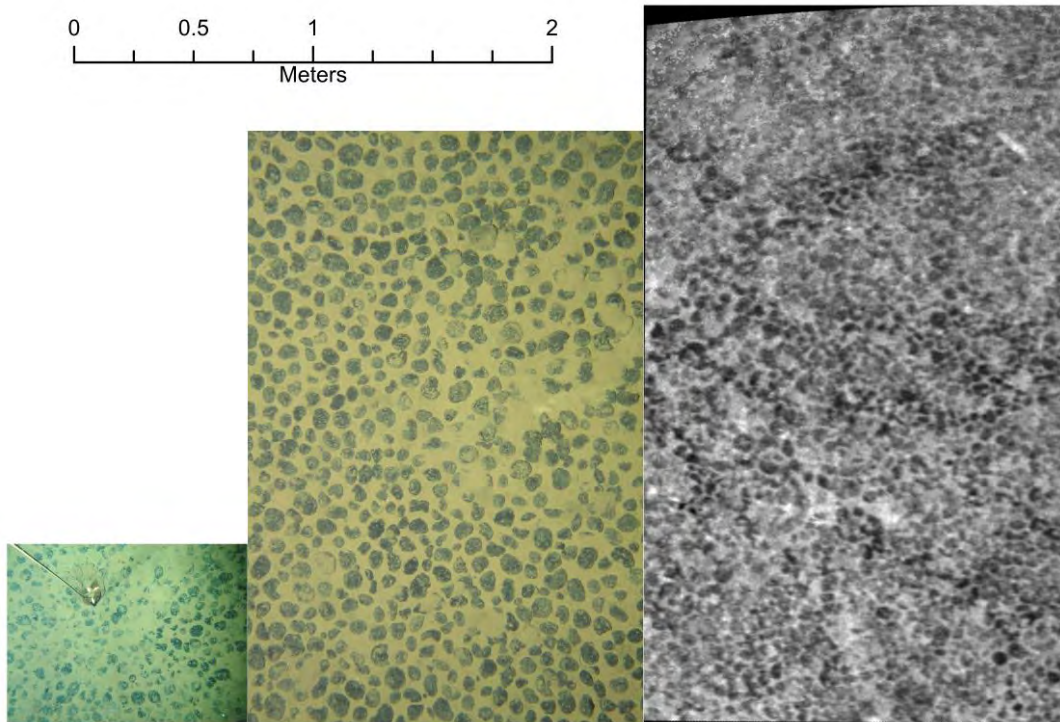


Figure 3-9: Comparison of the three photo datasets

From left to right box-core bottom shot CCZ15-B99; Neptune towed camera CCZ15-F01:2015_08_11_033236; AUV camera CHP_3:tf_1525453183_0000007298

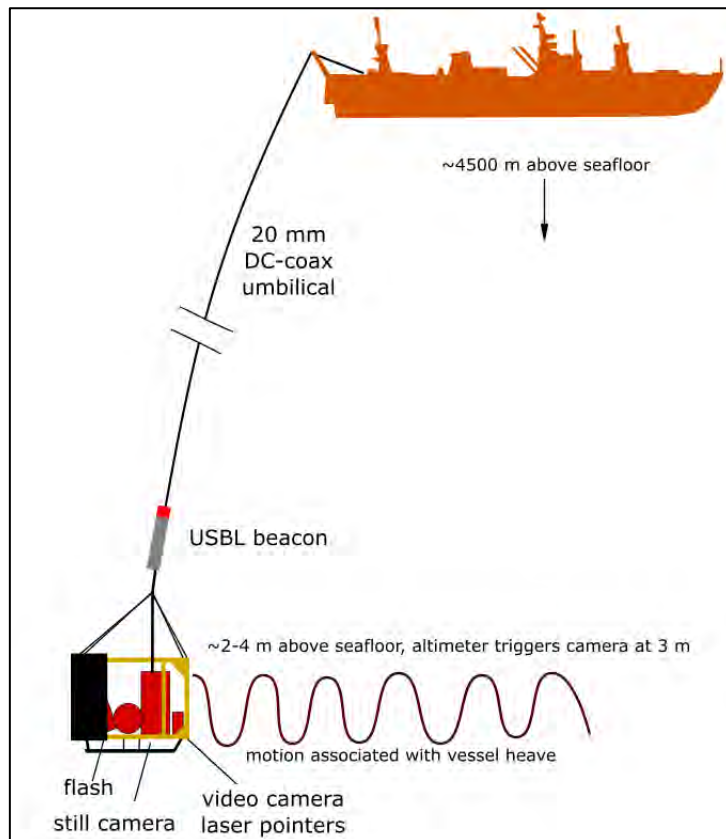


Figure 3-10: Neptune Deep-towed camera system

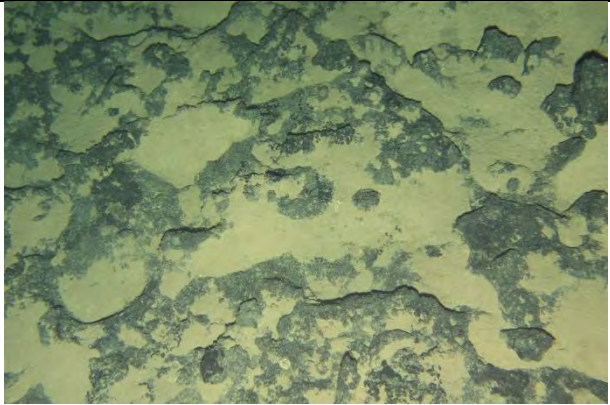
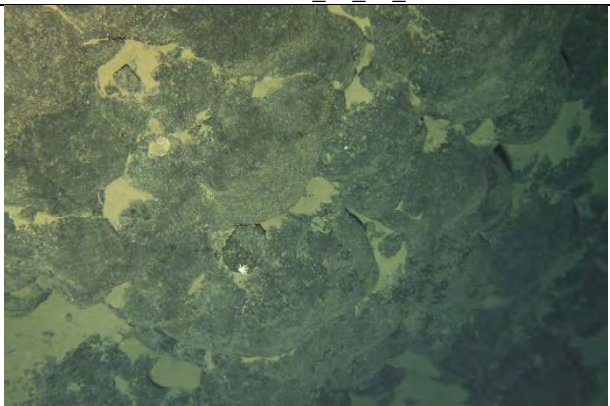
Table 3-5: Neptune Photo-profile lines in TOML Contract Area, CCZ

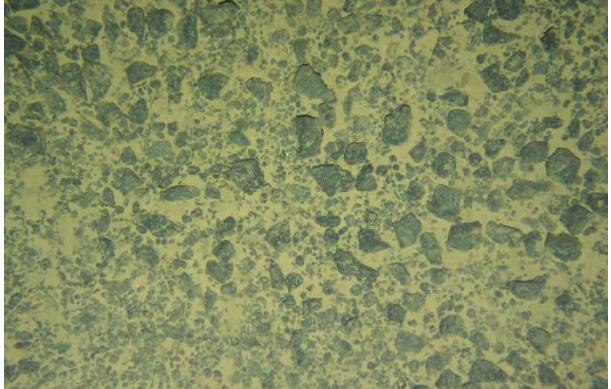
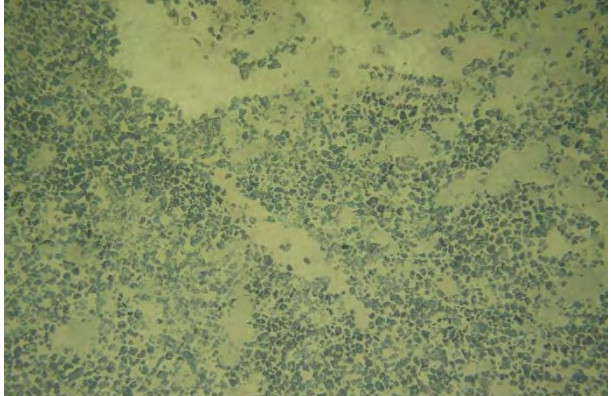
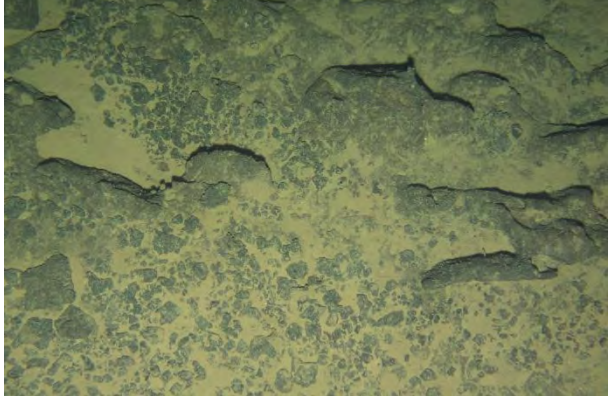
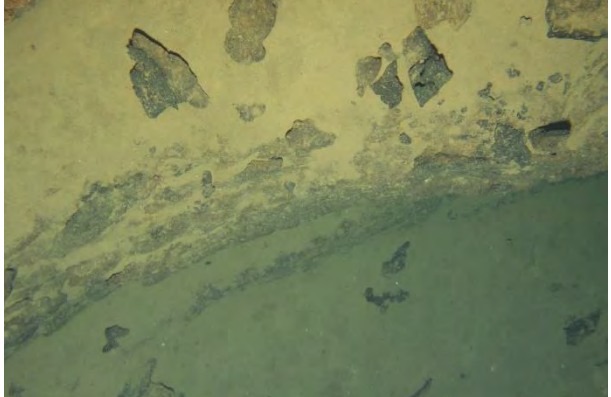
Line ID	Location	Date (UTC)	Start		End		Depth (m)	Length (km)
			Lat.	Long. (W_)	Lat.	Long.(W)		
CCZ15-F01	Area B1	10/08/15	13.578417	132.951583	13.813533	132.401383	4916	65
CCZ15-F02	Area B1	16/08/15	13.641100	132.965150	13.792283	132.606850	4892	42.2
CCZ15-F03	Area B1	21/08/15	13.575067	132.795983	13.753050	132.376467	4961	49.5
CCZ15-F04	Area B1	26/08/15	13.609400	132.958167	13.687817	132.775467	4871	21.6
CCZ15-F05	Area C1	28/08/15	15.001250	130.117967	15.269783	129.535733	4916	69.6
CCZ15-F06	Area C1	01/09/15	15.027750	130.212200	15.308767	129.605567	4910	72.2
CCZ15-F07	Area C1	03/09/15	15.108217	130.192550	15.278807	129.819797	4949	44.3
CCZ15-F08	Area C1	08/09/15	15.025833	129.914667	15.215667	129.499000	4941	44.7
CCZ15-F09	Area D1	13/09/15	13.411183	125.333033	13.544950	125.015600	4609	38.9
CCZ15-F09B	Area D	14/09/15	13.544017	125.019967	13.871117	124.244433	4586	91.5
CCZ15-F10	Area D2	16/09/15	13.834783	124.657617	14.001717	124.261367	4453	46.8


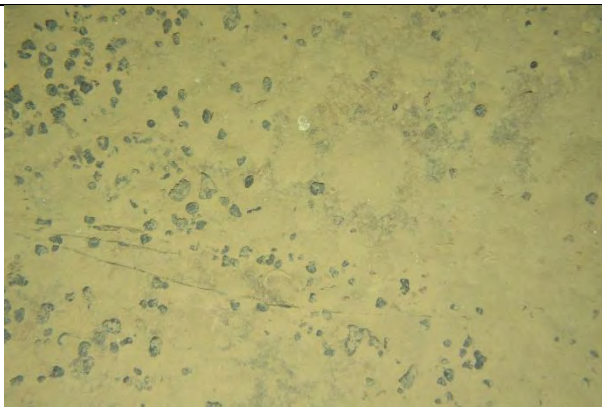


3.2.7 Seabed photo units

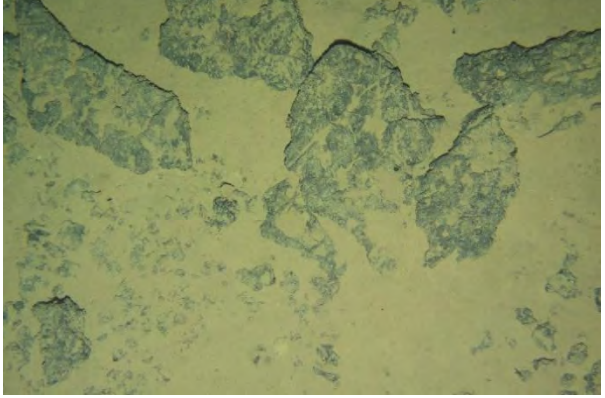
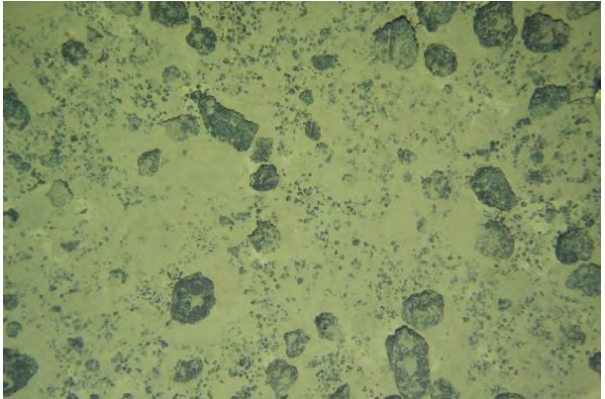
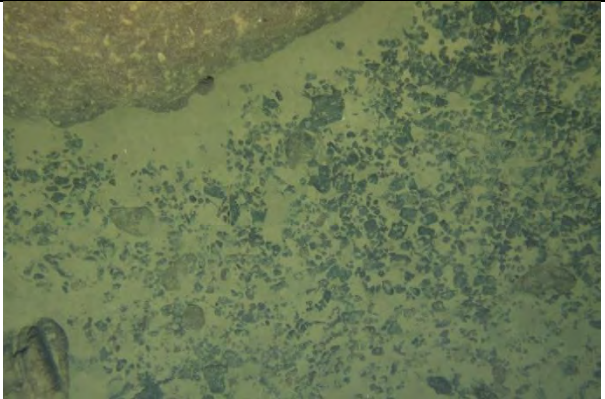

These are in Table 3-6 below. Note the photos are referred to only in some type areas. Systematic high-level logging was done by the CCZ15 science team and is not reproduced here. A more detailed review of the polymetallic nodule units is included in Chapter 4.

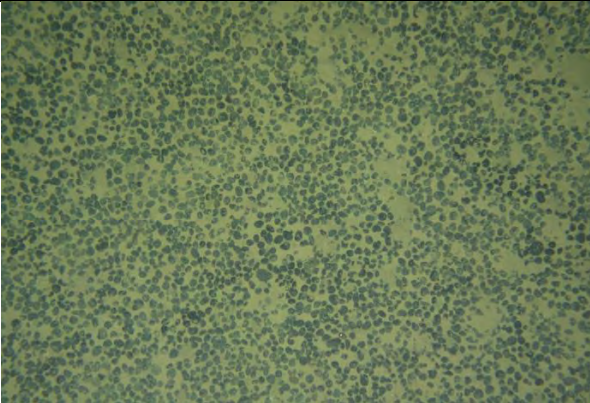
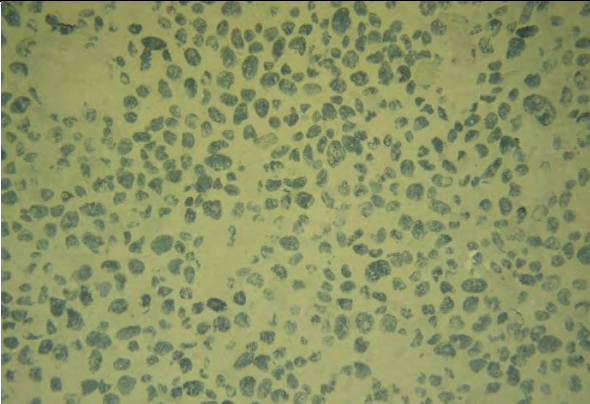
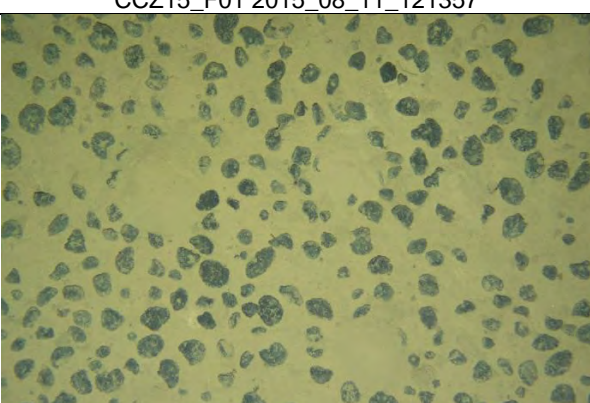
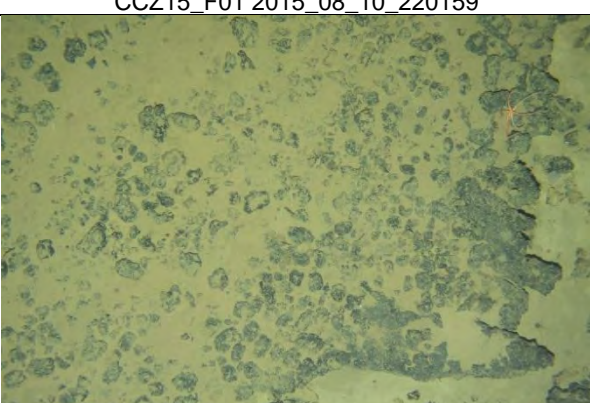
Table 3-6: Photo outcrop and fragment units legend

Unit/Code	Example	Description
Volcanic units		
V_c	 <p>CCZ15-F02 2015_08_17_094816</p>	Coherent lava with variable sediment cover. Usually associated with small or no nodules.
V_cl	 <p>CCZ15-F02 2015_08_17_091854</p>	More pillow to lobate forms of the coherent volcanic rocks

Unit/Code	Example	Description
V_n	 <p>CCZ15-F02: 2015_08_17_065055</p>	Non-coherent (breccia) facies
	 <p>CCZ15-F02: 2015_08_17_125022</p>	Finer grained variant of breccia facies
Carbonate units		
c_m	 <p>CCZ15-F02: 2015_08_17_130037</p>  <p>CCZ15-F03: 2015_08_22_152908</p>	<p>Massive carbonate outcrop. Generally smooth to cusped surfaces.</p> <p>Light brown in colour (varieties coated with ferro manganese may be indistinguishable from coherent volcanic units except by association with other carbonate units)</p> <p>Usually seen at escarpments or the edge of collapse structures. Usually associated with small or no nodules.</p>

Unit/Code	Example	Description
	 <p>CCZ15-F09: 2015_09_14_000103</p>	
c_mp	 <p>CCZ15-F02: 2015_08_17_125427</p>  <p>CCZ15-F02: 2015_08_17_015034</p>	<p>Massive carbonate pavement outcrop often with minor cover of soft sediment and carbonate ± ferro-manganese fragments. Usually light brown in colour and showing some lineaments up to 1 m long and several cm wide reminiscent of flint seams or of stylolites albeit very linear ones.</p>
c_ms	 <p>CCZ15-F02: 2015_08_17_124612</p>	<p>Sheet like expression of massive carbonate. Irregular cusped edges often proud for several cm to tens of cm.</p> <p>Tend to be dark grey in colour which is thought to be due to ferromanganese coating, but may include halmyrolysis related zeolite precipitation.</p> <p>Interpreted to be chalk or chalk-flint layers that are more resistant to CO₂ dissolution, than the overlying and underlying chalk layers.</p>

Unit/Code	Example	Description
c_fl	 <p>CCZ15-F10 2015_09_16_140728</p>  <p>CCZ15-F10 2015_09_16_185038</p>	<p>10 cm to 1 m fragments of carbonate</p> <p>The larger fragments often show lineaments as seen in pavement carbonates</p> <p>Small and darker fragments may be difficult to distinguish from diagenetic crusts.</p> <p>Sometimes found in lines (outcropping strata)</p> <p>Usually associated with small or no nodules.</p>
c_fs	 <p>CCZ15-F01 2015_08_11_163832</p>  <p>CCZ15-F02 2015_08_17_054739</p>	<p>Small (1-10 cm) often irregular platy fragments, some with veins (cf lineaments). Colour ranges between light brown and dark grey; the later may reflect ferromanganese coating.</p> <p>Usually associated with small or no nodules.</p>

Unit/Code	Example	Description
Ferro-manganese units (refer also to Chapter 4)		
s-RS	 <p>CCZ15_F03 2015_08_22_115003</p>	Small rough-smooth nodules Small mounds are result of bioturbation
m-RS	 <p>CCZ15_F01 2015_08_11_121357</p>	Medium rough-smooth nodules
l-RS	 <p>CCZ15_F01 2015_08_10_220159</p>	Large rough-smooth nodules
Fe-Mn crust	 <p>CCZ15_F10 2015_09_16_025313</p>	Only collected in dredge samples, these rest on or in mud and are thought to be diagenetic in nature grading from ferromanganese concretion at surface to mud. Usually associated with large nodules.

3.2.8 Other datasets

Sample data available includes nodule form and abundance, nodule chemistry and sediment chemistry per Table 3-7 and Figure 3-11.

Table 3-7: Sample information by area

Sample type	NORI D	TOML B1, C1, D1, D2, F	Marawa	NORI A, B, C; TOML B, C, D, E (other TOML)
Historical nodule samples (unknown FFG or BC) Abundance in kg/m2 Ni, Cu, Co, Mn chemical analysis	yes	yes	yes	yes
Boxcore nodule samples Abundance in kg/m2 Logging of form Multielement chemical analysis (~20 elements)	yes	yes	yes	no
Boxcore sediment samples Multielement chemical and biochemical analysis (~20 elements)	yes	no	no	no

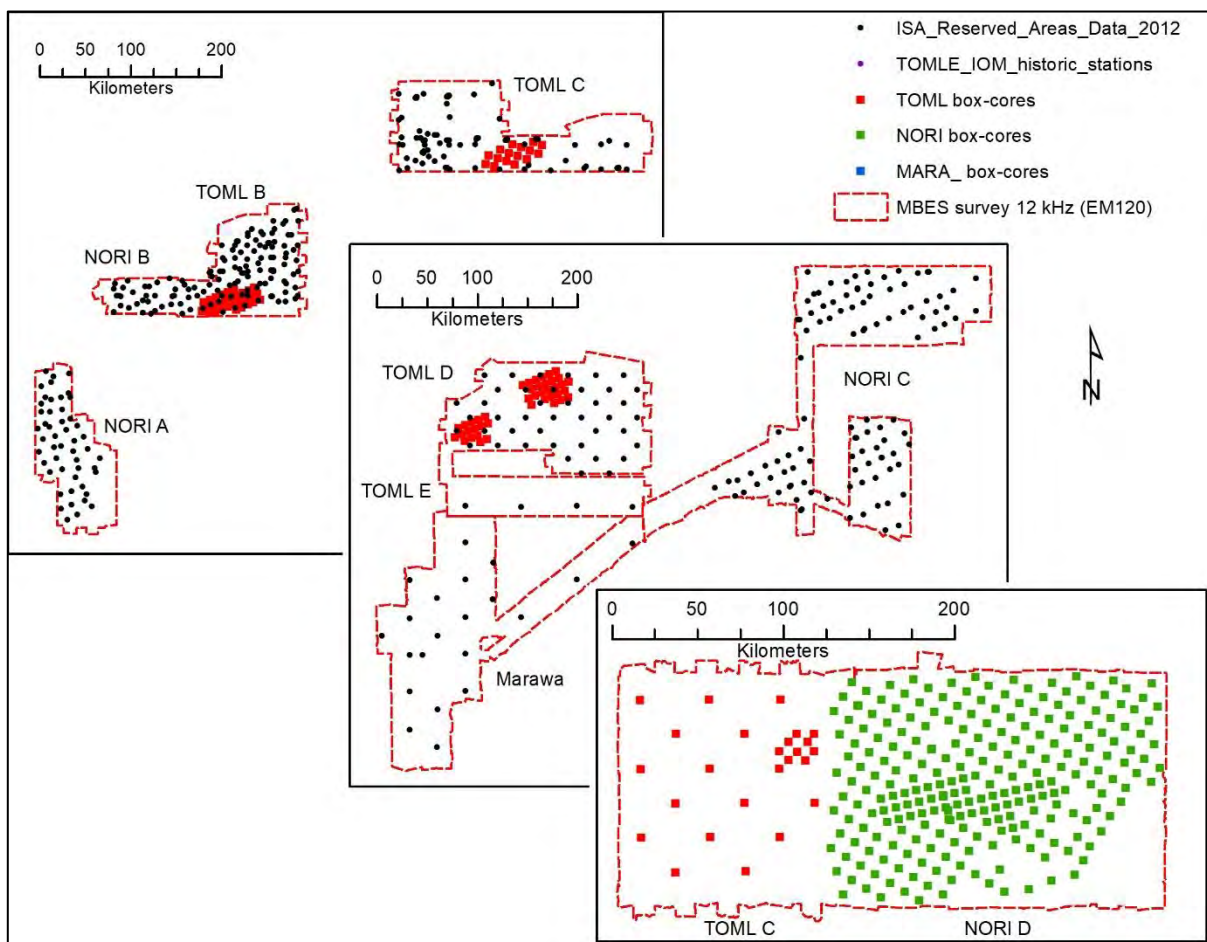


Figure 3-11: Sample data by area

Discussion on nodule attributes including chemistry, density, and moisture content comprise Chapter 4. Sample attributes were only used here to validate or support the interpretation made in this chapter.

3.2.9 Summary of software used

For the 1:250,000 maps: Multibeam data was processed using CARIS HIPS and SIPS and Geocoder, with grids and images stretched and finished in Geosoft. Sound Velocity Profiles (SVPs) used for correction of the MBES data consist of real time synthetic derived from CTD casts, that were compared with the synthetic profiles from the WOA13 sound speed database. Interpretation and map compilation was done in a combination of ArcGIS 10.4.1 and qGIS 3.10.7. Terrain Ruggedness Index (TRI) analysis was done using the native tool in qGIS 3.10.7. Derivation of slopes used SAGA Mesh Denoise, qGIS 3.10.7 Slope tool, Aspect tool, Raster Calculator tool, Contour tool, Lines to polygons tool Oriented Minimum Bounding Box tool, Zonal Statistics tool, (as detailed in section 9.11 Appendix 3C). Areas were estimated using ArcGIS 10.4.1 Calculate Geometry tool. Terrain profiles for the cross-sections were derived using (Profile Tool 4.1.8) in qGIS 3.10.7, and assembled/interpreted in Inkscape 0.92.3. Data preparation for the rose diagrams and segment speed estimates used Microsoft Excel (version 16.0). Rose diagrams were prepared using GeoRose 0.5.1. The maps were compiled and set in ArcGIS 10.4.1.

For the 1:25,000 maps and sections: Sidescan and sub-bottom profiler data was processed in-house by Yuzhmoregeologiya using proprietary software and supplied raster images used in the interpretation. The maps were compiled and interpreted with MBES, photo-profile locations and sample data in ArcGIS 10.4.1. To maintain maximum resolution, the sub-bottom profiles and attendant sidescan swaths, were assembled/interpreted in Inkscape 0.92.3. MBES terrain profiles for the cross-sections were derived using (Profile Tool 4.1.8) in qGIS 3.10.7.

Figures were drafted either in ArcGIS 10.4.1, qGIS 3.10.7 or Inkscape 0.92.3.

3.3 Commentary by stratigraphy

Per Figure 3-2 this essentially comprises:

1. Basement volcanic rocks of between 42 Ma and 18 Ma age (mid Eocene to early Miocene), from west to east, that define the abyssal hills;
2. A lower unit of predominantly carbonate chalk strata of mid Eocene to Miocene age, equated to the Marquesas Oceanic Formation of Tracey et al., (1971).
3. An upper unit of siliceous sediment believed to be of between 18 Ma to current age (Early Miocene on), regressing from west to east and from north to south, and equated to the Clipperton Oceanic Formation of Tracey et al., (1971).
4. Other unconformable volcanic rock units, aged from coeval with the basement volcanic rocks to the present period, including seamounts/knolls and other forms.
5. Surficial ferro-manganese deposits; expected to be mostly of Pleistocene to current age (< 2 Ma) but potentially including fragments as old as late Miocene or more (10 Ma+). These are discussed further in Chapter 4.

3.3.1 Basement volcanic rocks and escarpments

The abyssal hills units define the majority of the landforms in terms of area (>80%; section 3.3.3.1), and strongly influence the sediments that host the polymetallic nodule mineral resource. Their arrangement will also very likely prove important in terms of any future mine planning (i.e. through slope angles and swath width and length).

3.3.1.1 Introduction to abyssal hills

Abyssal hills are the most common landform on the ocean floor and indeed thus the earth (Menard, 1964 in Buck and Poliakov, 1998; Olive *et al.*, 2015). These elongate hills (Figure 3-12) are believed to have formed from normal faulting (and maybe growth block faulting) following the process of seafloor spreading (Macdonald *et al.*, 1996; Buck and Poliakov, 1998), with variations in form related to: tectonic reorganisation related to the stress field at the time of formation; spreading rate (and associated pressure fronts); geothermal gradient and magma effusion; and perhaps also the rate of cooling related subsidence.

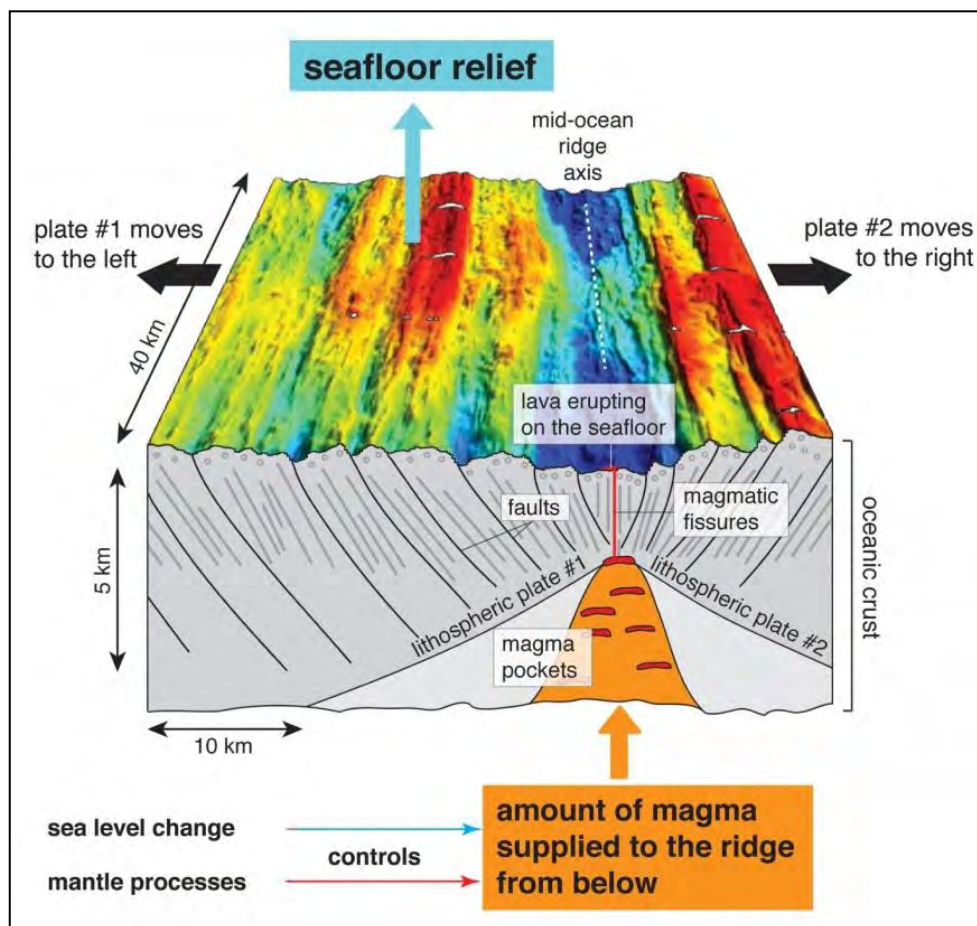


Figure 3-12: Formation of abyssal hills at mid-oceanic ridges

Reproduced from: Olive *et al.*, (2015)

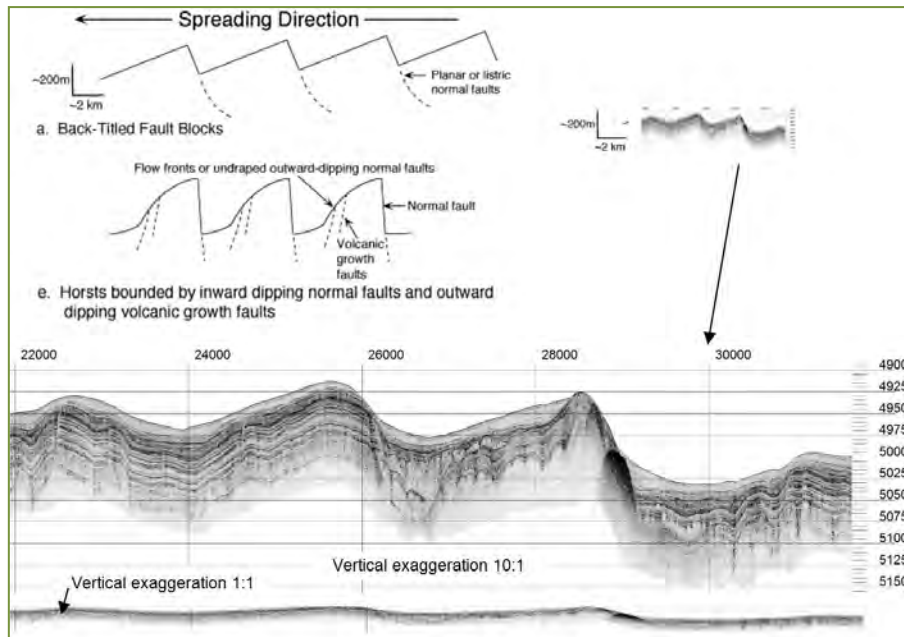


Figure 3-13: Two models for the development of abyssal hills and an example SBP section in TOML Area C. Diagrams modified from Macdonald et al., (1996): a, back-tilted fault blocks (episodic inward-dipping normal faulting off-axis), e, horsts bounded by inward-dipping normal faults and outward-dipping volcanic growth faults (episodic faulting off-axis and episodic volcanism on/near-axis). Models b-d not shown. Sub-bottom profile (5kHz) also shown at same scale.

3.3.1.2 General characteristics of abyssal hills in the mapped areas

Within the central-eastern CCZ, the abyssal hills are typically oriented parallel to each other and the mid-ocean ridge, i.e., generally to 345-355° (Figure 2-8, Chapter 2). Scale of the hills is generally smaller than those modelled by (Macdonald et al., 1996) in Figure 3-13, and while the schematic diagrams in Figure 3-12 and Figure 3-13 indicate a strong asymmetry, (with fault scarps facing the spreading center), within the CCZ fault escarpment-slopes face roughly equally in both directions (Figure 3-14). “Full” grabens with opposing fault (slopes >6°) are dominant although “single sloped” half grabens are also seen in both directions. The hills generally have an amplitude of 50 to 300 m and wavelength of 1 to 10 km (Figure 3-17).

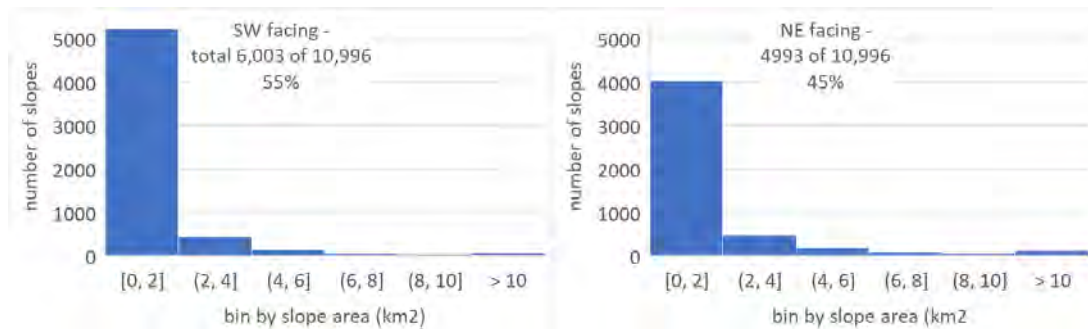


Figure 3-14: Slope ($\geq 6^\circ$) facings for the mapped area within the CCZ

Abyssal hills have significant strike (usually <100 km). Accommodation at the ends of abyssal hills can be through relay ramps (between common facing slopes) and conjugate relay zones (between opposing slope pairs; (Childs et al., 2019)). Both relay types are common. The conjugate relay zones more often cut through the grabens (i.e., divergent horst relays in example Figure 3-15). In these instances, this may represent local areas of anticlinal accommodation. Significantly, there is no discernible focus for potholes at these horst relays.

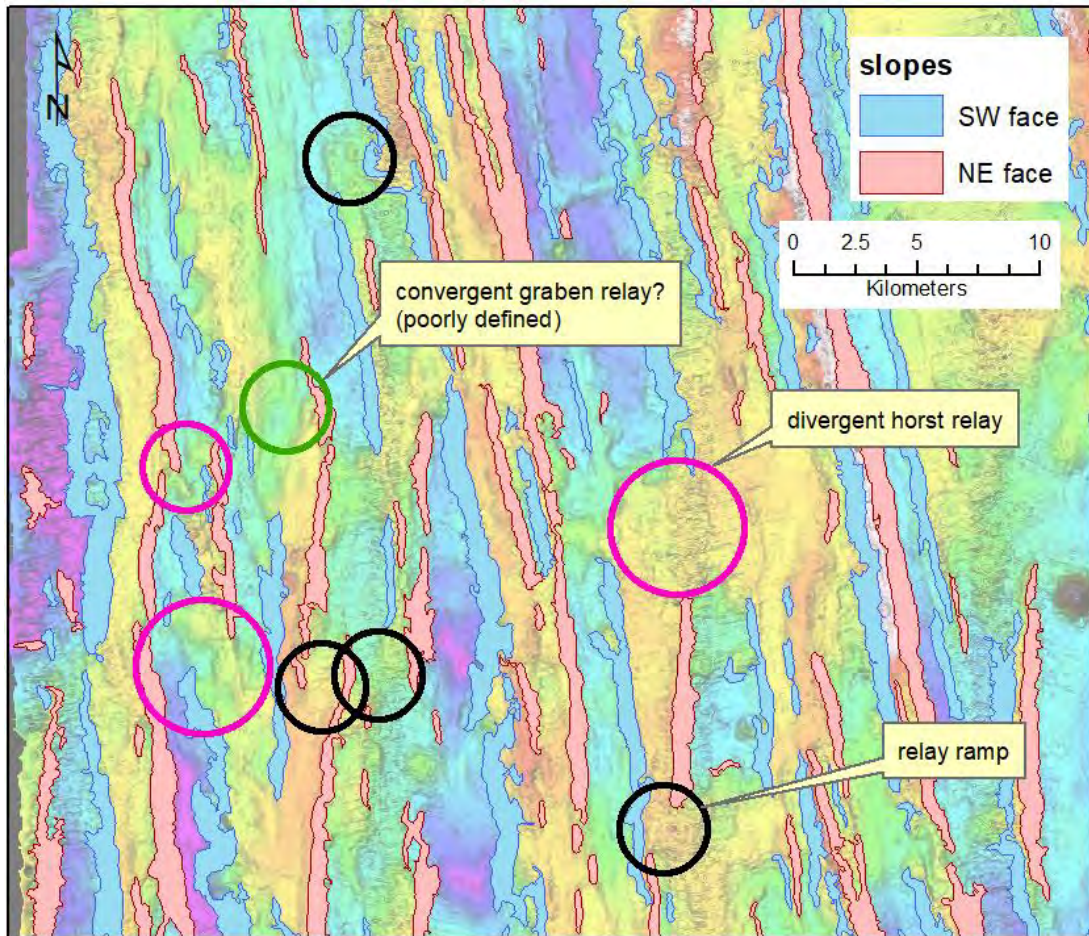


Figure 3-15: Example abyssal hill accommodation geometry (TOML F)

3.3.1.3 Composition of basement volcanic rocks

The limited, publicly available seabed volcanic analyses within the CCZ are generally either basal units of abyssal hills from the DSDP/ODP or samples from seamounts (Figure 3-16). While there is considerable overlap in composition:

- Oceanic crust samples are dominantly tholeiitic to sub-alkaline basalts to basaltic andesites;
- Rift and fracture sources volcanic samples are often slightly more alkaline
- Seamount samples are generally trachytic and range from basanite to trachyte (in the east). Some of their analyses include REEs and these indicate they are mostly of N-MORB basaltic composition i.e. $(La/Sm)_n < 1$ and $SiO_2 < 53\%$ (Section 9.14, Figure 3-16).

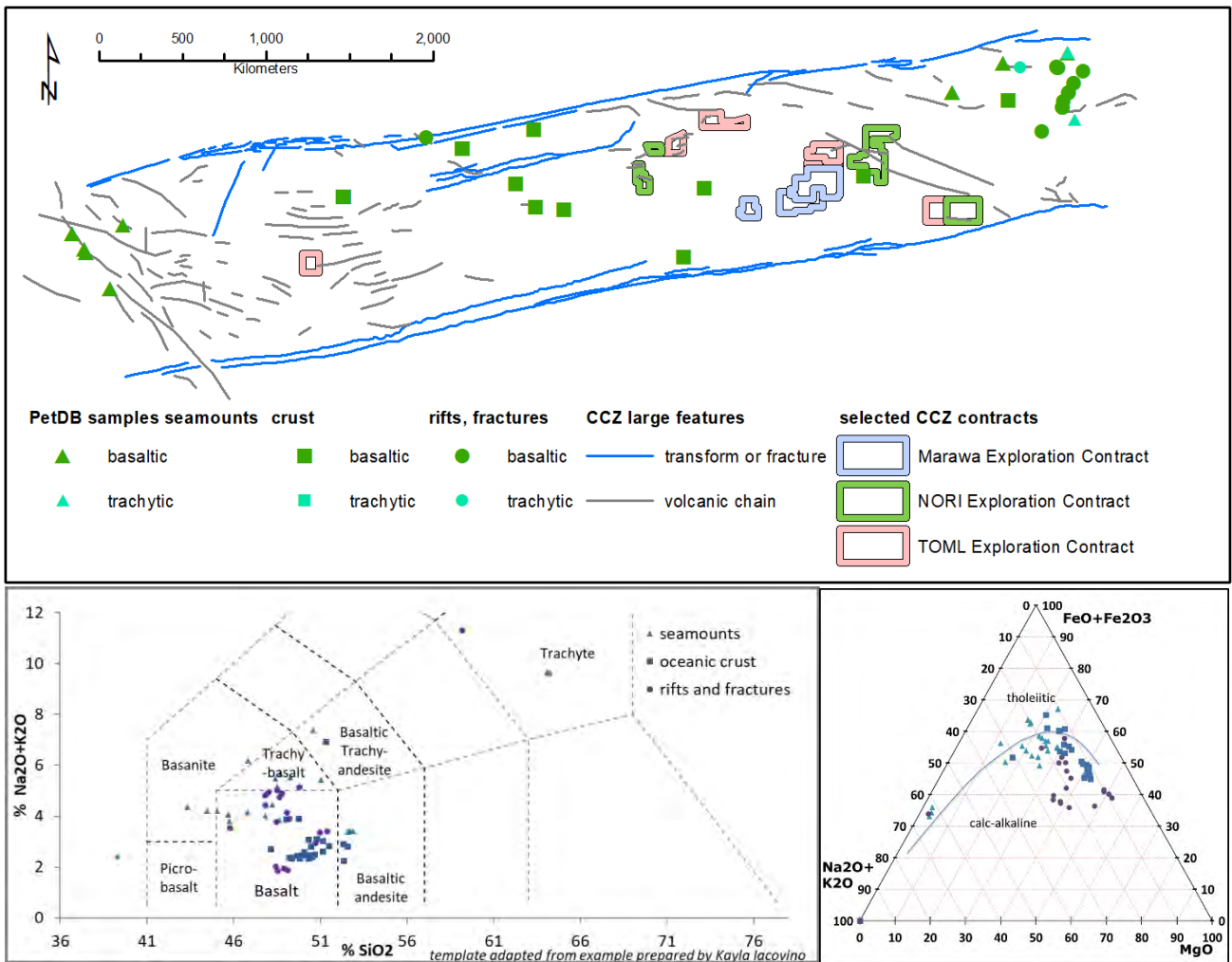


Figure 3-16: Seafloor volcanic compositions from the CCZ

Total alkali silica diagram after Le Maitre et al., (2002). AFM diagram after Kuno, (1968). Data in Section 9.14 sourced from in PetDB at <http://earthchem.org/>. Refer to Chapter 2 for description on the CCZ large features

3.3.1.4 Slopes as Escarpments

Using MBES bathymetry to definitively identifying fault escarpments is not known to be possible. However, likely escarpment locations can be mapped using slope. Contouring of the slope can then be used to delineate the “escarpments” (once other steeper units such as cones and seamounts are excluded. Selection of the threshold value used here (6°) was derived using three steps:

1. Comparison of SBP sections with corresponding MBES profiles (Section 10.3) shows the MBES accurately measures the angles of escarpments at the scale of mapping done here;

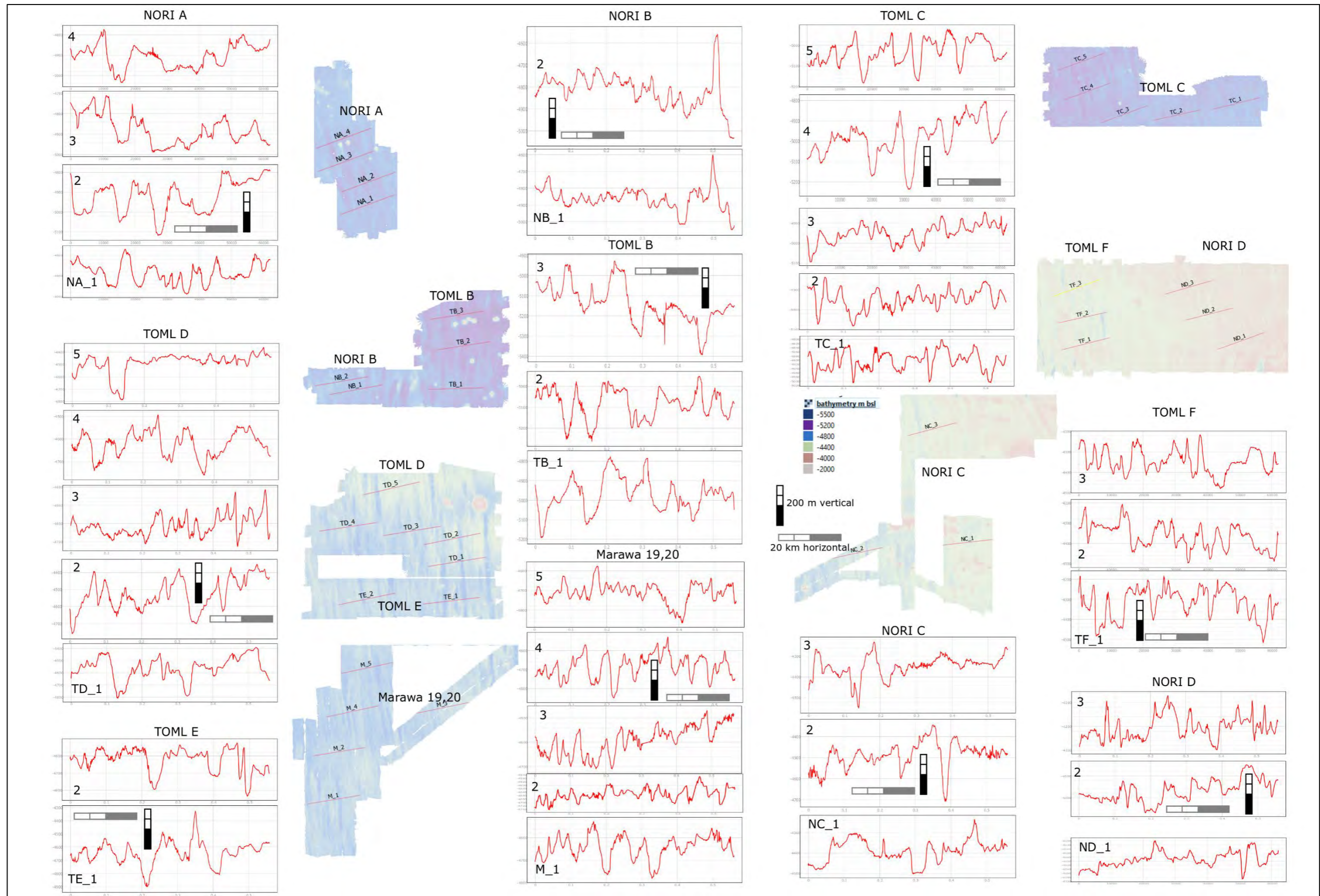


Figure 3-17: Example comparative abyssal hill frequencies between the survey areas

2. Slope angle plots (also Section 10.3) show that escarpments typically include variably sharp upper breaks, generally gentle lower breaks and peak slopes in the order of 8-15°, with the sharper breaks correlating with changes in slope of the order of 5-6°. Some discrete slopes are present at 6-8% but these are on the flanks of small discrete units (volcanic cones or collapse features);
3. A histogram of the slope data (excluding the more obvious volcanic units; Figure 3-18, Figure 3-19) shows a natural break in the data between 5 and 6°;

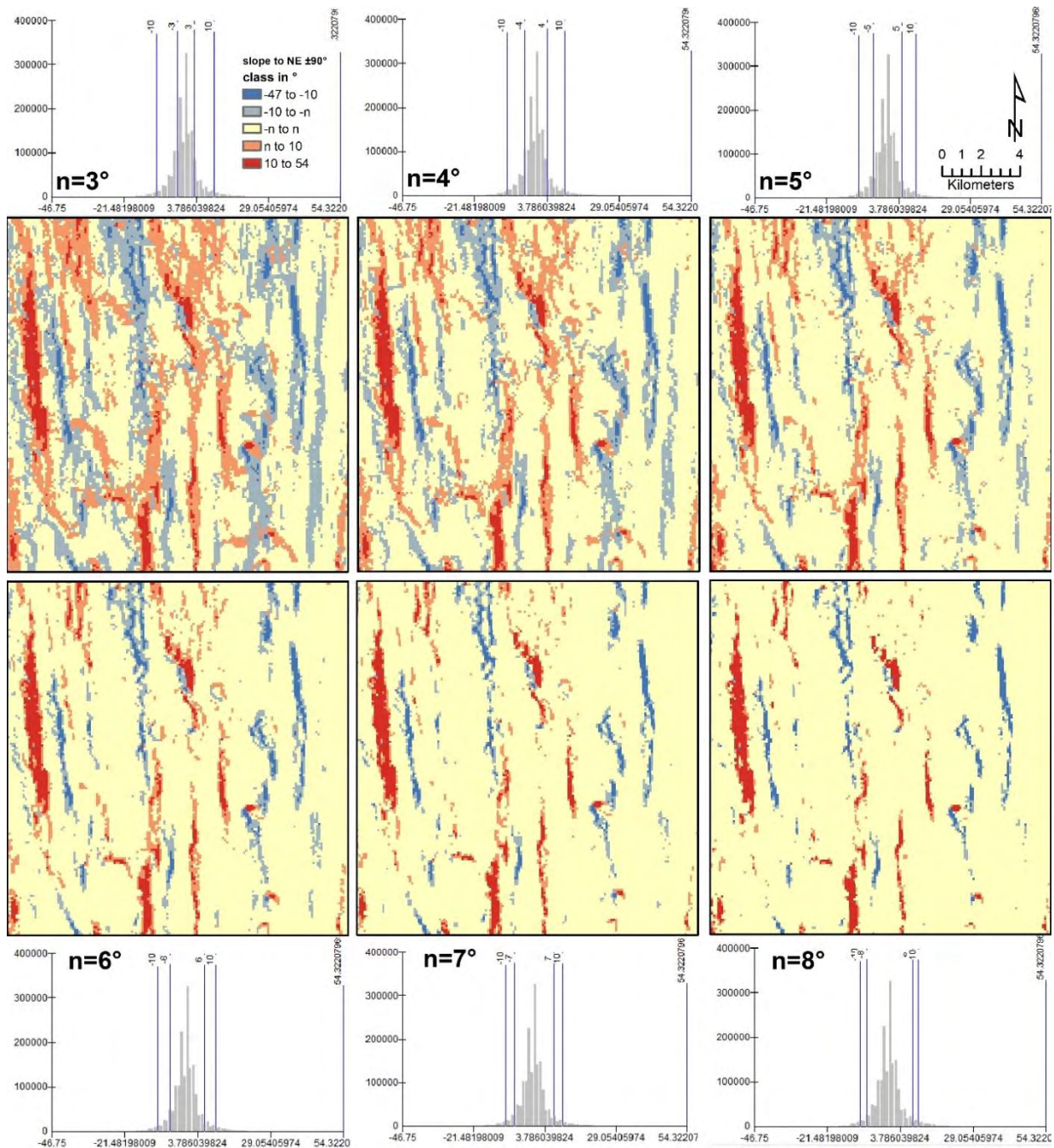


Figure 3-18: Seabed slope threshold test - 1

A commonly faulted but often sediment covered area within TOML Area B selected. Volcanic edifices excluded.

- Slope threshold plots (Figure 3-18, Figure 3-19) at 6° are less noisy than at 5° without losing key features i.e. extensions of escarpments with slopes >10°

Thus, while six degrees seems a very shallow angle for a normal fault plane, from point 2 above it is likely that most 6° slopes will include steeper faults along their mapped length. This is also at similar scale to the published abyssal hill schematics in Figure 3-13.

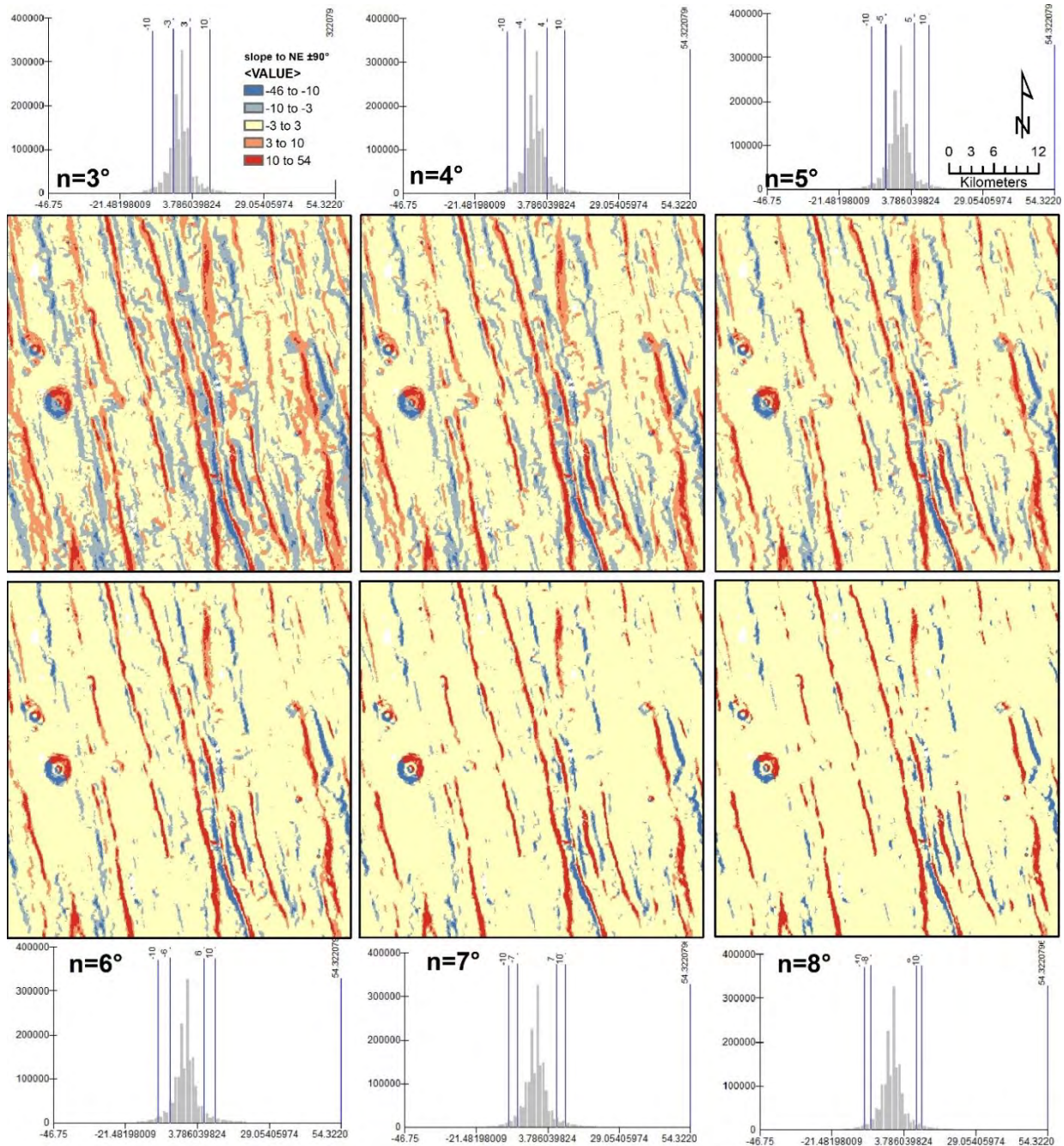


Figure 3-19: Seabed slope threshold test - 2

A commonly faulted but often sediment covered area within TOML Area F selected. Volcanic edifices excluded.

Slopes were then derived for the 1:250,000 geological map (Section 10.2) using multibeam and then backscatter grids in GIS, as described in Section 9.11.1. Each of the ten survey sub-areas (NORI A, B, C, D; TOML B, C, D+E, F; Marawa 19+20) was processed separately (due to the large datasets) with up to 17 discrete steps needed as described in section 9.11.1.

3.3.1.5 Types of Abyssal Hills at the Deposit Scale (Ab, Abl)

Each survey block was classified by depth and by terrain ruggedness index or TRI per (Riley et al., 1999). Details of the processing are included in Section 9.11.2.

The TRI was coarsened to a 5 x 5 km grid to span individual abyssal hills and this proved useful in supporting and refining the initially more visually intuitive discrimination of the flatter Abl units from the more general Ab units (Figure 3-20). Used this way the TRI effectively provides roughness weighted averages of the proportion of abyssal hill (and other) slopes in for each block. In the application of this processing, any volcanic edifices (e.g. TRI >4.3 in Figure 3-20) need to be ignored.

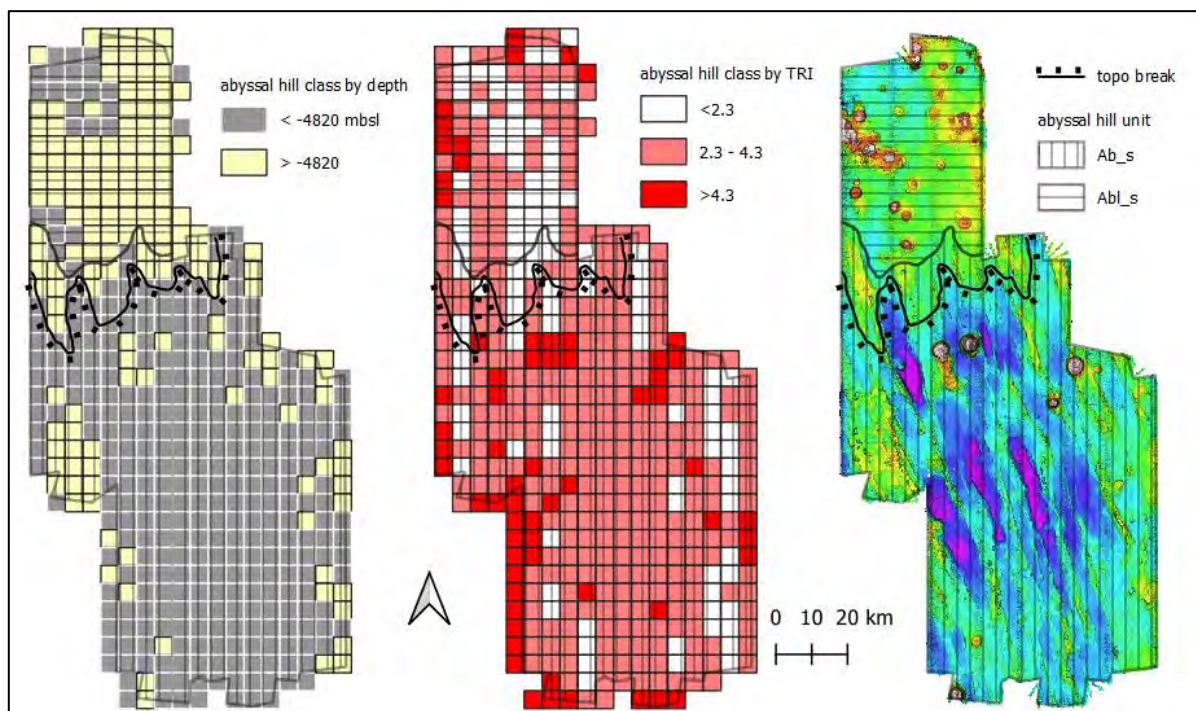


Figure 3-20: NORI A: depth and TRI classes and bathymetry

Blocks are 5 km a side; section 9.11.2 contains processing details, bathymetric depth range is -4,500 to -5,000 mbsl

The depth classes were adjusted manually until two or more depth classes were evident (Section 9.11.2). These supported the tb (topographic break-line) unit.

The Ab_c and Abl_c units were mapped only in TOML F and NORI D, where there is a distinct and characteristic softening of the backscatter response. Refer to section 3.4.11.

Note that prior classification of abyssal hills by the author in Lipton et al., (2016) did not prove adaptable to the mapping done here. Their profile-based classes were too small in scale, varying on almost a hill-by-hill basis, and their geomorphological approach was more subjective and to a large extent addressed by the above-described process for defining topographic break-lines.

3.3.1.6 Classification of slopes

Slopes (S1_NE_h, S1_NE_s, S1_SW_h, S1_SW_s, S2_NE_h, S2_NE_s, S2_SW_h, S2_SW_s) in the 1:250,000 map (Section 10.2) were classified as follows.

- 1) **Orientation (S1 or S2).** Once slopes obviously related to volcanic edifices (section 3.3.4) were removed from the working map, most slopes were parallel to the regional abyssal hill strikes (Figure 2-8 in Chapter 2). Along with some irregular directions – these are classed as S1. In some areas a distinct secondary orientation was evident, and these are classed as S2. Classing was done manually. There is no implication in the classing slopes as S2 as to their mode of genesis. For example, the secondary set in TOML F is thought to be related to drag stress across the Clipperton Fracture Zone, and the secondary set in NORI C is thought to be related to rifting associated with the tectono-volcanic opening of the tip of Victor Low (section 2.4.3.1).
 - a) **Facing (NE or SW).** Slope maps were tagged by aspect with slopes facing between 315° and 135° tagged as NE and slopes facing between 135° and 315° tagged as SW. Classing was done as part of the derivation process in section 9.11.1 This simple tagging of aspect was very useful in quickly discriminating positive relief features (abyssal hills, volcanic edifices) from negative relief features (abyssal valleys, potholes), and also helped discriminate MBES artifact response at edges and along the nadir, from real features located in those zones.
 - i) **Hardness (s or h).** Slope polygons were informed with the average of backscatter response within their boundaries as part of the derivation process in section 9.11.1. Consideration of SBP and towed photo datasets showed that escarpments can comprise some combination of basement coherent volcanic rocks, carbonate outcrop, and soft clay-ooze. Statistical analysis (section 9.11.2) indicated a lower discriminant threshold be used than for volcanic edifices, and this is thought to be due to escarpments exposing a combination of units and also the change in angle of reflectance (albedo) from a slope versus other types of seafloor. Thus, more absorbent slopes (soft or s) are thought to be composed mostly of silicious clay-ooze and carbonate and more reflective slopes (hard or h) are thought to be composed of basement volcanic rocks and some measure of carbonate and silicious clay-ooze. Smaller scale mapping may benefit from more critical discrimination, probably in association with a broader range of defined slopes (e.g. $\geq 6^\circ$ vs $\geq 10^\circ$ vs $\geq 15^\circ$).

3.3.2 Marquesas Formation

Definition of the Marquesas Oceanic Formation was by the shipboard scientific party of the Deep Sea Drilling Program Leg 8 (Tracey et al., 1971a), who described it as “*a homogeneous middle unit of predominantly white highly calcareous nannofossil ooze, of Oligocene and Miocene age.*”. Tracey et al., (1971) also started the practice in labelling the units in sectional interpretations from top down as A, B and so on (per Table 3-3).

3.3.2.1 Introduction to equatorial deep-sea carbonates

The study of the distribution and history of equatorial carbonates has been considerable (Pälike et al., 2014), as it is a major deep sea carbon sink. This includes the mounting of at least four major deep sea drilling programs (Leg 16; (van Andel and Heath, 1973); leg 138 (Mayer et al., 1991); leg 199 (The Shipboard Scientific Party, 2002); and leg 320 (Pälike et al., 2009a); section 9.7; Figure 3-2). Despite these programs and

the circa 30 sites investigated, the distribution of carbonates is still fairly imprecisely defined simply due to the scale of the region (~ 9,000,000 km²).

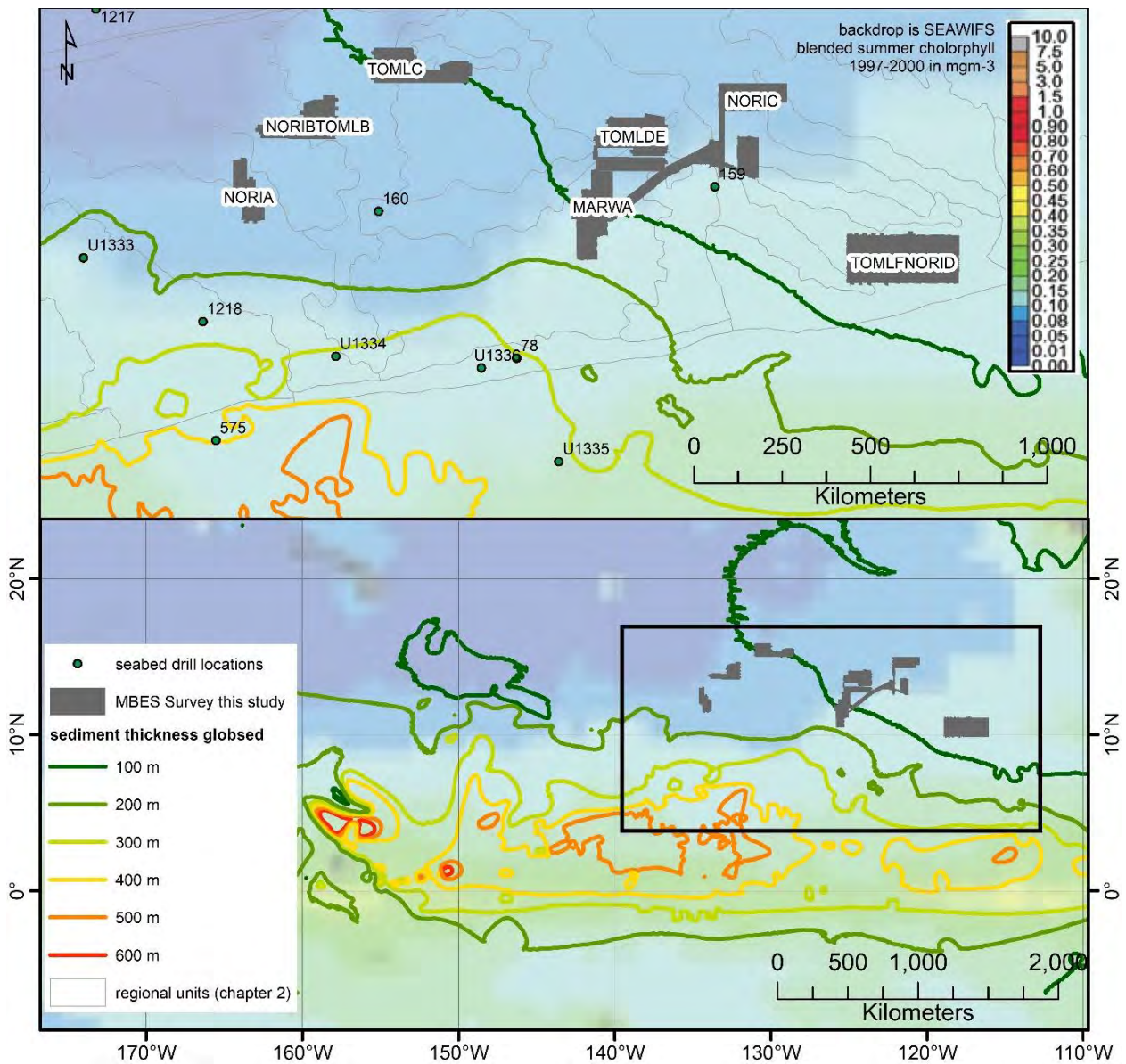


Figure 3-21: Equatorial mega-mound and survey areas

The carbonates form from net export of surface primary productivity (essentially chalks from accumulated coccoliths and foraminifera tests). Higher rates of accumulation at equatorial latitudes has led to formation of a so-called ‘mega-mound’. The CCZ is located on the northern edge of the mound which is migrating NW with plate motion (Figure 3-21, Figure 3-22). Thus, older parts and more southerly parts of the CCZ plate segment naturally seem to have thicker piles of sediment (dominantly but not exclusively carbonate).

As the drilling is sparse and the SBP profiles relatively limited in terms of depth penetration (and extent), the summary of the carbonate sections in Figure 3-2 is correspondingly limited. It is also worth noting that while carbonate markers from SBP were common between sections within an area (e.g. TOML B and TOML D; Table 3-3) it was not possible to find distinctive marker horizons between the areas. Thus, it is interpreted that any detailed differences in carbonate accumulation relates more to local scale changes.

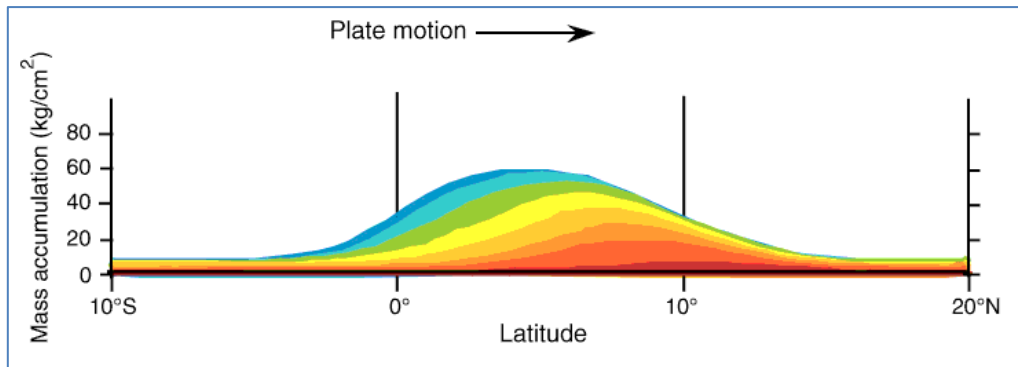


Figure 3-22: Schematic of migration of the equatorial mound

Reproduced from: Pälke et al., (2009)

3.3.2.2 Shoaling carbonates

Carbonate outcrop (Ab_k) is seen in towed photo-profiles with different examples of massive and associated brecciated forms making up a considerable portion of Table 3-6. Carbonate is normally seen on escarpments, but is exposed on the tops of hills, edges of potholes, and on top of ancient volcanic knolls. Side-scan and MBES interpretation also has it shoaling as domes and on abyssal hills.

Discrimination of shoaling carbonate from nodule poor silicious clay-ooze is effectively impossible based on backscatter response alone (Figure 3-6). The bathymetric setting can sometimes be used as a clue i.e., shoaling carbonates as discrete patches on top of abyssal hills (horsts) and parallel to their strike versus sediment drifts mantling valleys and adjacent slopes, usually in a less discrete manner. However, this is not always clear during interpretation. Discrimination of the unit seemed to be more straightforward in the survey areas at higher latitude (e.g., TOML C) and harder at lower latitudes (e.g., Marawa 19,20).

Within the Marawa 19,20 survey blocks, sediment drifts (unit Ab_d; section 1.1.1.1.2) are very common and shoaling carbonates were not able to be effectively discriminated. There are very some high absorbance patches on some hills, near potholes, that might be shoaling carbonate. Thus, it is likely that outcrop of shoaling carbonate is under-represented in the map in section 10.2, and portions underestimated accordingly in Figure 3-33.

3.3.2.3 Local area carbonate features

Per the mapping in section 10.2, carbonate exposures at the seabed are relatively rare, and seen in escarpments and as residual surface rubble (Table 3-3, Table 3-4, Table 3-5). But there are three quite common features related to the carbonate formation namely:

- Potholes (discrete small circular to linear depressions mostly found on hills and seen in the MBES and SSS/SBP datasets);
- Carbonate domes (blocky to hexagonal areas of carbonate uplifted in the centre seen in the SSS/SBP); and
- Carbonate Strata Breccias ((CSB); seen in SBP transects in some valleys).

3.3.2.3.1 Potholes

Within the mapped areas, potholes are typically circular or semi-circular ranging in diameter from double the MBES bathy resolution (~100 m) up to 1.4 km (Figure 3-23) and up to 100 m deep (more typically 40-60 m deep). They can be found in isolation but are typically arranged along the strike of the wider abyssal hills. They are often offset from the centre of the hills indicating that there might be particular strata that favours their formation. Within NORI A especially they also often develop as linear features up to 11 km long and several hundred m wide and 10-30 m deep that grade into escarpments (Figure 3-23). In one part of TOML B there is an association between potholes and underlying volcanic dykes (section 3.3.2.3.2).

The features have long been recognised (Mayer, 1981; Moore *et al.*, 2007; Fouquet *et al.*, 2014) but the assigned names of these features keeps changing. Pothole is preferred by this author as it is less restrictive in terms of shape than the “troughs” of Mayer, (1981) and not dependent on mode of origin like the “hydrothermal pits” of Moore *et al.*, (2007) and “carbonates dissolution depression” of Fouquet *et al.*, (2014).

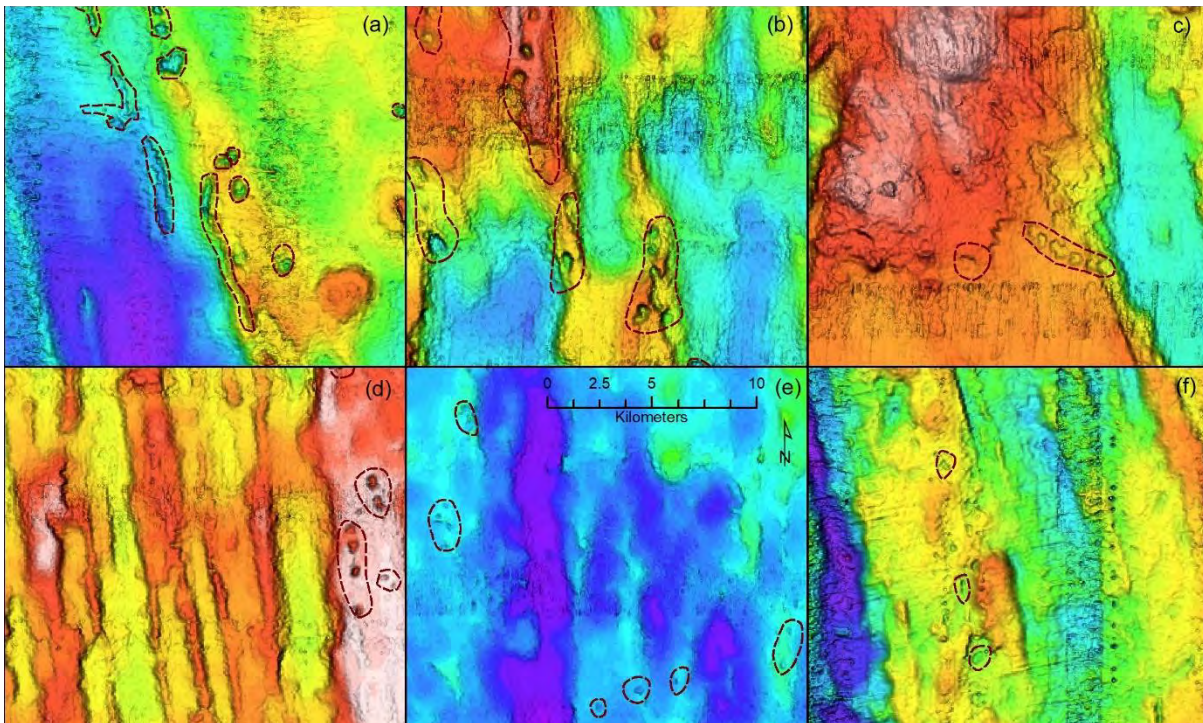


Figure 3-23: Example potholes

(a): circular and “trough” shaped features in NORI A, (b) potholes grading to escarpments in NORI B, (c) line of potholes associated with a dyke off the volcanic edifice to the NW in TOML B, (d) association of potholes only with a wider hill in TOML C, (e) smaller potholes in TOML D, (f) potholes amongst artifacts in the bathymetry in TOML F.

Mayer, (1981) and Moore *et al.*, (2007) studied potholes in the Galapagos-Clipperton segment (south of Central Rise) during marine expeditions in 1976 and 2006 respectively. They immediately noted that the holes are located on abyssal hills rather than in the valleys and used this relationship to interpret the mechanism behind their genesis. Note that at these latitudes the seabed is thought to be above the lysocline with net carbonate sedimentation effective at the seabed. (Mayer, 1981) interpret that differential accumulation and compaction may explain their origin with thicker sediment in slopes and valleys generating a tensile-stress field over the hill-top thus causing slumping and faulting. Subsequent turbulent currents could then result in local erosion by dissolution. Moore *et al.*, (2007) expanded on this mechanism, adding

hydrothermal convection based on calculations involving the crustal geothermal gradient. Both authors suggest that carbonate dissolution may also very likely play a role.

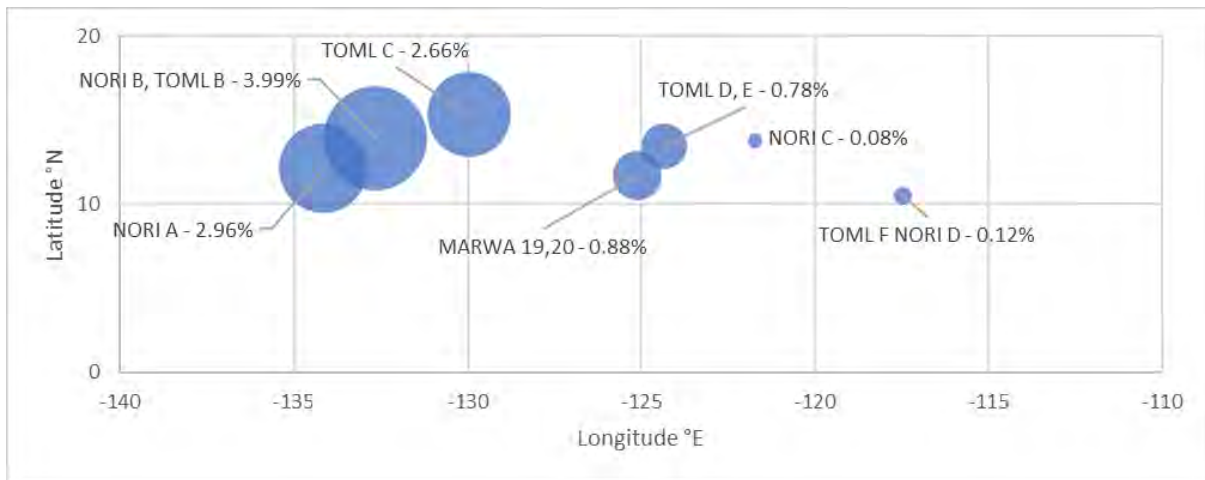


Figure 3-24: Proportion of mapped potholes (zone area) on mapped abyssal hills (Ab unit)

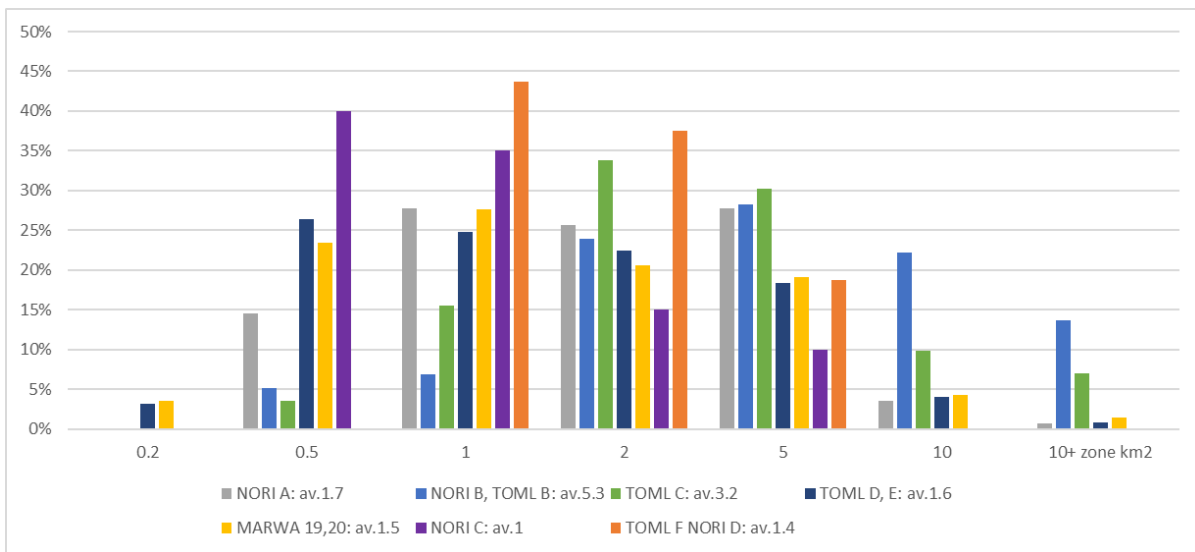


Figure 3-25: Size distribution of pothole zones mapped between different survey areas

A contribution made by this study relates to the changes in the distribution of potholes between the survey areas as illustrated below in Figure 3-24. The survey areas likely to have been below the lysocline for longer (more north-westerly) clearly have many more potholes. This is clear evidence to support carbonate dissolution being involved in their formation. Potholes located further east in TOML D and F also seem to be in general of smaller size (e.g. Figure 3-23). Note that the method of mapping at 1:250,000 scale involves zones of potholes (Figure 3-25) rather than individual potholes, so an accurate comparison of pothole sizes between areas is not possible. Nonetheless the pothole zones in NORI C and TOML F/NORI D (more easterly) are somewhat smaller than the pothole zones in the other more westerly areas.

3.3.2.3.2 Pothole example area

The SBP/SSS and photo-profiles carried out during the CCZ15 expedition aimed to help define a polymetallic nodule mineral resource and so were not planned to encounter and study seafloor features such as potholes. However, within TOML Area B1, adjacent small potholes were encountered along an SBP line (M04) and a photo profile line (F02), as shown in Figure 3-26. This area (as discussed further below in section 3.3.4.3) includes a swarm of recent basalt dykes and the potholes here are associated with some of the dykes, which is not thought to be a typical situation. The presence of dykes is certainly expected to add to the hydrothermal convection driver interpreted by Moore *et al.*, (2007); but it is worth noting that dykes found in other areas (e.g. TOML D2) are not associated with any potholes.

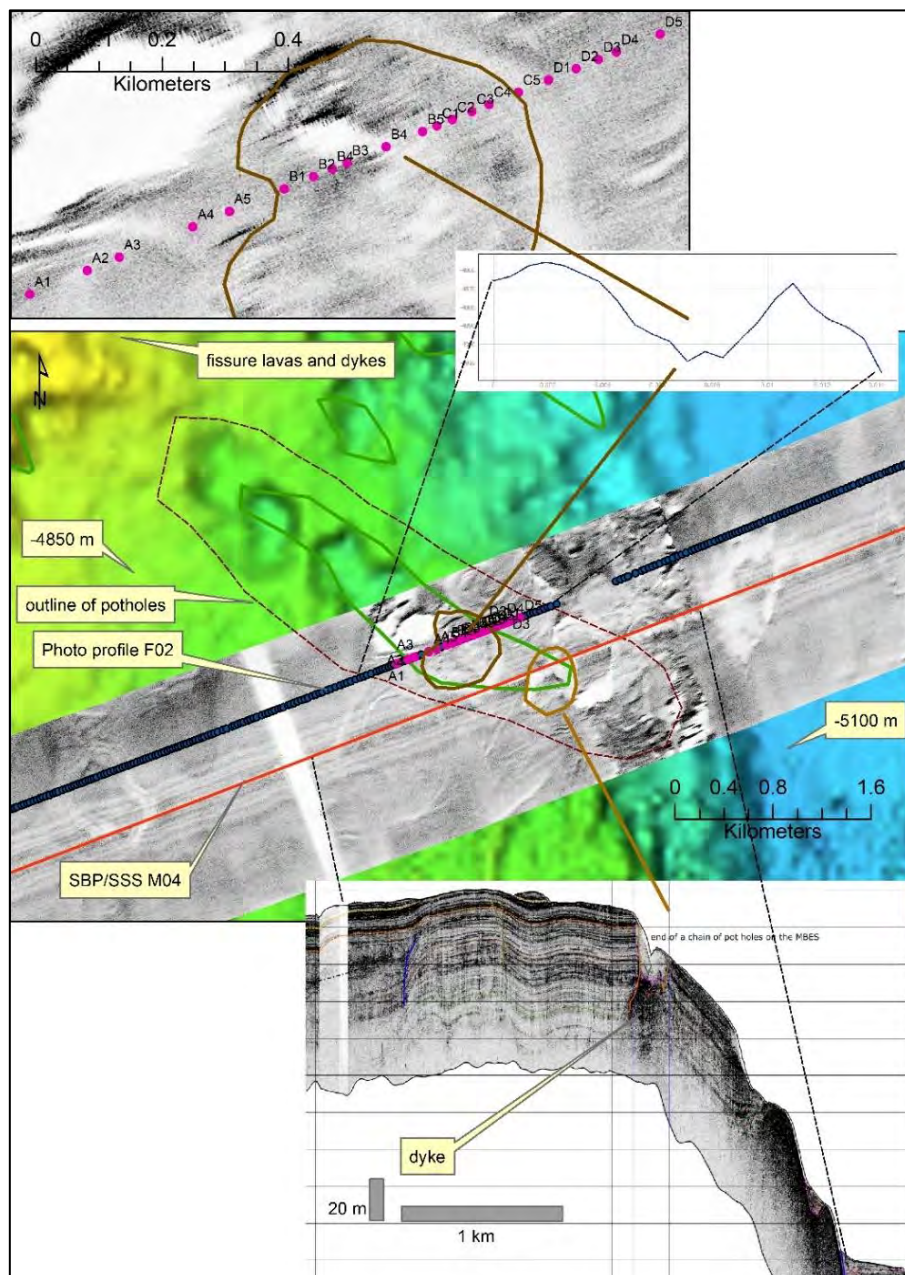


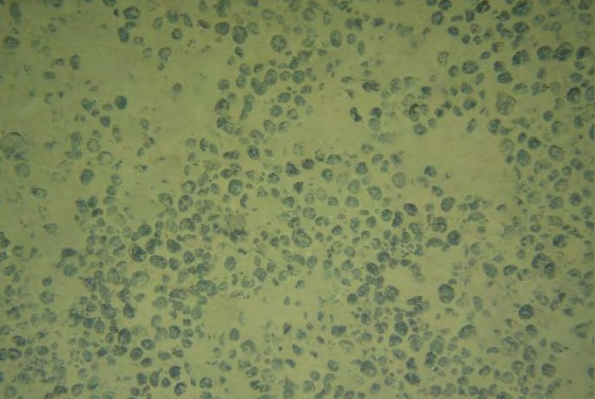

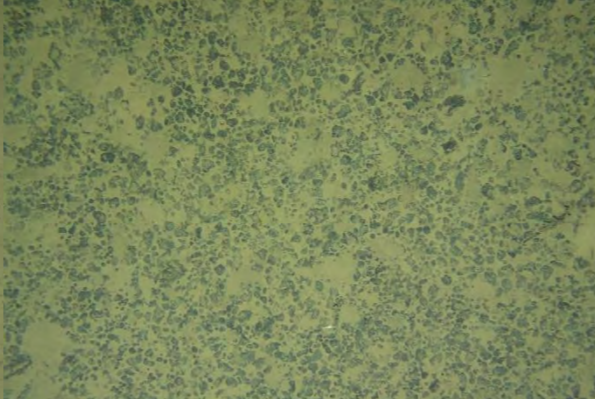
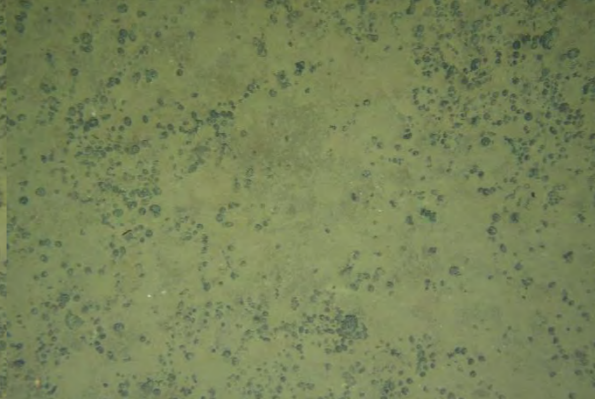







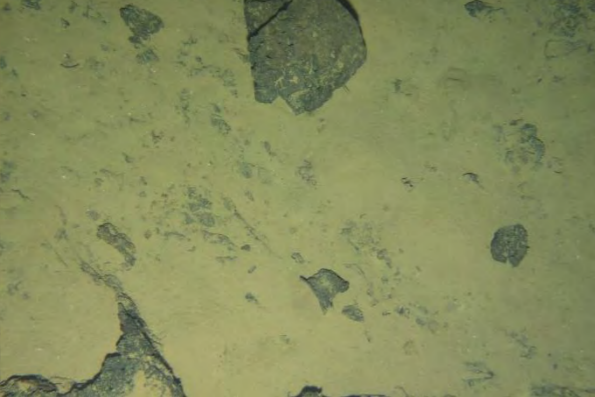


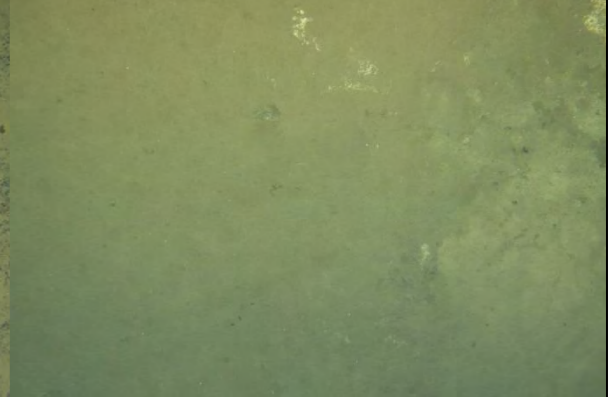

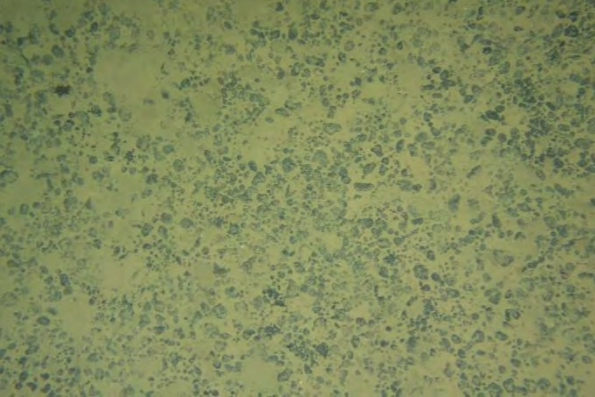
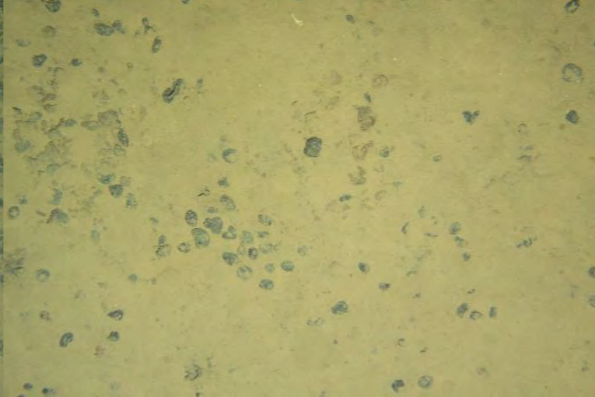
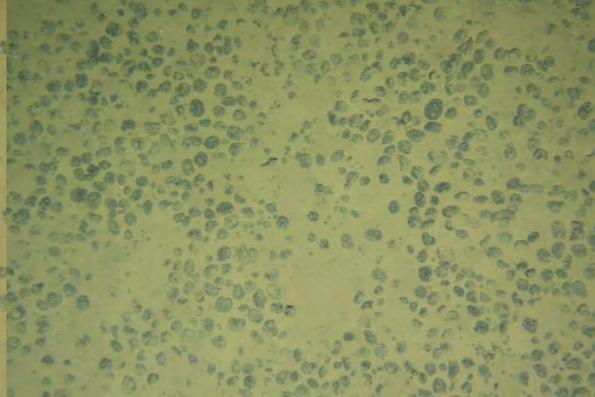
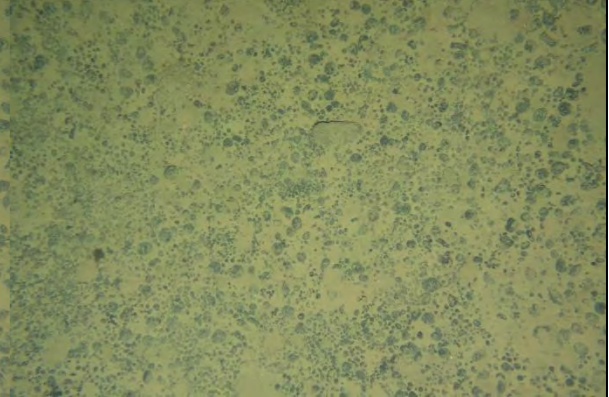
Figure 3-26: Example pothole area TOML B1

Refer to Table 3-8 for the referred to photos; section 10.3 for the full SBP sectional interpretation and Table 3-3, Table 3-4, Table 3-5 for relevant data legends

The SBP/SSS from M04 (refer also Table 3-3, Table 3-4 and section 10.3) shows that on the eastern edge of the hill, siliceous sediment (A) is very thin and that the carbonate (B) package is eroded in places. The escarpment exposes both basement volcanic rocks and carbonates with likely complete removal of the top two markers (Bt_b in Table 3-3) and poor discrimination of the third. On the SBP, the pothole happens to intersect the escarpment edge (with reference also to the SSS and MBES). The SBP return for the pothole is not helped by the location, but indicates 20-30 m of blanked material (likely damaged carbonate given a couple of faint marker beds) onto a hard floor which looks to be a dyke (vertically cross cutting the carbonate strata). While the MBES resolves discrete but closely packed potholes along the likely dyke strike, the SSS indicates they are more likely to be often nested against or within each other.

The photo profile in Table 3-8 shows from WSW to ENE: nodules grading to carbonate fragments; emergence of carbonate pavement with common areas of sediment (silicious clay-ooze) cover; then a steep dropping slope with carbonate rubble; before more carbonate pavement including both sides of a rising slope; and finally a gradational change back to more nodule coverage. The common occurrence of pavement within the pothole was a surprise, and this may indicate that the pothole might only develop to the level of a more resistant stratum but note this is not entirely at odds with what is seen in the SBP.

Table 3-8: Selected seabed photos WSW to ENE across pothole in NE TOML B1

				
A1; CCZ15-F02; 2015_08_17_013318.jpg Typical medium to large nodules in soft sediment	A2; CCZ15-F02; 2015_08_17_013543.jpg Nodules covered with sediment, common Xenophyophores.	A3; CCZ15-F02; 2015_08_17_013704.jpg Mixed small-medium nodules and carbonate fragments	A4; CCZ15-F02; 2015_08_17_014011.jpg Small-medium nodules on ?stripped carbonate pavement	A5; CCZ15-F02; 2015_08_17_014144.jpg Sediment with slump ripples to ENE (up in image)
				
B1; CCZ15-F02; 2015_08_17_014404.jpg Carbonate rubble, minor nodules falling to the E	B2; CCZ15-F02; 2015_08_17_014519.jpg Exposed carbonate pavement and minor sediment/nodules	B3; CCZ15-F02; 2015_08_17_014644.jpg Thin sediment on carbonate pavement	B4; CCZ15-F02; 2015_08_17_014823.jpg Thin sediment on carbonate pavement	B5; CCZ15-F02; 2015_08_17_014957.jpg Carbonate rubble on pavement
				
C1; CCZ15-F02; 2015_08_17_015034.jpg Carbonate pavement with few fragments	C2; CCZ15-F02; 2015_08_17_015113.jpg Carbonate rubble on pavement	C3; CCZ15-F02; 2015_08_17_015203.jpg Small smooth nodules	C4; CCZ15-F02; 2015_08_17_015247.jpg Small nodules and carbonate fragments on pavement	C5; CCZ15-F02; 2015_08_17_015402.jpg Carb. pavement minor sediment rising to NE (top of image)
				
D1; CCZ15-F02; 2015_08_17_015520.jpg Carbonate pavement	D2; CCZ15-F02; 2015_08_17_015630.jpg Medium to large nodules	D3; CCZ15-F02; 2015_08_17_015727.jpg Few large nodules and carb. frags on carb (transported?)	D4; CCZ15-F02; 2015_08_17_015814.jpg Large nodules in sediment	D5; CCZ15-F02; 2015_08_17_020006.jpg Mixed nodules and a few carbonate fragments

All Photos: 2.4 x 1.6 m. Full resolution images in Section 9.13

3.3.2.3.3 Domes

From the SSS and SBP (section 10.3), the carbonate dome structures appear to form from large scale (± 1 km) jointing/warping and faulting within the abyssal hills. They are not apparent in any of the valleys transected by the SBP. A primary orientation is parallel to the abyssal hills (normal faults) and other orientations are variable but antithetic. In some cases the domes are covered with thin silicious clay-ooze, and resultant distinctive semi-circular patterns in the SSS form a slightly larger diameter than indicated by the underlying joints in the SBP. Under thick silicious clay-ooze the domes are not apparent at surface. It is possible that the same structural set is related to the potholes (*cf* anticline-syncline). This could be why potholes tend to be semi-circular in form and in at least one location the two features are found together (example 1 in Figure 3-27).

Note that the SBP/SSS lines were all carried out at a high angle (60-90°) to the abyssal hills.

3.3.2.3.4 Carbonate Strata Breccias

Based on the SBP dataset at hand, Carbonate Strata Breccia (CSB) are much more common than potholes or domes, at least in some areas. The author has not been able to find any documented study on them, probably because they are not known to express at surface. It is highly likely that Russian CCZ workers (Yuzhmorgeologiya) have at very least noted the formations, as it was their in-house acoustic system that is used here to map them, and as they have many years of work on their ISA exploration contract nearby to TOML B.

CSBs are also not found everywhere. They are common and well developed in the abyssal valleys covered by SBP profiles through TOML B and TOML C, but there are none in the profile though the elevated carbonate platform underlying TOML D2 and only a minor stratabound occurrence in one of the several abyssal valleys covered in TOML D1. This indicates, that like potholes, they may be more common in older stratigraphy.

Examples of CSBs are shown in Figure 3-28 (refer also to section 10.3 and Table 3-3). There are more examples within the cross-sectional interpretations in section 10.3.

As CSBs are only found in valleys, it is likely that their formation is influenced from stress fields unique to the valleys (i.e., counter to that in the abyssal hills helping form the potholes). An indication of this might lie in that there are two main forms of CSBs:

1. a vertically well developed and cross strata form termed “breakthrough”; and
2. a stratabound form (Table 3-3).

These terms are adapted from terrestrial caves and cave fill breccias, with which they are compared, in table below.

Thus, CSBs are thought to form due to ongoing extension undermining preferentially susceptible chalk strata leading to formation of breccia. The breccia forms under water saturated conditions, with effectively no opportunity for fragments or dissolved CaCO_3 to move from their initial location. Upward doming of the upper contact likely relates to inflation due to the in-situ breccia related expansion (Figure 3-31) exceeding the space added from the extension, and any solution loss.

Table 3-9: Similarities and differences cave fill breccias and CSBs

Cave fill breccia (Ohle, 1985; Loucks, 1999)	Carbonate strata breccia
Stratabound and cross strata forms	Stratabound and cross strata forms
<p>Form under phreatic to vadose conditions</p> <p>Rely on moving water to remove dissolved carbonate; Cave collapse is into cavities once the structural strength of the rock is exceeded by the growing size of the cavity or cave-tunnel often after phreatic waters drain away.</p>	<p>Form under water saturated conditions but below the lysocline</p> <p>There are no obvious cavities seen in the SBP, and no obvious mechanical mechanism to remove material. Even water flow with dissolved carbonate is expected to be very slow compared to terrestrial situations, so the breccia is likely to be saturated (both with water and chemically with CaCO₃).</p>
<p>Domed top in some case e.g. Figure 3-29; (Ohle, 1985)</p> <p>Caused by dolomitization.</p>	<p>Domed top in some cases</p> <p>Reason unclear; maybe some type of dispersive inflation as noted in some avalanche breccias by (Pollet and Schneider, 2004).</p>
Fragments of original strata common.	Almost certainly composed of original strata
<p>Often limited to a particular hanging wall stratum; i.e. incipient phases likely to be stratabound.</p> <p>Stratabound caves, termed branching root-type are a well-known form (Ohle, 1985; Loucks, 1999) and these may branch off more vertical and larger forms termed breakthrough type (Figure 3-30)</p> <p>Caves usually start at higher levels and move downwards, often with tectonic uplift or a dropping water-table</p>	<p>Often limited to a particular hanging wall stratum; i.e. incipient phases likely to be stratabound, and these may branch off more vertical and larger forms (Figure 3-28)</p> <p>Common inverted tear drop form fairly common (note this can be emphasised by refraction patterns from the SBP). This may form due to downward growth perhaps related to expansion of the strata from partial dissolution or ongoing extension and shrinkage in the abyssal hills basement.</p>
<p>Stratabound cave fill breccias vary relative to breakthrough type.</p> <p>Can form at more than one level with certain strata more prone.</p>	<p>Stratabound type CSBs typically develop off the top of breakthrough.</p> <p>Can form at more than one level with certain strata more prone.</p>
Wide range of elaborate forms <i>cf</i> Ramiform Maze form of (Loucks, 1999).	Very unlikely to have just formed in systems parallel to the SBP lines
<p>No evidence for inflation of strata.</p> <p>However, a breccia takes more space than consolidated rock and (Loucks, 1999) showed how even a small cavity can equate to large volumes of breccia (Figure 3-31).</p>	<p>Common uplift of upper contact indicating inflation, despite some likely measure of tectonic extension and shrinkage in the volcanic basement to the abyssal valleys.</p>

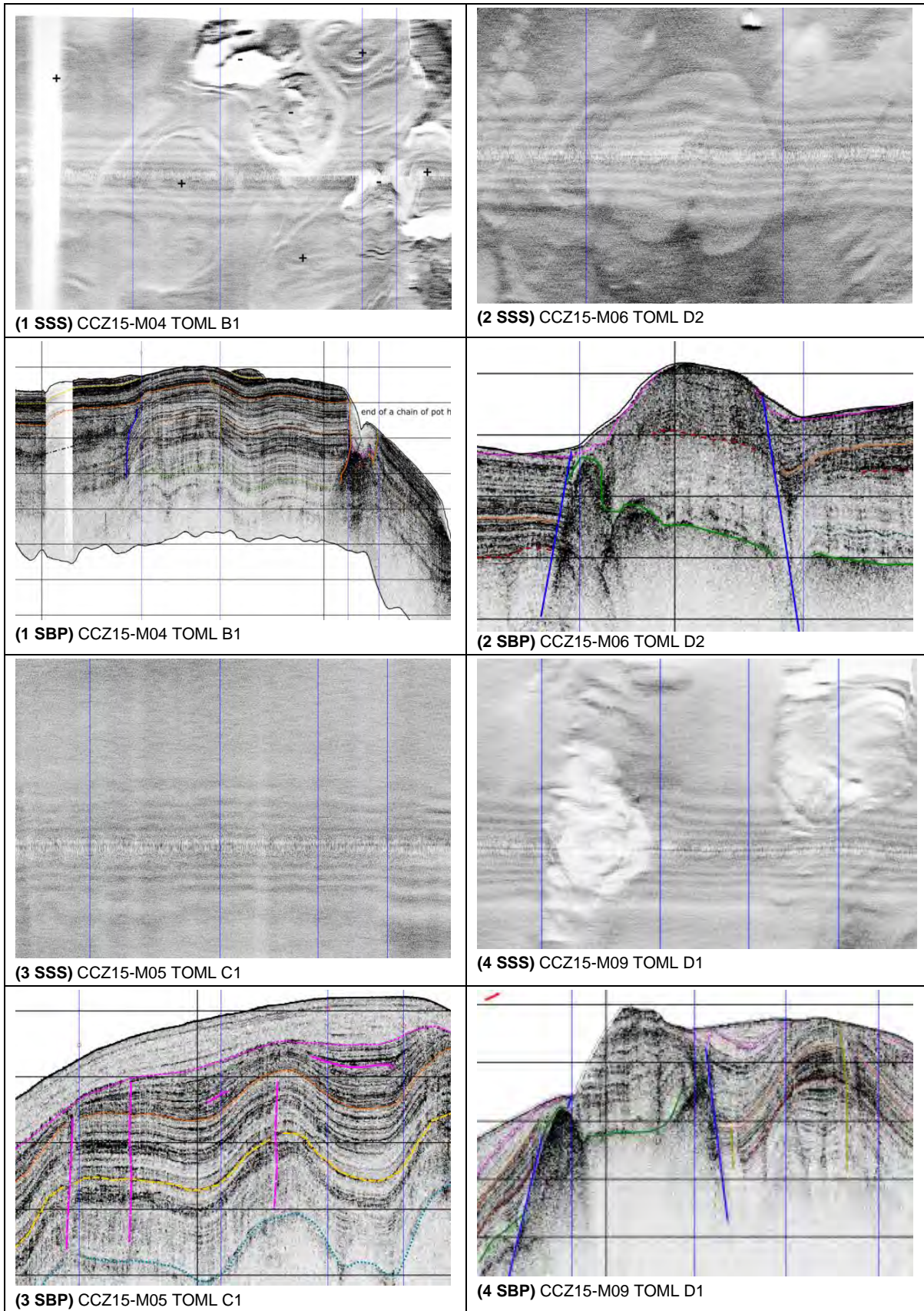


Figure 3-27: Carbonate dome examples

Refer to the cross-sectional interpretations in section 10.3 for a more complete interpretation and legend.

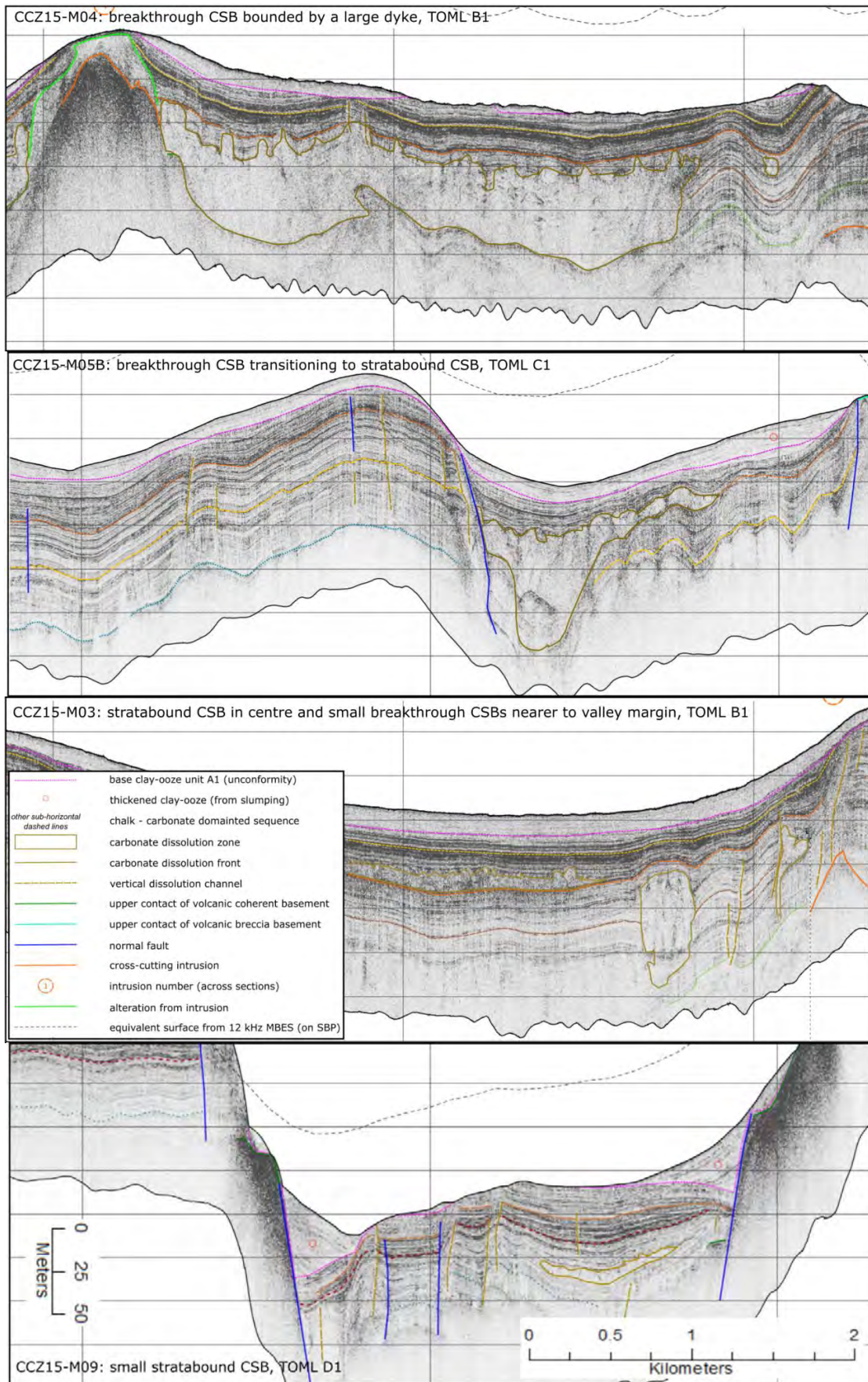


Figure 3-28: Carbonate Strata Breccia examples

Note "other sub-horizontal dashed lines" relate to marker horizons in the chalk, refer also to section 10.3.

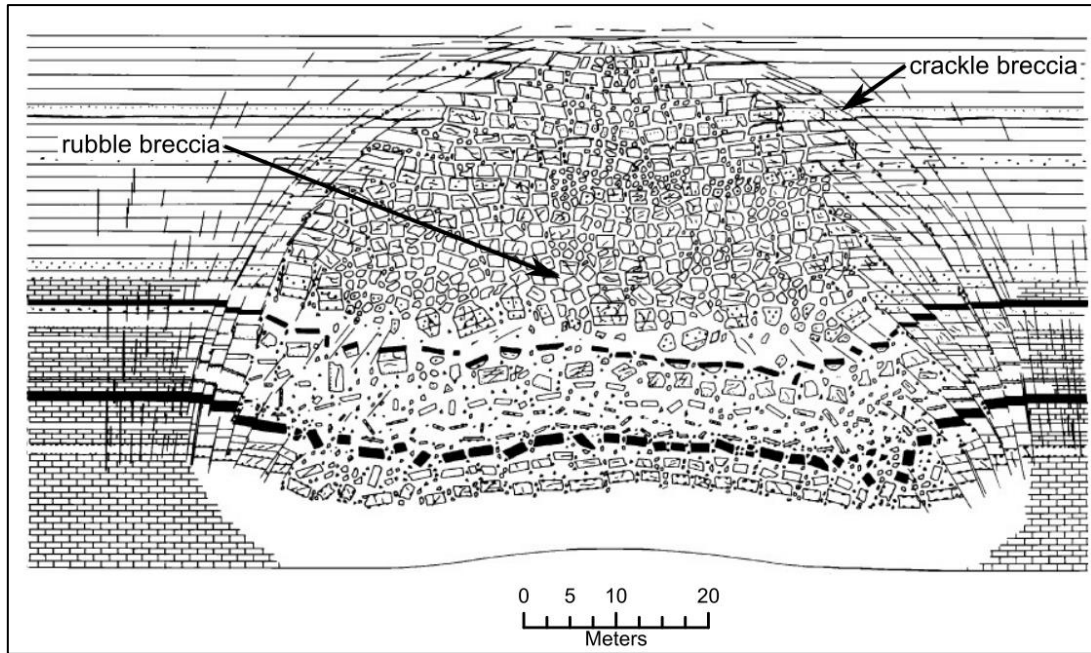


Figure 3-29: Simple domal breakthrough carbonate breccia
Modified from Ohle (1985)

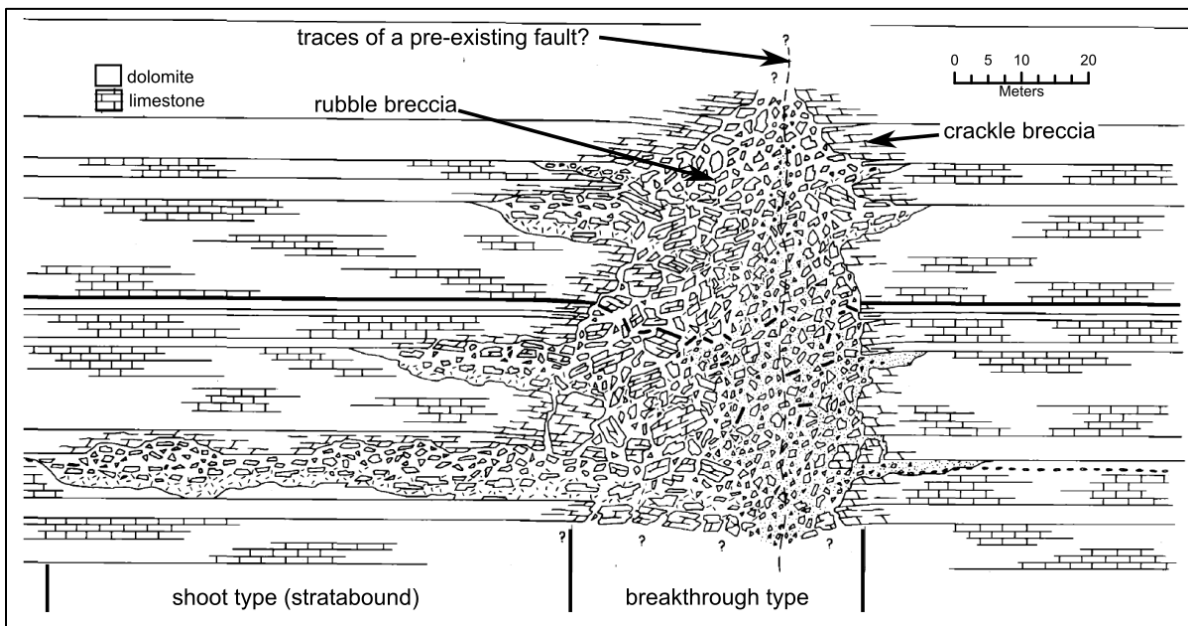


Figure 3-30: Breakthrough and branching shoot type carbonate breccias
Modified from Ohle (1985)

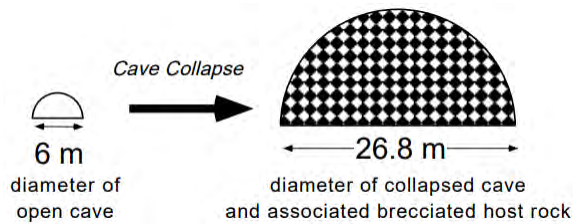


Figure 3-31: Volume of an open cave against a limestone breccia
Cave is 100% void and breccia assumed to be 5% void from Loucks (1999)

3.3.3 Clipperton Formation

The surficial siliceous clays and oozes of the Clipperton Formation is one of the most important units economically and environmentally in the CCZ. It is the host to the polymetallic nodule deposit, is the home for the majority of life in the ecosystem, and is the medium in which any mining equipment will need to interact (along with the overlying water column). In the MBES survey areas, subtypes of this unit comprise between 80 and 88% of the surface area (Figure 3-33).

The definition of the Clipperton Formation (or Clipperton Oceanic Formation) is attributed to the shipboard scientific party of the Deep Sea Drilling Program Leg 8 (Tracey et al., 1971a), who based on drilling in the western CCZ, described it as, “a heterogeneous upper unit of Miocene to Holocene age consisting of radiolarian ooze, of cyclically bedded calcareous and siliceous ooze, and of light colored highly calcareous ooze containing purple, green and blue-gray bands or beds”.

A partial review and analysis of some aspects of the formation is presented here as data coverage is patchy (Table 3-10) and as a thorough review and closure of knowledge gaps would be a thesis topic in its own right.

Table 3-10: Data coverage in the survey areas for the Clipperton Formation

	NORI A	NORI B TOML B	TOML C	TOML D+E	Marawa	NORI C	TOML F NORI D
MBES	Y	Y	Y	Y	Y	Y	Y
SBP SSS		Y	Y	Y			
Chemical Analysis							Y (NORI D)

Compilations of data on the surficial sediments in the CCZ in Figure 3-32 show that they are also transitional between the calcareous oozes of the Clipperton Galapagos segment and the pelagic clays of the Molokai – Clarion segment. The distribution of sediment compositions is distinctive, with mixed calcareous-siliceous-mud grading through siliceous muds to siliceous ooze, apart from a few ‘islands’ of mixed calcareous-siliceous-mud. CaCO₃ contents tell a similar story with almost all samples under 26% CaCO₃ and most under 4%. Biogenic silica content shows a broader range but also in general transitions to lower values from south the north. Calcareous oozes, CaCO₃>26% and biogenic SiO₂ >20% are by and large restricted to the Galapagos Clipperton segment.

Neither compilation includes samples within the NORI D survey area but MBES backscatter response and samples from that area also indicates a SE to NW transition to less calcic sediments with some chemical composition support (section 3.4.11, section 4.5.2.5).

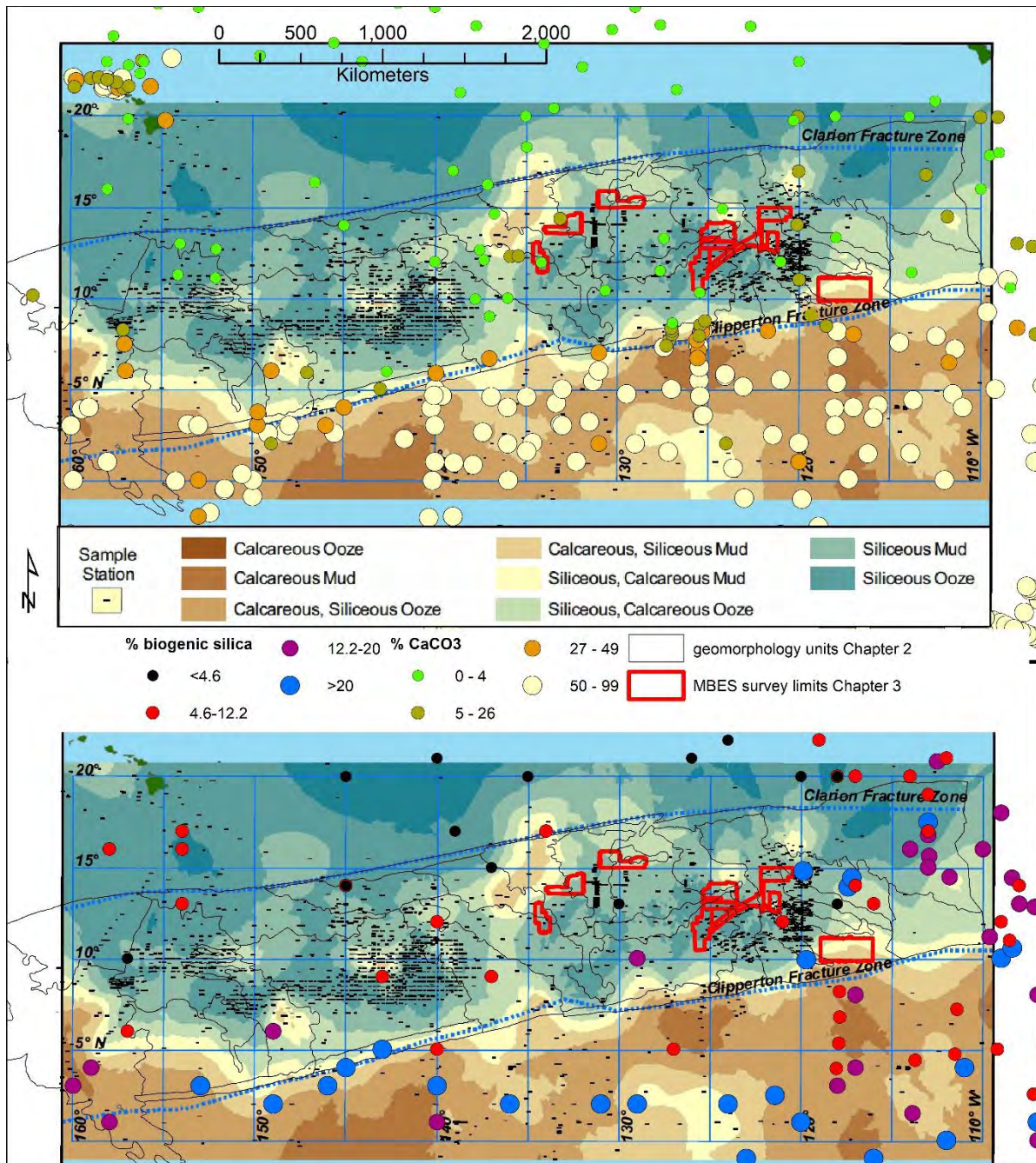


Figure 3-32: Surface sediment composition across the CCZ

Sources: (Archer, 1999; International Seabed Authority, 2010b). Archer supplies the compilation of %CaCO₃ and % biogenic SiO₂.

Note that the ISA2010 classification necessarily combined disparate datasets from several exploration contractors and public sources. It thus does not for example apply the deep sea sediment classification of Dean and Leinen (1985). Mud is defined as <0.004 mm and Calcareous/Siliceous Mud as containing ≥25% of the respective constituent in biogenic form and ≥25% Mud. Oozes have dominant biogenic material and are qualified in the order of contribution by calcareous and siliceous biogenic material.

3.3.3.1 Sub-types and their mapped proportions (horizontal)

Proportions of the MBES mapped units (defined per Table 3-1) are shown below. The proportion of mapped survey area that the clay-oozes cover overall only varies slightly between 80 and 88%. However, there are significant variations in the proportions of sub-units i.e.:

- areas with flatter plains (Abl) range from 0 to 16%;
- areas also likely to have higher volumes of nodules (hN) also varies widely from 0.2 to 17%; and
- areas likely to have few nodules including sediment drifts (Ab_d) ranges from 1.8 to 41%.

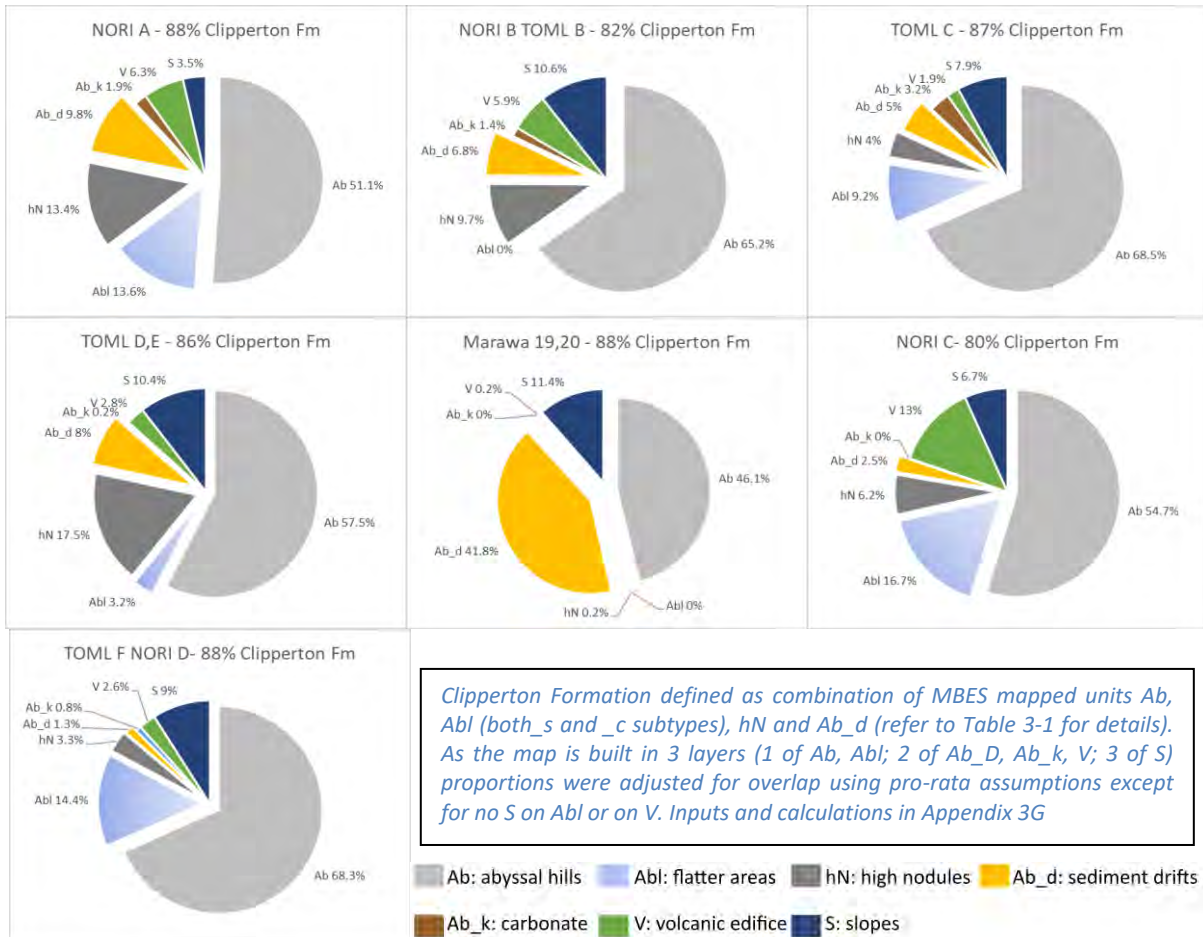


Figure 3-33: Proportion of surface unit types by area

1.1.1.1.1 Nodule bearing units

An example of unit Ab from the TOML C survey area is shown below in Figure 3-34. Consistent 5-7 m thick siliceous clay-ooze is mantling gentle abyssal hills with consistent abundances of polymetallic nodules.

Of special interest to explorers is the use of MBES, more specifically the backscatter, to help find areas with higher nodule abundances. Nodule abundance is a major economic consideration as seabed polymetallic nodules present as a very low tonnage of mineralised material per square metre, and for almost any mineral deposit, tonnage ore per square metre is a basic, and often linear, factor in estimating mining development and operating costs and thus mining economic margins.

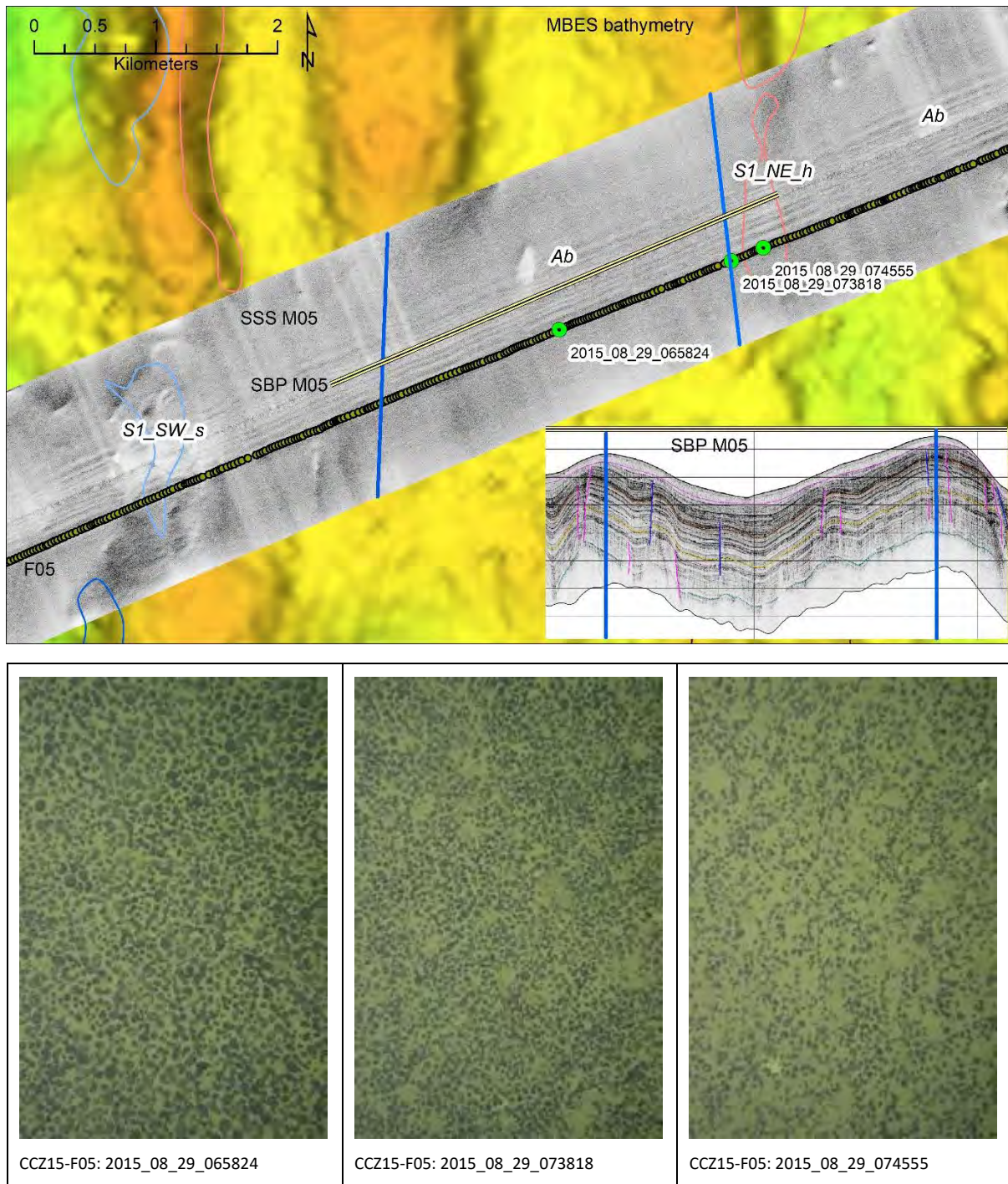


Figure 3-34: Comparison of an MBES Ab unit with SSS, SBP and towed photos - TOML C

All photos 2.4 x 1.6 m; SBP has V/H=10:1, vertical lines are 2 km apart and horizontal lines are ~25 m. Refer to section 10.3 for SBP and SSS interpretations. Full resolution images in Section 9.13

The CCZ15 expedition successfully used backscatter to prioritise areas for the exploration program needed to increase the level of confidence in parts of the TOML mineral resource from inferred to indicated. This was a key target for the TOML project at the time. A requirement of the NI 43-101 'code' (Chapter 5) is that a compliant pre-feasibility level study is only possible on a project that has sufficient indicated mineral resource to support the pay-back phase of the project economic model (via a probable mineral reserve).

The CCZ15 expedition used scarce endurance and budget to test five priority areas (B1, C1, D1, D2 and F1 as discussed further below). The areas were selected using a combination of backscatter, bathymetry and historical sampling. Backscatter cannot reliably provide a quantitative estimate of nodule abundance (e.g. (Ruhlemann et al., 2011)), but it can improve exploration's chances for success, and in some situations, it may be able to be used constrain deposit extents. This is because the response is a combination of some or all of: nodule size; nodule abundance; host sediment composition; rock/sediment composition immediately below the surface; and slope of the seabed surface.

In moving between datasets to characterise or even constrain nodule abundance, a key issue is one of scale. To contextualise:

- Nodule types and abundances can remain consistent for kilometres or can change every ten or so metres;
- The towed photographs were taken roughly every 30 metres;
- A physical seabed sample represents at best (TOML large box-corer) 0.86 x 0.86 metres (~7500 m²);
- Processed backscatter from an EM120 2°x2° MBES has a maximum resolution of about 30 metres but the signal is often 'smeared' over 90 or 120 metres, and is very badly damaged in the nadir;
- The deposit scale mapping in this Chapter was drafted to be accurate at 1:250,000 scale, and at this scale, 100 metres (2-3 times effective MBES resolution) is 2.5 millimetres.

Thus, the hN areas mapped here are not able to be used as a domain for mineral resource estimation. However, they do help differential areas with greater nodule abundance prospectivity at a large scale (hundreds of m to kilometres) as illustrated for TOML C1 and TOML D1 in Figure 3-35. Apart from photograph 2015_09_13_172109, the photographs are of nodules on thick clay, on relatively flat ground. In the TOML D1 example most of the nodules are of large to medium-large size and backscatter generally reflects abundance. In the TOML C1 example nodule size clearly plays a more important role alongside abundance. The photographs shown were selected to be representative, however note that the response can change literally from pixel to pixel in the backscatter or from photo to photo in the images.

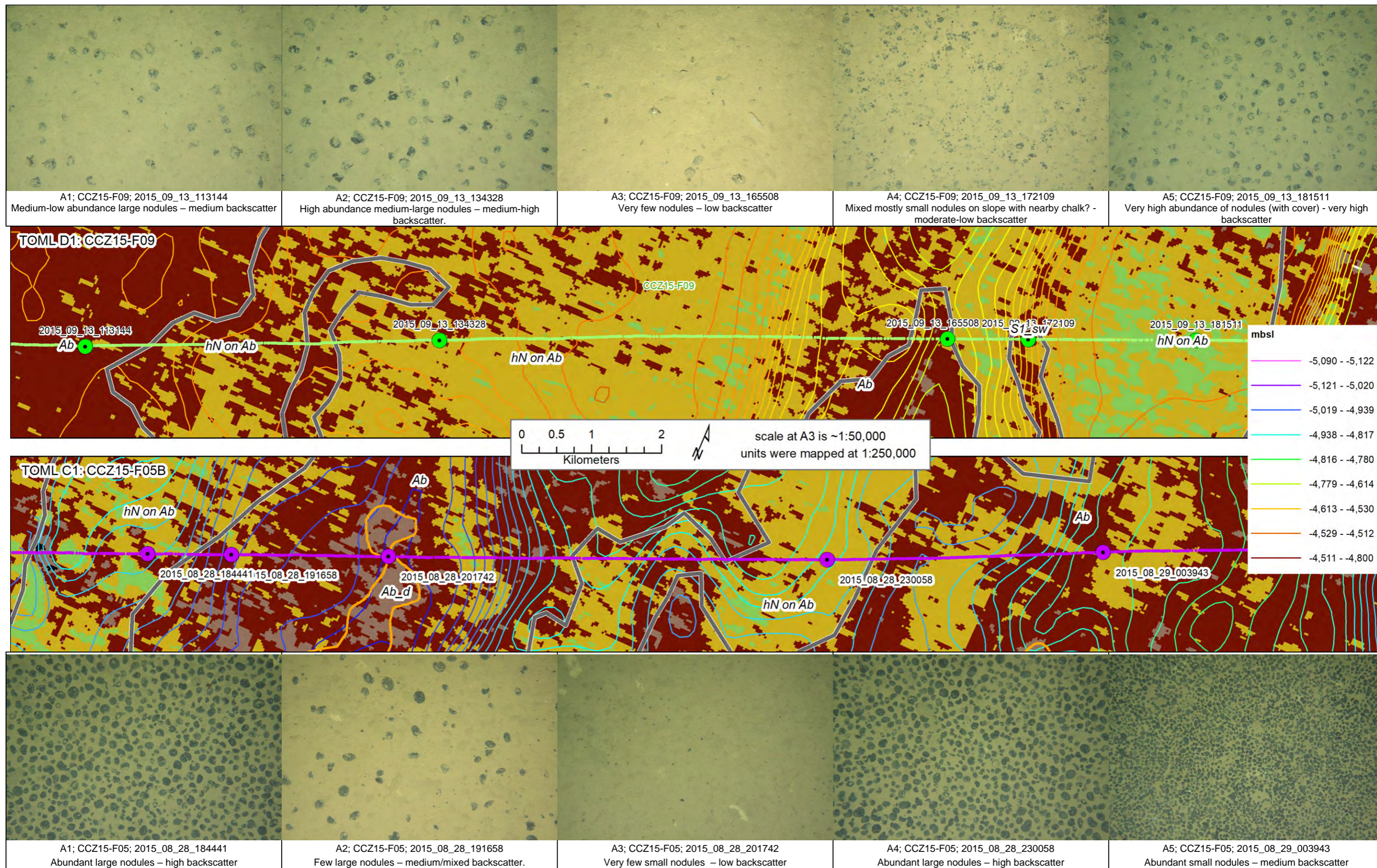


Figure 3-35: Comparison of high nodule potential abyssal hill units with backscatter and seafloor photographs

All photos 2.4 x 1.6 m; full resolution images in Section 9.13

In some areas, a further issue for explorers is cover of the nodules by small amounts of clay-ooze (termed 'powder'). Sufficiently high levels of powder in effect becomes "cover" (Figure 3.36) this restricts the usefulness of photographs to map and measure the nodule abundance (Chapter 4, Chapter 5). The TOML D area commonly has this issue as shown in Figure 3.38, Figure 3.36, Figure 3.37.

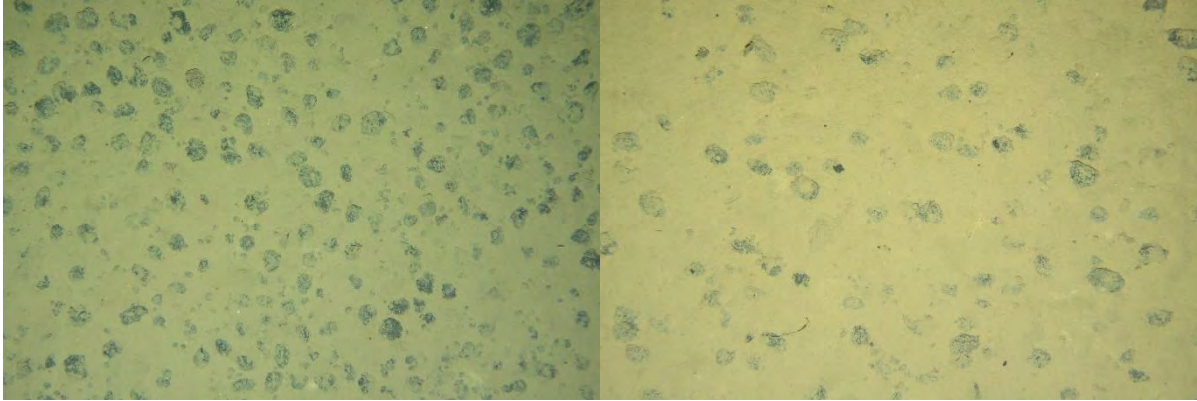


Figure 3.36: High degree of sediment "powder" and cover in Area D

Images are 2.4 x 1.6 m in size. L is CCZ15-F09B 2015_09_14_180140; R is CCZ15-F09B 2015_09_15_085013. Full resolution images in Section 9.13



Figure 3.37: Covered nodules CCZ15-B75, Area D2

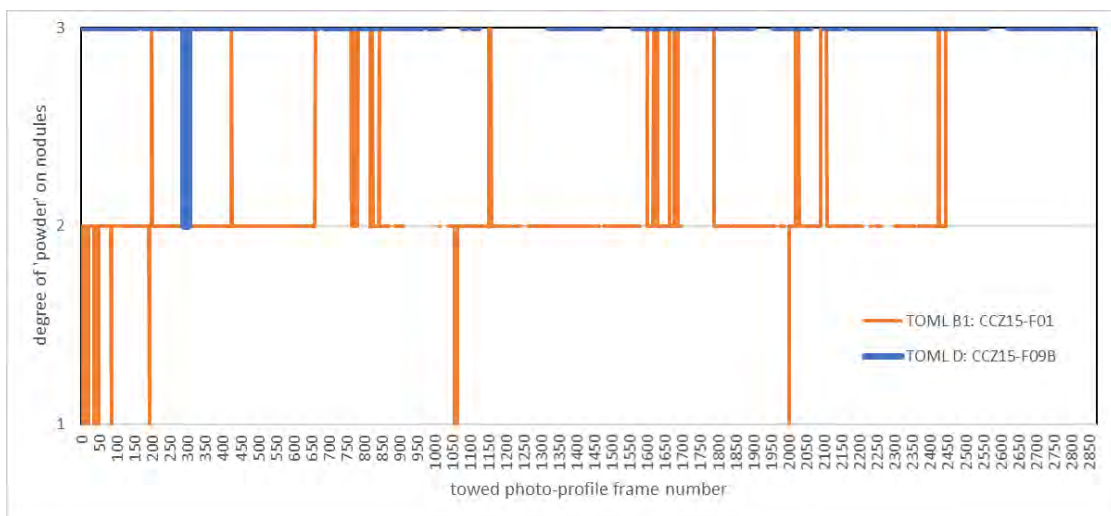


Figure 3.38: Degree of powder on visible nodules in TOML Area D vs TOML Area B1

Note that level 3 is the highest possible per the logging schema used during the CCZ15 cruise.

This thin sediment cover does not appear to affect the MBES backscatter response. The TOML D area also has generally large nodules and the highest proportion of the hN unit amongst the mapped areas (Figure 3-33).

1.1.1.1.2 Low nodule areas and sediment drifts (Ab_d)

The Ab_d unit is often ponded in depressions (Figure 3-39), which reflects the importance of lateral transport of the Ab clay-ooze sediment. There is also evidence for significant clay-ooze movement elsewhere around seamounts (Figure 3-40) and at the base of steeper slopes (Figure 3-41). This is all interpreted to result from a combination of seabed currents and (gravity) slumping. Slumping of clay-ooze is also seen in the side-scan sonar (e.g. Table 3-4).

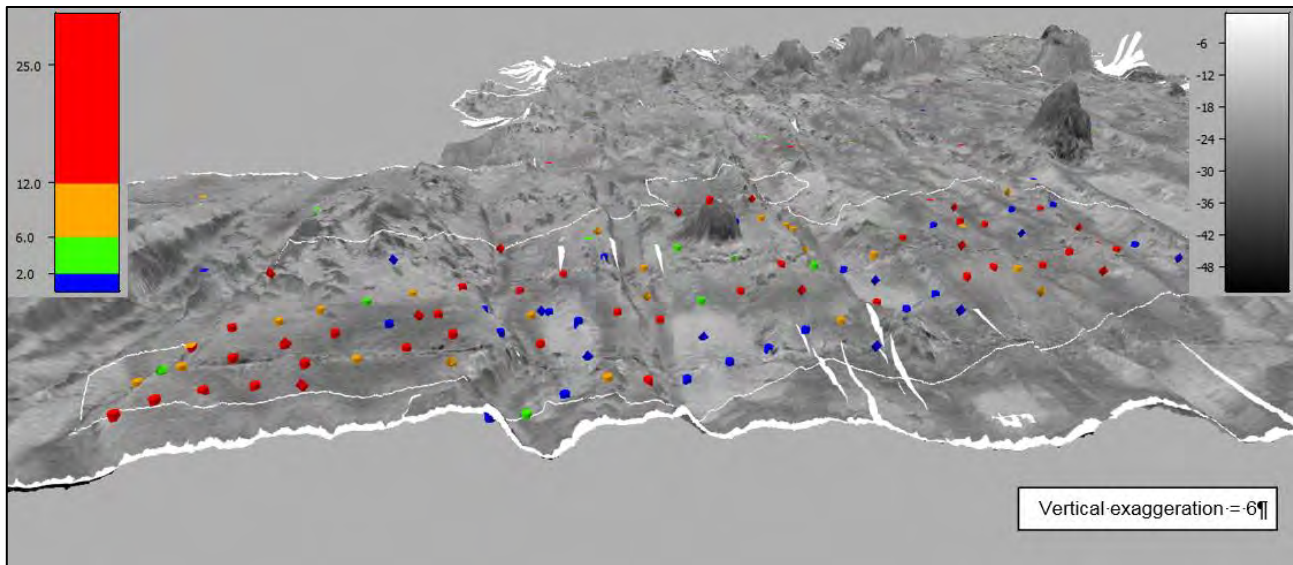


Figure 3-39: Example of “ponded” sediment drifts in TOML Area B

Source: from TOML MBES backscatter and sample data; Diamonds are box-cores, cylinders are photo based, squares are historical samples. Abundance (coloured) in wet kg/m²; acoustic absorption (backscatter; grey scale) in dB.

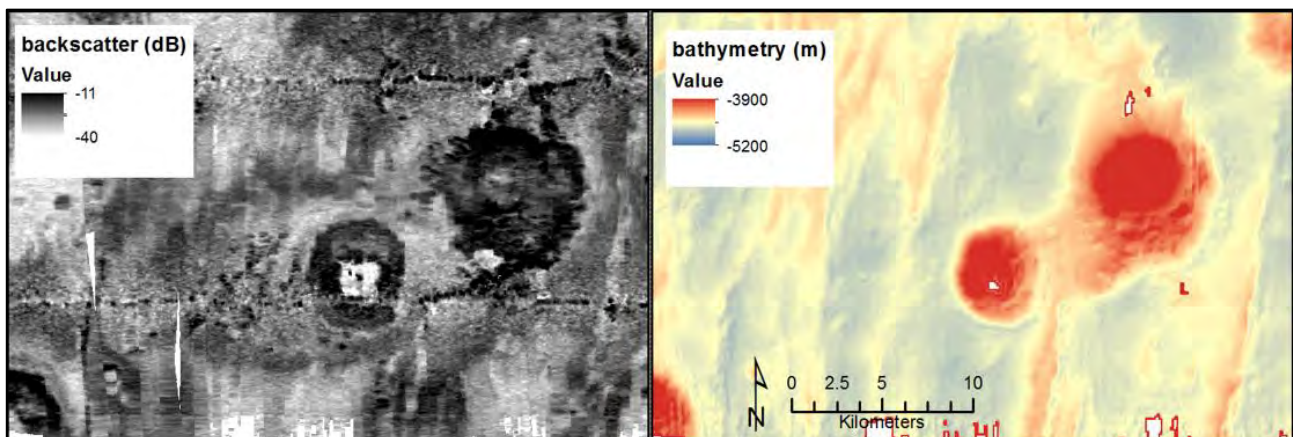


Figure 3-40: Example of sediment accumulating around seamounts
Sediment drifts are high attenuation units in the MBES backscatter; TOML Area B

Dynamic changes in current and temperature near the CCZ seafloor have been known since the DOMES study in the late 1970s (Hayes, 1979). This includes current changes related to: tides; likely inertial reaction (e.g. to the Coriolis force); and more significant seasonal or episodic events. Hayes (1979) also interprets the likely formation of boundary layers ~ 25 m above the seabed, which would be locally affected and focused by

seafloor topography. Such effects may progress closer to the seafloor where currents around nodules have been posited to be a possible mechanism to often keep them free of sediment (T. Peacock 2019, pers. Comm. 19 July).

Published long term data from current meters suspended above the seafloor is to date at best sketchy, and often filtered e.g. (Hosoi, 2010; Ju et al., 2010), so “peak” bottom current related events are likely under reported. Nonetheless, the seabed is typically quiet as:

- Seabed currents measured from near-bottom moorings are typically low (~ 4 cm/s and up to ~ 12 cm/s); and
- Typically there is no detectable permanent nepheloid layer (stirred up sediment) observed during survey (see also global review by Gardner *et al.*, (2018)).

Gardner *et al.*, (2017) describe conditions around benthic storms in the NW Atlantic. Typically seabed currents of > 20 cm/s are associated with benthic storms, but lower current speeds can transport sediment; i.e. 6-8 cm/s for low-density aggregates of phytodetritus (mm to cm in size), and 10-15 cm/s for non-cohesive silt. Within the CCZ, west travelling meso scale (50-500 km, 10-100 day) eddies formed from the Central American Gap Winds have been observed at the ocean surface. Inall *et al.*, (2015) and Aleynik *et al.*, (2017) describe data from a spring 2013 event, associating surface eddy currents of 40 m/s at the surface with stronger current events, 12-16 m above the seabed, approximately 1 week later. This included veering of the near seabed currents and a 4-6 times increase in speeds with peak values of 17-24 cm/s.

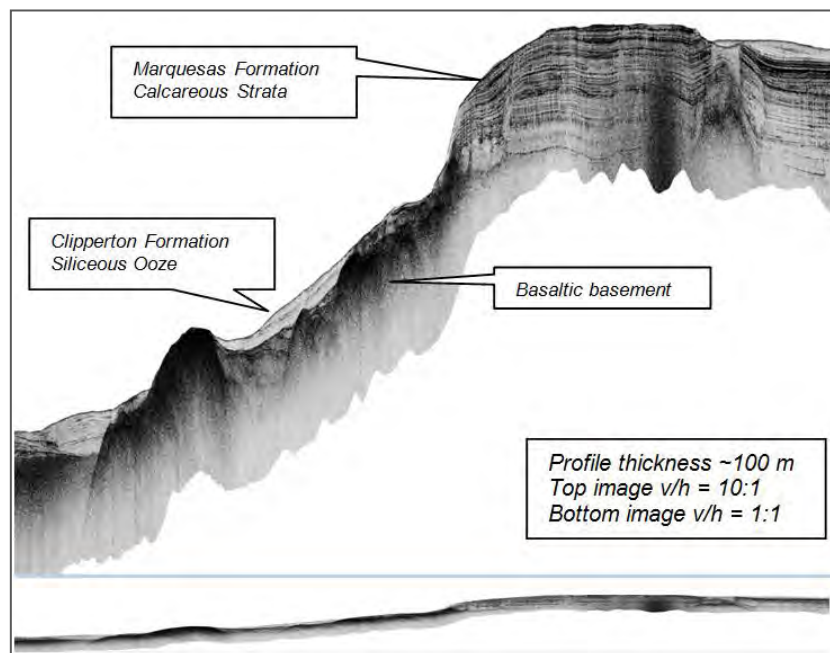


Figure 3-41: Example of “stripped clay-ooze” collecting in step benches
TOML Area B; collected using 5kHz sub-bottom profiler

The only Ab_d unit captured on SSS/SBP was at the eastern end of the line M01 in the TOML B area (Figure 3-42). A nearby photo profile shows a clear transition from a narrow unit of hN (in this case common large nodules on hummocky clay-ooze) to clay-ooze sediment without nodules. There is close correspondence between the SSS/SBP and the photo profiles and the MBES interpretation. Analysis of prolate nodules from a site several km to the east (section 4.3.1.3), shows them to grow parallel to slope indicating that a nearby sediment drift is a contourite.

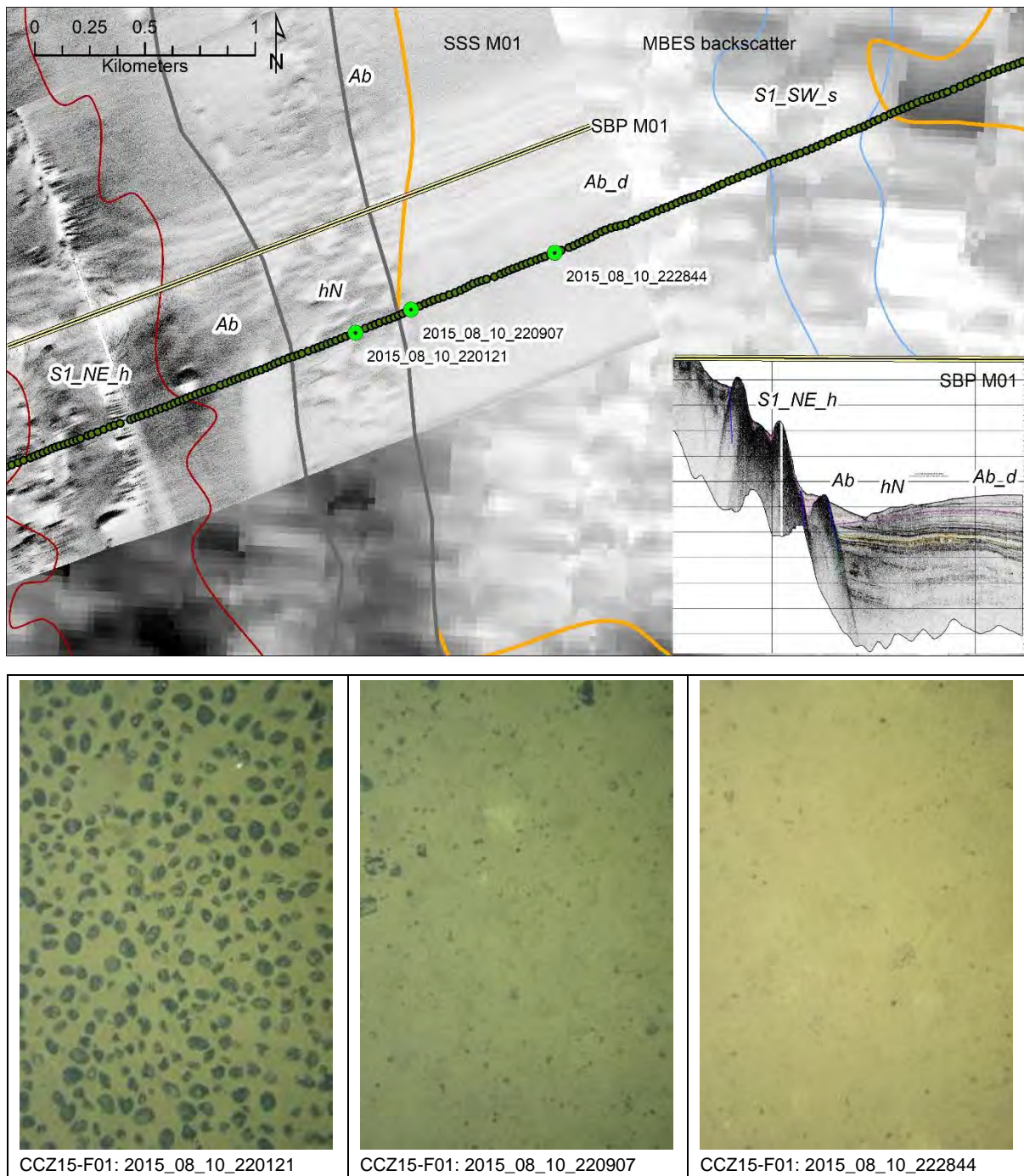


Figure 3-42: Comparison of an MBES Ab_d unit with SSS, SBP and towed photos - TOML B

All photos 2.4 x 1.6 m; SBP has V/H=10:1, vertical lines are 2 km apart and horizontal lines are ~25 m. Refer to section 10.3 for SBP and SSS interpretations. Full resolution images in Section 9.13

3.3.3.2 Thickness variation

DSDP site 159, which is located immediately south of the NORI C area (Figure 3-2), returned 18 m of upper Miocene to Pleistocene clay (van Andel et al., 1973a), that can be assigned to the Clipperton Formation. Site 160, located some 400 km south of TOML C and 300 km east of NORI A found some 27 m of clay of later early Miocene and younger age (van Andel et al., 1973b) that could be similarly assigned. Site 160 reported this unit to be disturbed – partly attributed to the drilling process but micronodules with quaternary

radiolarians were found well down in the sequence presumably due to transport by caving. The sequence at site 159 seemed to be relatively intact.

Thickness estimates can be made from the SBP at TOML B, C and D (Table 3-11). The thickness of the clay-ooze was found to be highly variable (also Figure 3-43). In general, the 18 and 27 m thicknesses reported from the DSDP sites fall within the range of estimates, albeit well towards the thicker end – this may be a consequence of the holes being located further south and/or siting of the holes away from the edges of abyssal hills.

Table 3-11: Thickness of layer “A” (Clipperton Formation) from the SBP data

	TOML B1	TOML C1	TOML D1	TOML D2	NORI DSAO
Min	0	6	0	0	0
Mean	9	13	5	4	?5
Max	32	29	9	21	-
Count	23	8	9	35	-

For the TOML areas, locations were selected semi-randomly using a pan between sites then random mouse position. For NORI DSAO (Fugro Onboard Geoscience and Processing Team, 2018)

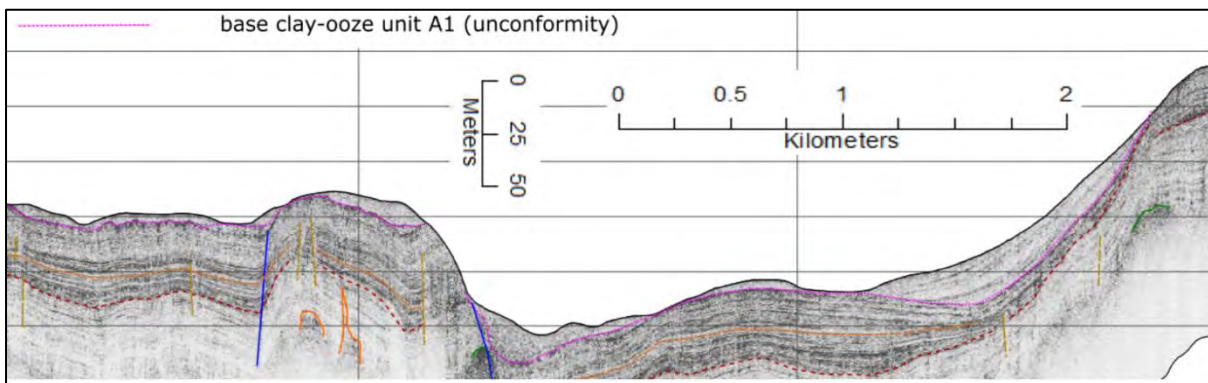


Figure 3-43: Example variable clay-ooze TOML D2

Line is CCZ15-M08. Clay-ooze of the Clipperton formation is above the pink dashed line. For a full legend and explanation of units refer to section 10.3 and Table 3-3

As illustrated in Table 3-4 the side-scan sonar images of the clay-ooze often reflect textures relating to the underlying stratigraphy (carbonate/volcanic) when the clay-ooze is thin (<10-20 m). In some cases (e.g., Figure 3-44) the texture can also be read on the MBES backscatter although mappable units at the deposit scale (1:250,000) were not able to be elucidated.

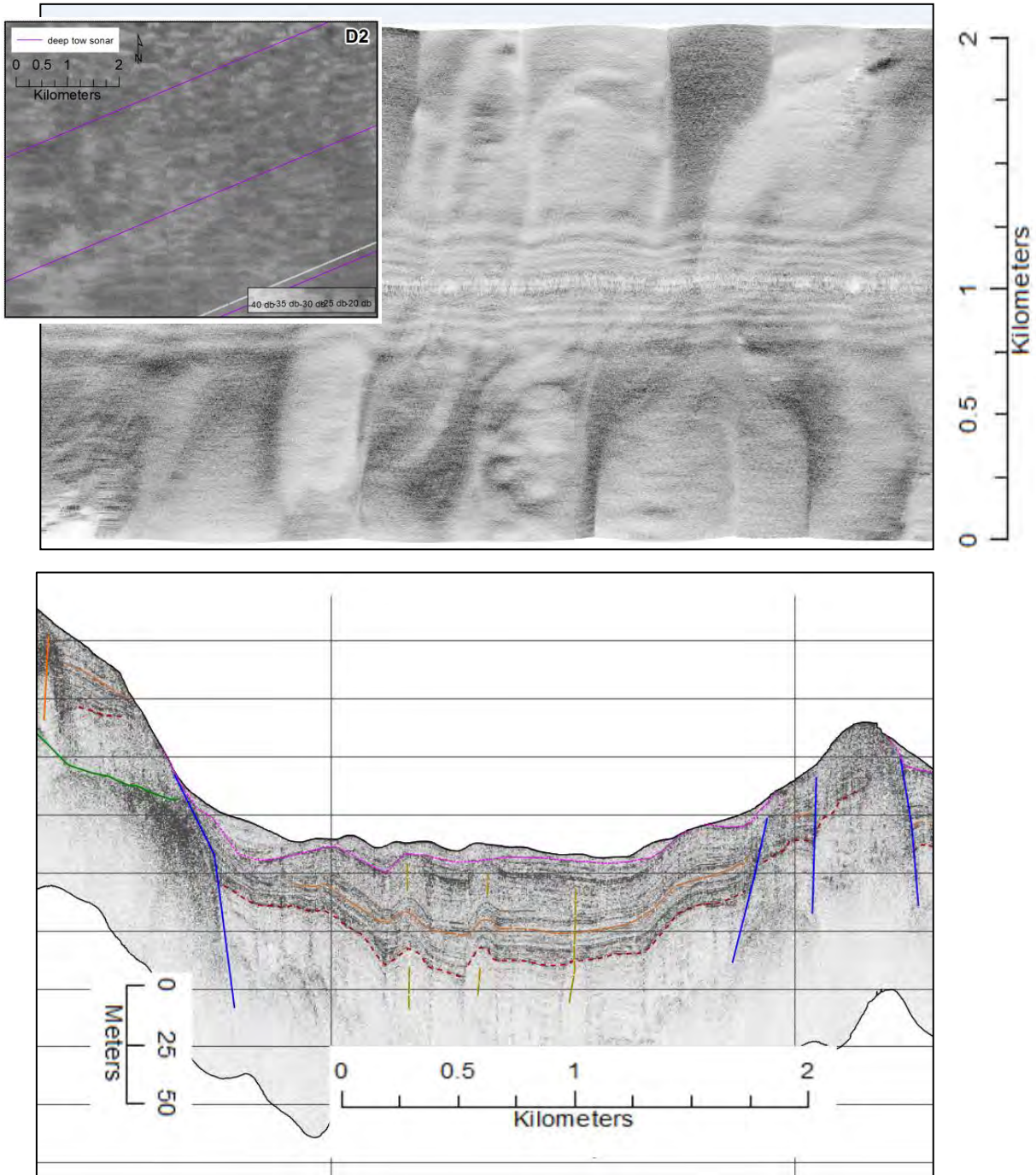


Figure 3-44: Large “mottled” texture of thin clay-ooze over surface warped carbonate strata

Inset at top is MBES backscatter from the region. Line is CCZ15-M06. Clay-ooze of the Clipperton formation is above the pink dashed line. Section V/H=10. For full explanation of units refer to section 10.3, Table 3-3 (SBP), Table 3-4 (SSS).

3.3.4 Volcanic edifices

Volcanic edifices (unit V) are volcanic units that are morphologically distinct from the volcanic basement to the abyssal hills (i.e., exposure along escarpments mapped with the MBES). It is very likely that some of the edifices are effectively coeval with the basement lavas, but there are numerous examples of volcanic activity that are clearly much younger, and there is no known consistent way to map these separately at the 1:250,000 deposit scale. However, the following edifice types were discriminated:

- Discrete volcanic knolls (V_k), composite knolls (V_c) and two seamounts (V_m, V_t) e.g., Figure 3-45), are apparent on MBES bathymetry and slope maps with support in most cases from MBES backscatter. An example area with photo profile coverage is presented further below in 3.3.4.1;
- Outcropping low aspect flows (V1_s) - seen on MBES due to very high backscatter reflectance. An example area is presented further below in 3.3.4.2;
- Outcropping fissure lavas and associated dykes (V_f) - seen on MBES and more clearly on SBP. An example area with SBP and photo profile coverage is presented further below in 3.3.4.3;
- buried dykes and sills seen on SBP (Figure 3-46, Figure 3-47).

Knolls and composite knoll are the most common unit (~93% of mapped features in section 10.2). They are believed to include to be comprised of both coherent lava (V1) and breccia facies (V2; Table 3-1, Figure 3-45). The exact breccia types are not really known in most cases, but most are likely to be gravity/debris flows, auto-breccia or hyaloclastite. There are only four seamounts (>1000 m elevation) in the survey areas. Talus from an ~3,000 m high seamount (the northernmost of the Acapulco chain is included in NE NORI C), and coherent lavas form a steep ~2,000 m high seamount in eastern TOML Area D. The other two seamounts only just qualify as seamounts (i.e. they are high knolls composed of lavas), in SW NORI C and at the northern edge of NORI D.

The knolls often occur in chains and sometimes the surrounding seafloor is deeper and less rugged than nearby abyssal hills indicating increased local heat flow associated with tectonic related thinning.

Intrusions that cross-cut the sedimentary stratigraphy are seen several times in the SBP (section 10.3) and are especially well developed in TOML D. Indeed, they may play a role in the preservation of the elevated abyssal plain that comprises TOML D2. A swarm of dykes ± hornfels and associated diffraction patterns can be seen in TOML D2 (Figure 3-46). They extend NW into the two SBP profiles to the north (ie up to 5 km away) but are less well developed. In one area within TOML D1 the carbonate sequence is stopped out by a later stage sill (with overlying peperite) (Figure 3-47).

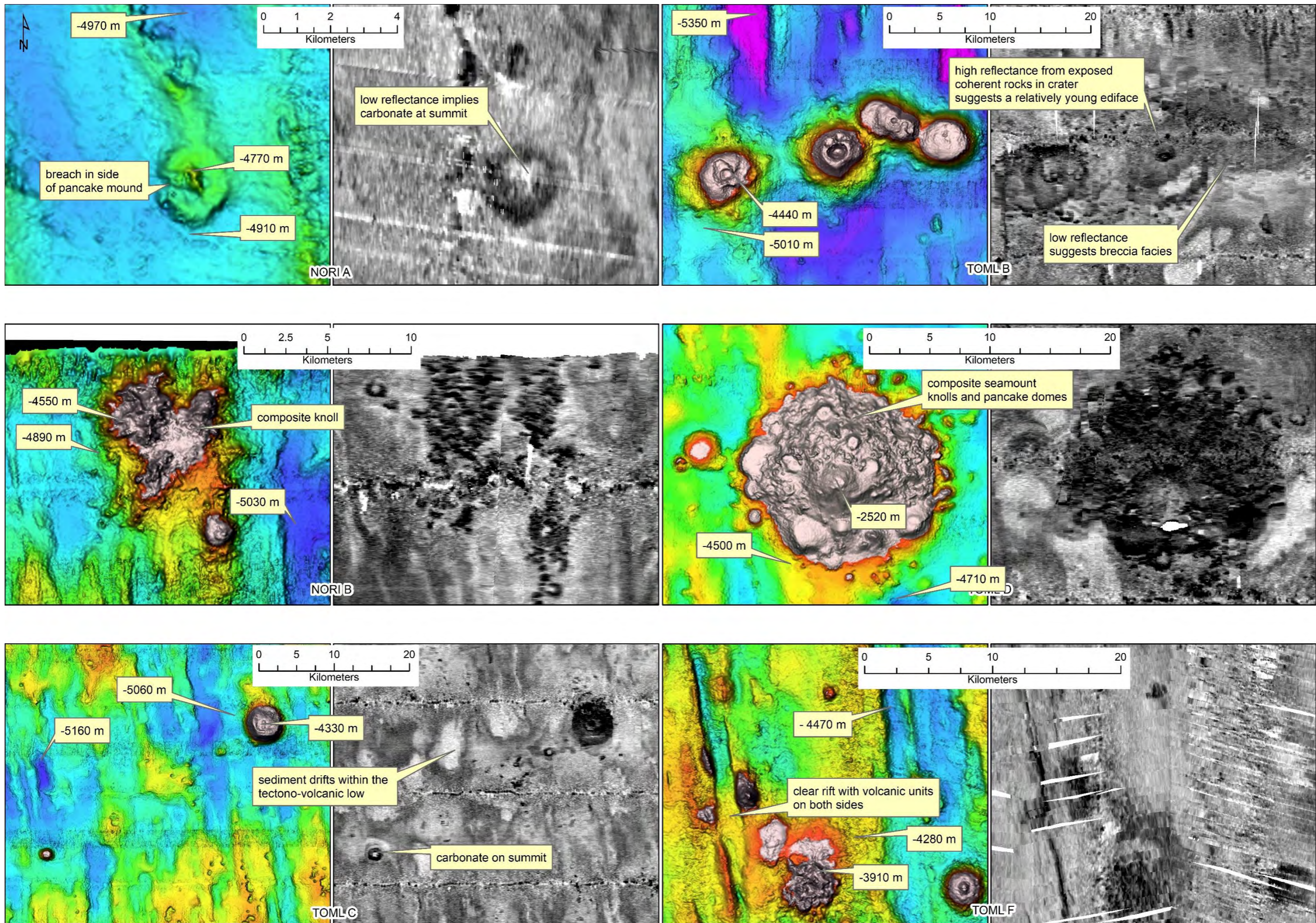


Figure 3-45: Example knolls and seamount on MBES
 Left image in each case is bathymetry, right is backscatter.

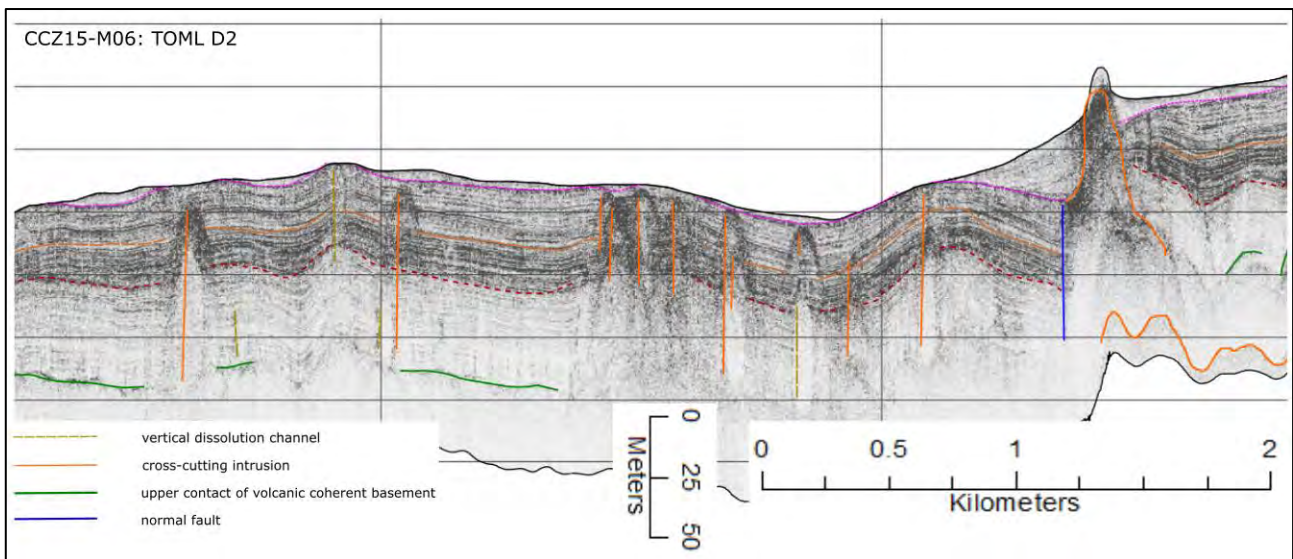


Figure 3-46: Possible dyke (+hornfels) swarm in western D2

Note refraction patterns off top of narrow high reflectance features. For full explanation of units refer to section 10.3, Table 3-3

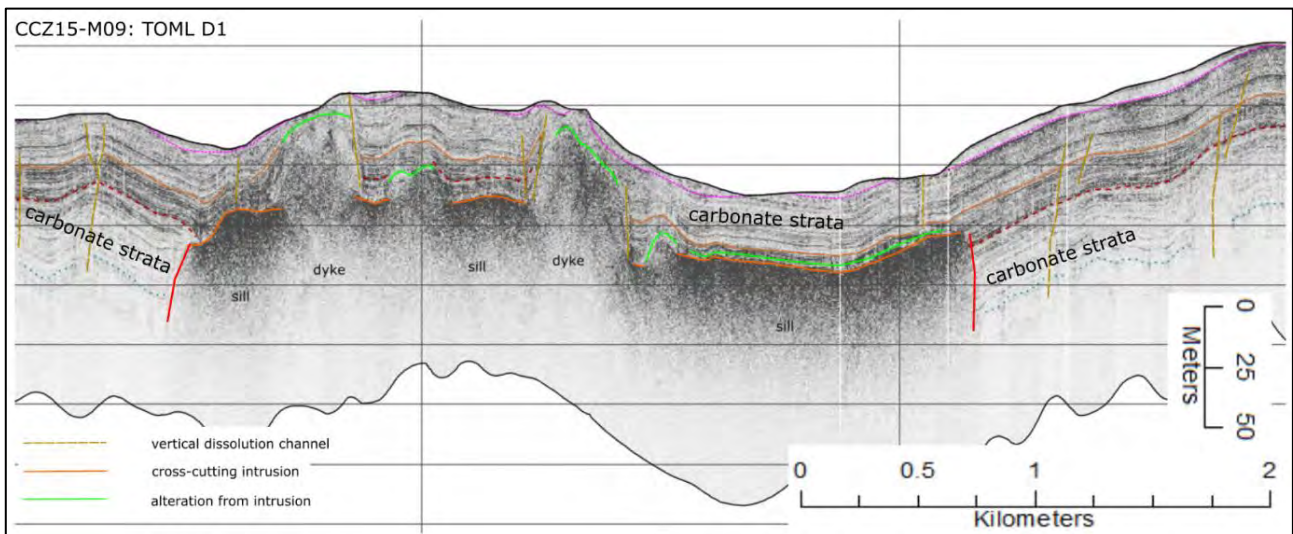


Figure 3-47: Possible late-stage sill/peperite and breaching dykes/feeders

Note stoping of carbonates by the sill. For full explanation of units refer to section 10.3, Table 3-3

3.3.4.1 Volcanic Knoll B4046 example area

Knoll B4046, also known as “Flynn’s Knoll”, is selected as an example area, as this is the only discrete volcanic edifice covered by towed camera photos (there are no such edifices covered by SSS-SPB survey) accessible to the author (i.e., from the CCZ15 expedition).

The knoll has a diameter of about 3.5 km, with a slight elongation to about 4 km NW-SE and rises about 500-600 m above the surrounding seabed (Figure 3-48). The summit of the knoll is gently convex with subtle ridges to north and east-north east.

The knoll was first surveyed with 12 kHz MBES at part of the CCZ13 expedition and then traversed WSW to ENE with the Neptune towed camera sled, as part of the CCZ15 expedition.

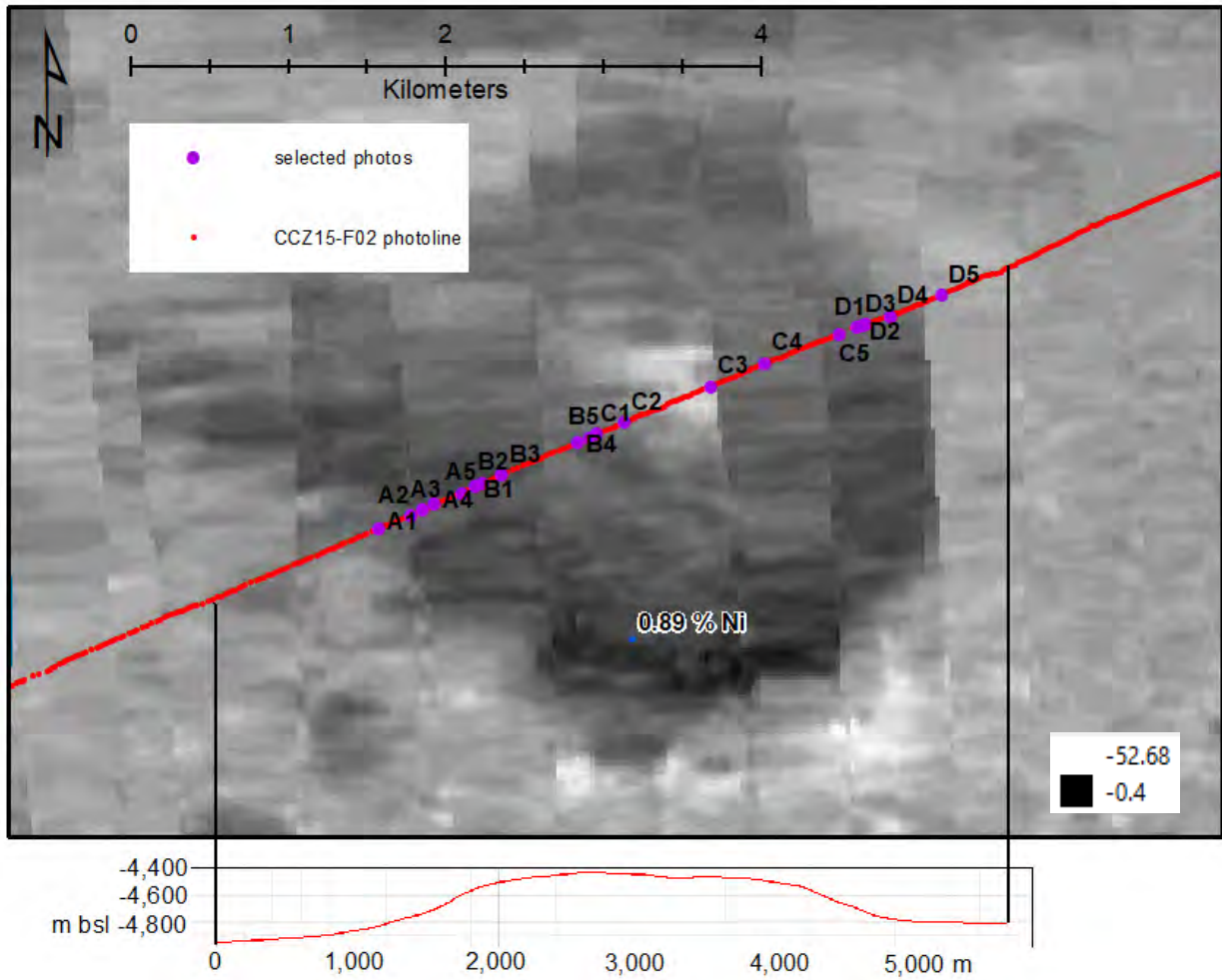
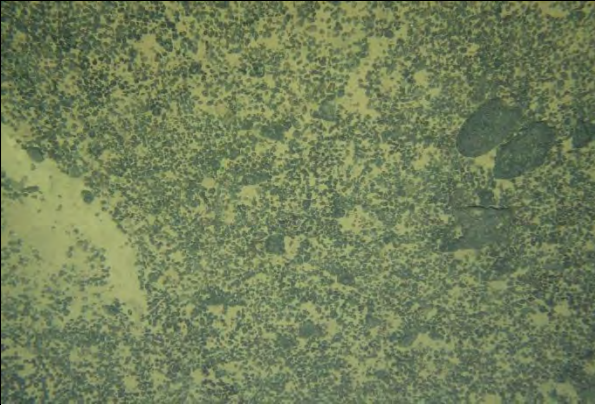
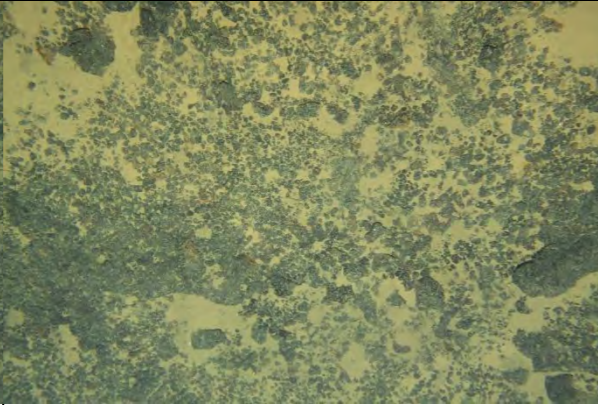
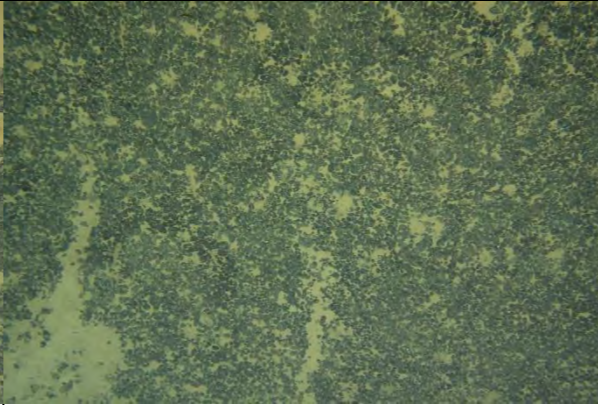
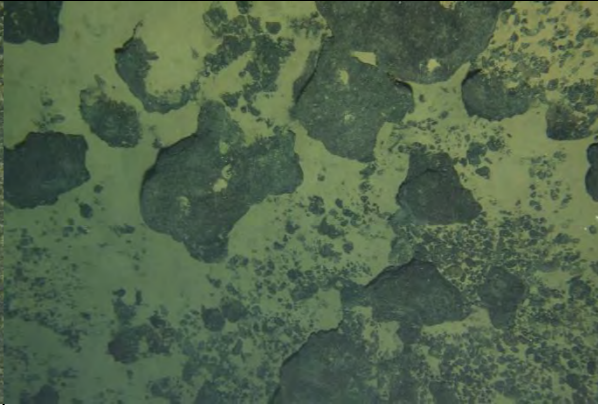
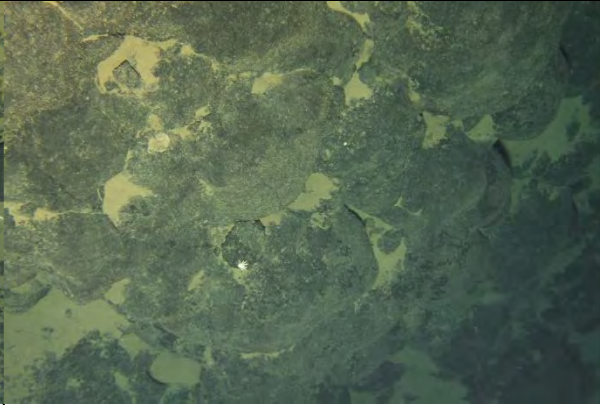

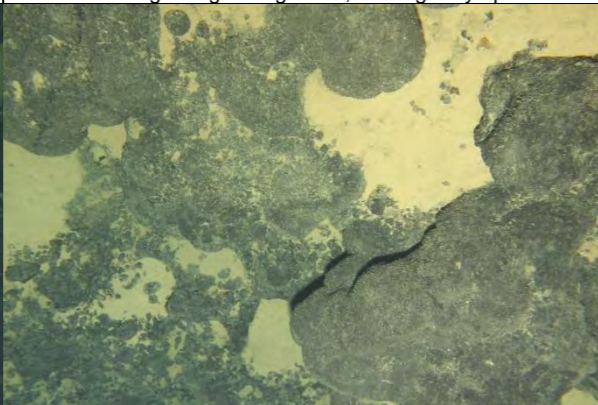
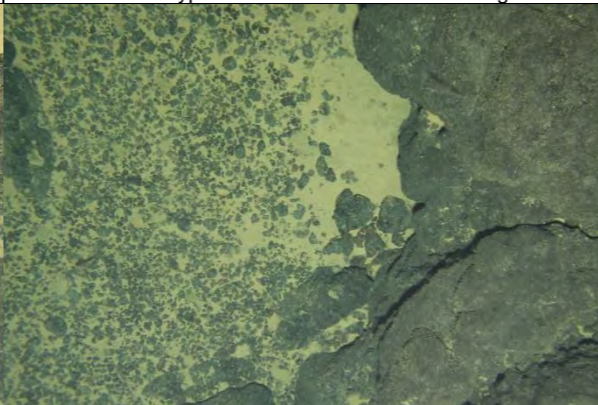
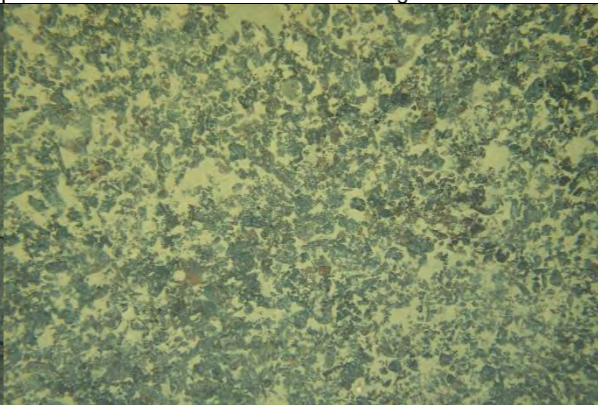
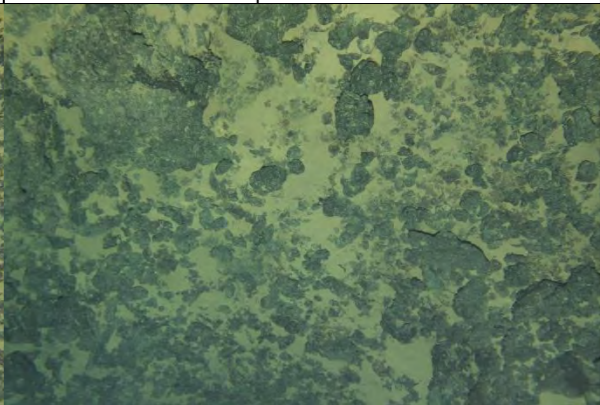
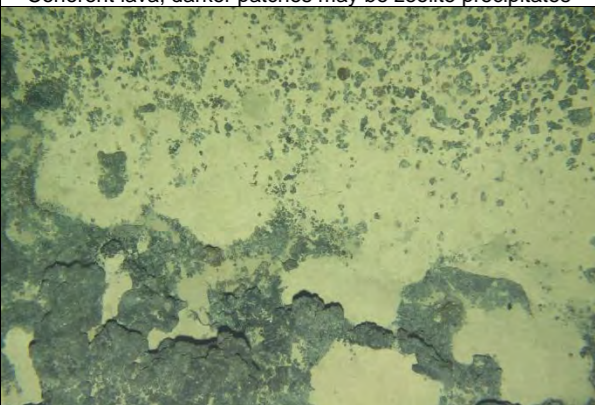
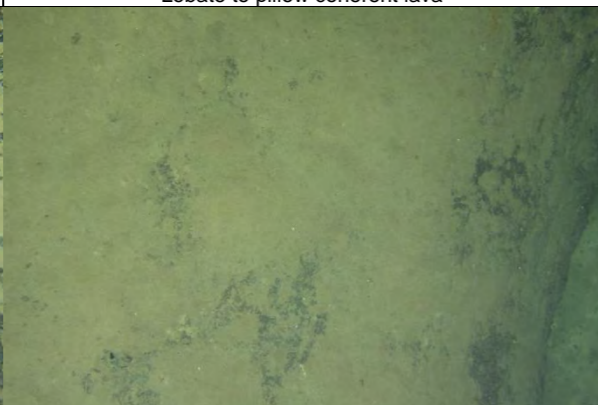
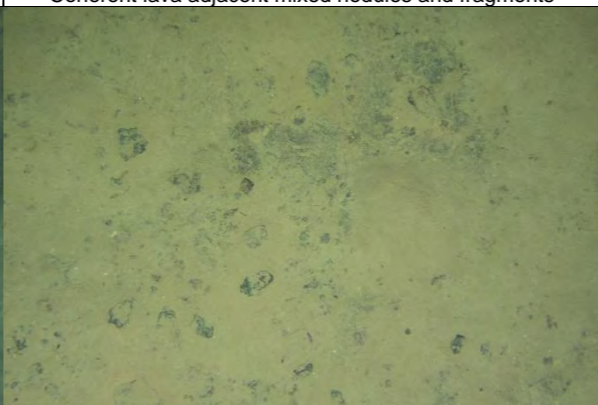
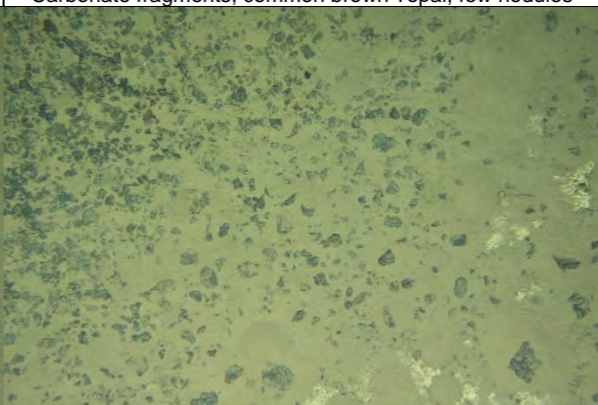
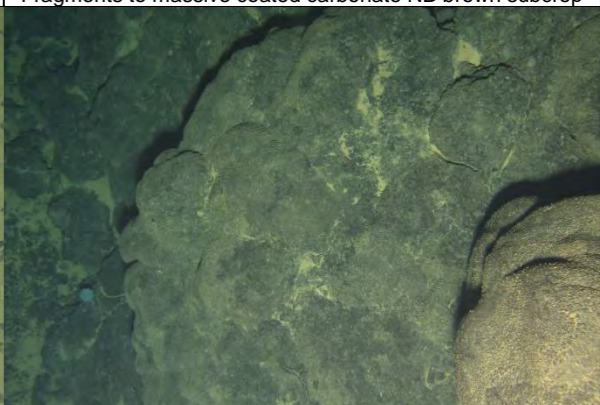
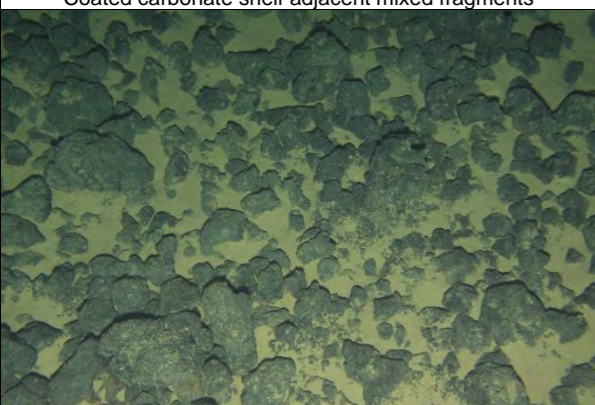



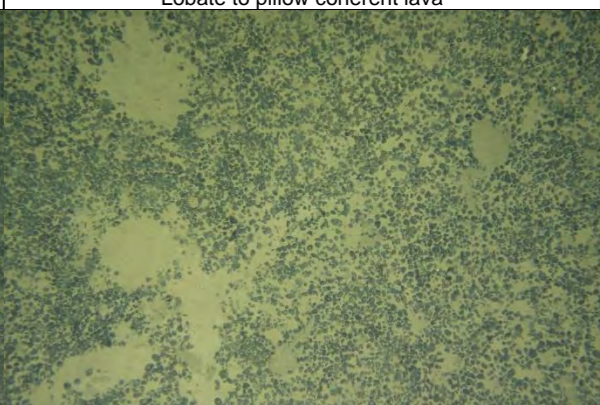


Figure 3-48: "Flynn's" Knoll B4046

Top is backscatter with the photo profile a red line. Bottom is surface section along the photo-profile line without any vertical exaggeration.

Twenty of the towed photos, selected from the ~180 that span the knoll, comprise Table 3-12.

Table 3-12: Selected seabed photos WSW to ENE across Knoll B4046

				
A1; CCZ15-F02; 2015_08_17_090308 Small nodules mixed volcanic fragments NB lobate forms	A2; CCZ15-F02; 2015_08_17_090928 Pavement grading to fragments, some glassy/opaline.	A3; CCZ15-F02; 2015_08_17_091200 Small smooth type nodules – no obvious rock fragments	A4; CCZ15-F02; 2015_08_17_091433 Lava blocks and smaller fragments	A5; CCZ15-F02; 2015_08_17_091854 Lobate to pillow coherent lava
				
B1; CCZ15-F02; 2015_08_17_092049 Coherent lava, darker patches may be zeolite precipitates	B2; CCZ15-F02; 2015_08_17_092206 Lobate to pillow coherent lava	B3; CCZ15-F02; 2015_08_17_092604 Coherent lava adjacent mixed nodules and fragments	B4; CCZ15-F02; 2015_08_17_094130 Carbonate fragments, common brown ?opal, few nodules	B5; CCZ15-F02; 2015_08_17_094345 Fragments to massive coated carbonate NB brown subcrop
				
C1; CCZ15-F02; 2015_08_17_094518 Coated carbonate shelf adjacent mixed fragments	C2; CCZ15-F02; 2015_08_17_095141 Thinly covered carbonate shelf	C3; CCZ15-F02; 2015_08_17_101105 Carbonate subcrop	C4; CCZ15-F02; 2015_08_17_102316 Mixed carbonate fragments and nodules on chalk subcrop	C5; CCZ15-F02; 2015_08_17_104049 Lobate to pillow coherent lava
				
D1; CCZ15-F02; 2015_08_17_104528 Lava blocks	D2; CCZ15-F02; 2015_08_17_104652 Lava blocks	D3; CCZ15-F02; 2015_08_17_104734 Blocky lava (?dyke) with some glassy rinds	D4; CCZ15-F02; 2015_08_17_105338 Few blocks amongst mixed lava nodule fragments	D5; CCZ15-F02; 2015_08_17_110601 Small nodules

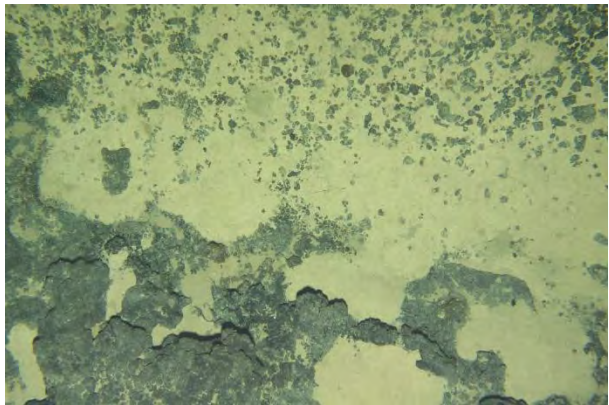
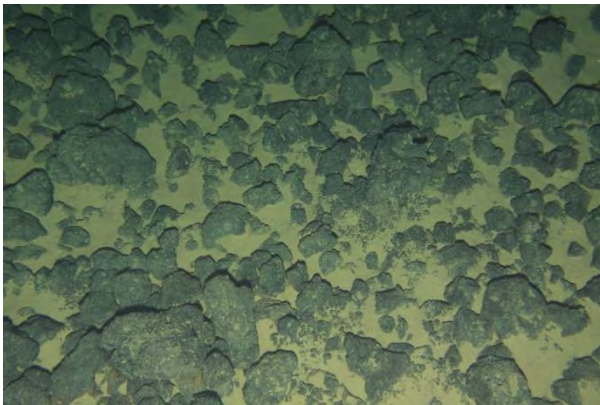
All Photos: 2.4 x 1.5 m. Full resolution images in Section 9.13

Near the WSW flanks of the knoll, small smooth nodules are present in the clay-ooze. Clay-ooze is present in varying quantities across the traverse (note also box-core results on southern slope of the knoll in Figure 3-49). As the slopes starts to steepen there are more variably sized fragments of rocky material, some appear to be composed of brown glass (*cf* Figure 3-55), and at one point on the lower slope to the WSW, there is minor outcrop of carbonate. At the steepest parts of the slope, boulders and gravels of what look to be lava, grade into coherent flows with some showing lobate to pillow forms (10-100 cm across).

On the western side of the top of the knoll there are often nodules occurring amongst lava outcrop. Over most of the top of the knoll however, massive carbonate is present amongst more extensive beds of sub-rounded medium grained (~1-5 cm at the major axis) carbonate fragments (interpreted to be the residual of surface dissolution of the strata, i.e. similar to residual fragments in terrestrial *terra rossa*). The 12 kHz MBES backscatter response supports this interpretation via a patch of relatively high sound absorbance (Figure 3-48). The presence of carbonate indicates that this is an old volcanic edifice that was very likely emplaced when the plate segment was located further south and above the lysocline (note that in this region, magnetic isochrons indicate that crust formed at around 37 Ma or late Eocene; section 2.4.3.4). So, based on Pacific Plate motion speeds (e.g. Figure 2-1) the underlying crust could formed as far as ~3,000 km to the ESE of its present position.

At the ENE edge of the top of the knoll coherent basalt lavas are again in evidence and these, mixed with often coarse volcanic breccia, continue to the base of the knoll where small smooth nodules become progressively more dominant. Carbonate fragments can be difficult to discriminate from volcanic fragments, but some guidelines are provided in Table 3-13.

Table 3-13: Discriminating features: carbonate from volcanic breccia B4046

Carbonate	Volcanic
Subrounded – angular fragments, edges often irregular. Often mixed with small to medium sized nodules. Fragment size grades from <5 cm across to a few large blocks < 1 m across to out-cropping rock that is often sheet-like in form. Brown fragments may be present (thought to be opal section 4.4.2).	Subrounded – blocky fragments, edges often smooth to semi-rough. Any nodules are usually small and smooth. Fragment size grades from <5 cm across to numerous large blocks to out-cropping rock that is often massive or lobate in form. Brown ?glassy rinds may be present in small amounts.
	
CCZ15-F02; 2015_08_17_094518 Coated carbonate shelf adjacent mixed fragments	CCZ15-F02; 2015_08_17_104528 Lava blocks

Full resolution images in Section 9.13

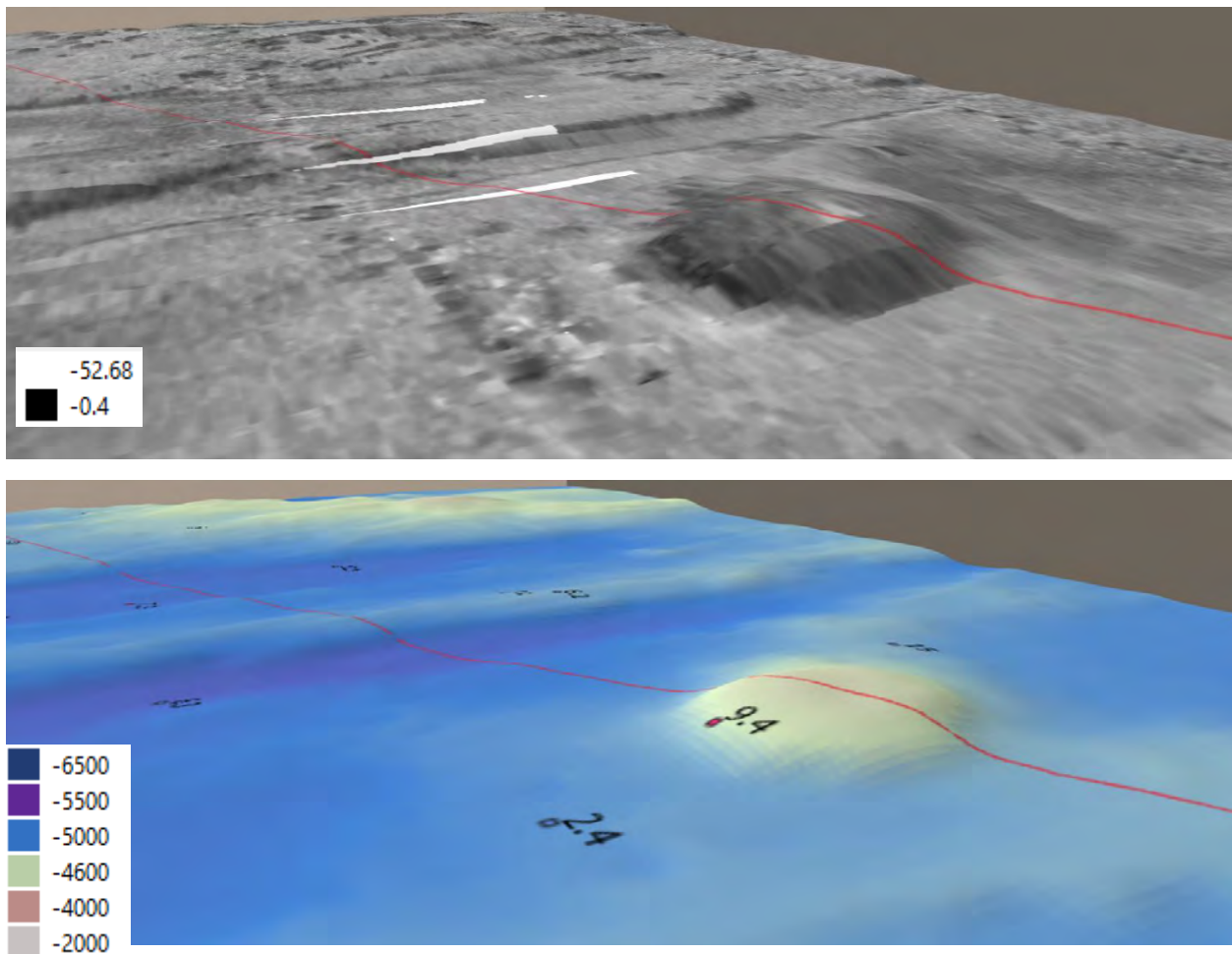


Figure 3-49: NW Perspective to Knoll B4046

Top is backscatter draped on to bathymetry, Bottom is bathymetry. There is no vertical exaggeration applied – knoll is 600 m high and about 3,000 m in diameter. Red line is the line of towed photos (CCZ-F02); green boxes are box-cores collected during the CCZ15 expedition, red boxes are historical data; labels for box-cores are of nodule abundance in wet kg/m².

3.3.4.2 Emerging seamount lavas northern area NORI C

A variety of volcanic units and associated structural elements, unique to the survey areas, have been mapped at the northern end of the NORI C area (Figure 3-51). This location is also at the northern end of the Acapulco Seamount chain within Victor Low (refer to Chapter 2) The following features (listed below from north to south and with reference to Figure 3-51) appear to relate to the development and possible northern progression of the Low. These are:

- 1) two sets of abyssal hills, at a significant angle (~10-25° to the west) to the regional abyssal hill set, with evidence for cross cutting. These are termed the western and eastern rifts. Volcanic knolls and mounds are found within the rifts as are broader flat areas of high reflectance interpreted to be sheet lavas.
- 2) several WNW-ESE trending mounds (up to 40 km long by 10 km wide) with minor attendant volcanism, that are located between the two rifts and on the eastern side. These may be possible breaching tops of laccolith like intrusions.
- 3) a NE to ENE trending line of volcanic knolls and sheet lavas located at the base of a seamount (with an indication in the MBES backscatter of more reflective volcanic rocks below shallow cover). The sheets

extend up to 5 km from the knolls that are possible vents for the flows as there are no obvious fissures. Variable backscatter is interpreted as a combination of coherent and fragmented facies at the knolls.

Note that these sheet lavas are significantly larger than the well documented and studied inflationary subaqueous basalt lava flow forms of Deschamps *et al.*, (2014). They document flows at 16° N on the EPR that are 0.1- 1.2 km across and up to 15 m high. Nonetheless, they also note that while thermodynamic convection would make submarine lavas form a thick and brittle crust, the relative buoyancy of lava sub-sea (in effect a reduction of 33%) would promote inflationary flow. (Allen *et al.*, 2007) report lavas, dykes and sills interbedded with volcanoclastic breccia and sourced from nearby vents, from the margins of a Miocene submarine volcanic system now exposed on the west coast of North Island New Zealand.

- 4) the talus slope of the northernmost Acapulco seamount (~2,700 m tall, coded KW-16116 per (Kim and Wessel, 2011)) extending up to 30 km from the summit. Within the MBES survey the slope is irregular but averages 16.6° which is similar to the diagrammatic submarine volcanoclastic aprons of Allen *et al.*, (2007) who have about 14° overall steepening to 21° proximal to the vent.

It follows then that given that the above features are likely linked, and that this area can serve as a type-area of how these kinds of seamounts start to form.

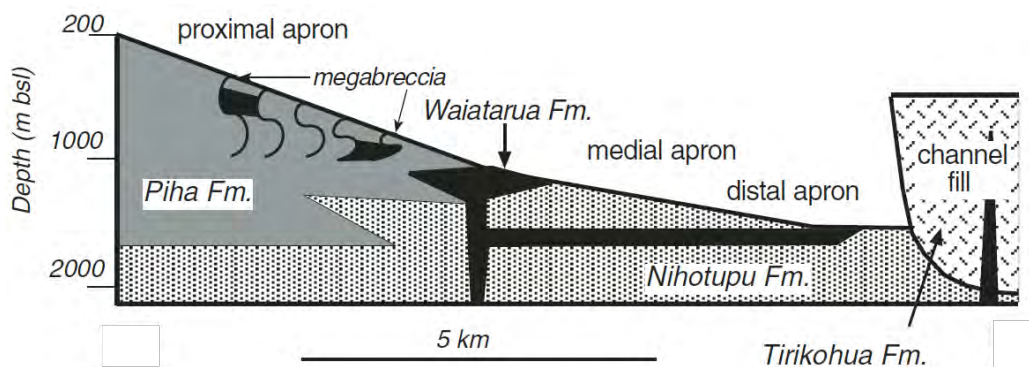


Figure 3-50: Facies schematic for the Manukau subgroup (submarine volcano)

Reproduced from: Allen *et al.*, (2007)

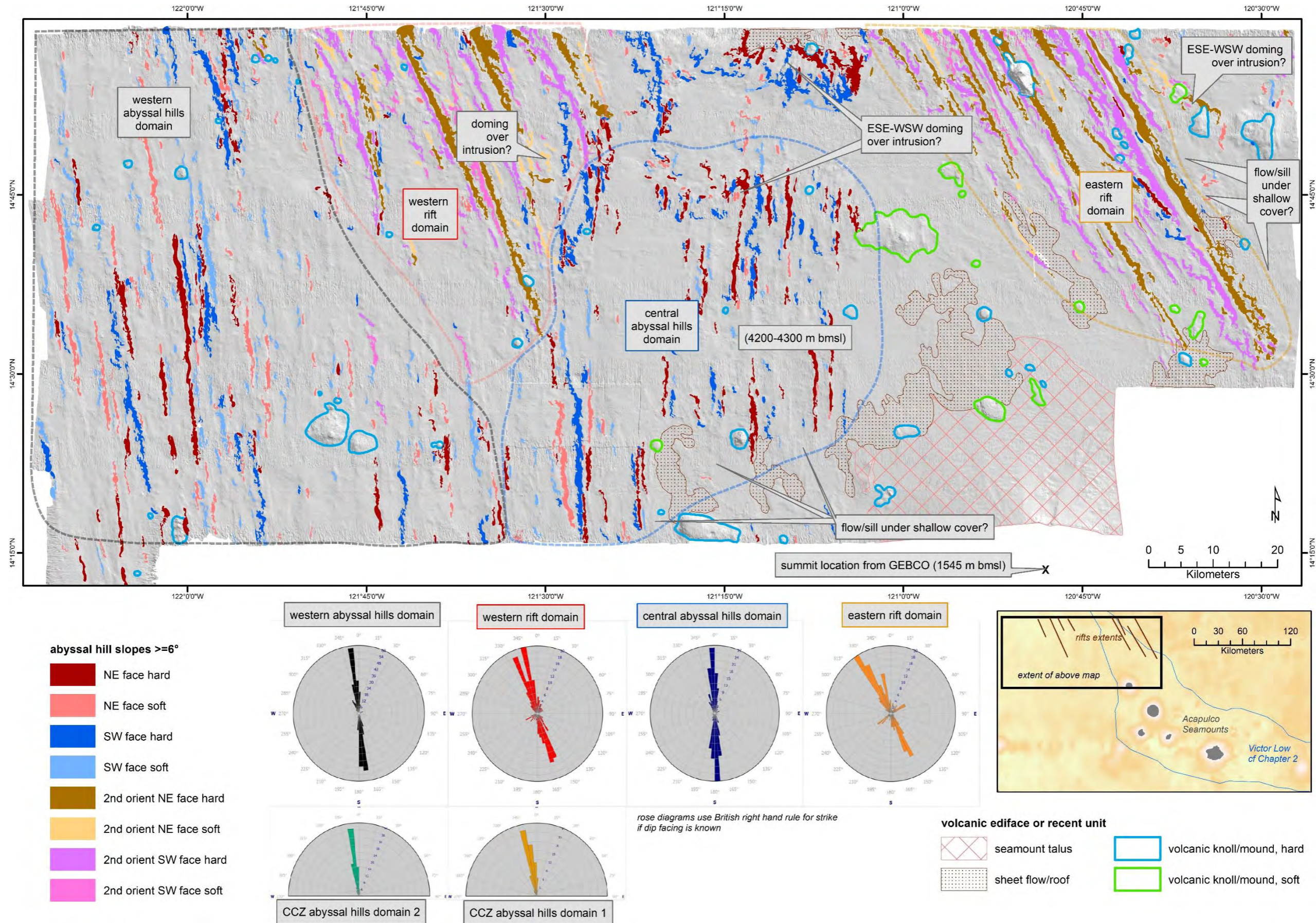


Figure 3-51: Sheet flows and other features at the northern base of the northernmost Acapulco Seamount

3.3.4.3 Fissure lavas, dykes and sills TOML B1

Fissure lavas, dykes and a small sill are mapped in relative detail in TOML sub-area B1 (B5338 field) thanks to overlapping MBES, SSS/SBP and photo-profiles. A sample of lava breccia was also recovered in a box-core.

A perspective view of the units (Figure 3-52) shows them mostly propagating southeast from a compound knoll that resulted (or helped form) a wide abyssal hill (~12 km across). The intrusions are interpreted to be due to dilation related ongoing adjustment of tectonic stress around this end of this wider than normal hill.

Up against the knoll, the dykes surface somewhat discontinuously, further to the SW they continue under cover expressing as linear mounds in the sediment and in the SBP profiles (e.g. Figure 3-54). Significantly, the potholes in this region seem to be related to the dykes, presumably increased hydrothermal convection helping form the potholes (section 3.3.2.3.2).

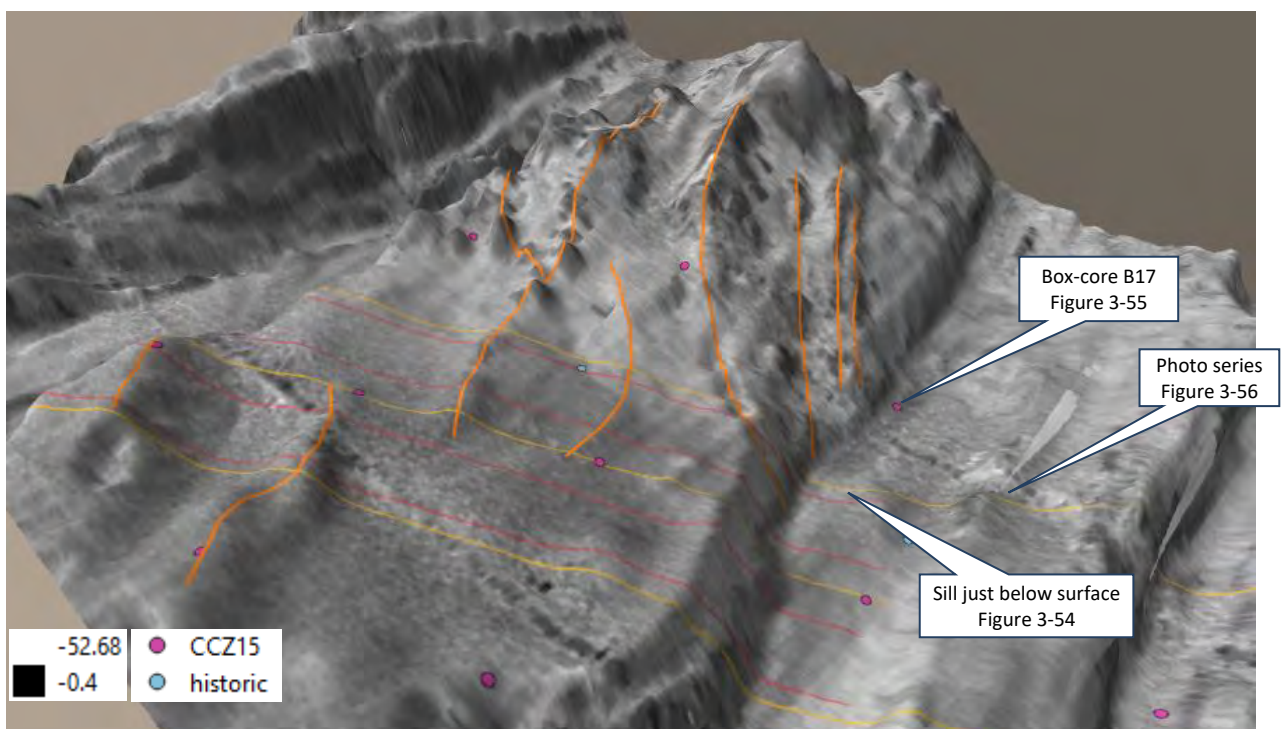


Figure 3-52: Perspective view fissure lavas/dykes in TOML B1 (B5338)

View has vertical exaggeration of 10:1. Both images is of backscatter (per scale shown) draped onto bathymetry (elevation change of 700 m). Orange lines are interpreted fissure lavas and associated dykes. Red lines are SBP/SS and are about 2 km apart. Yellow lines are photo-profiles. Small circles are box-core (nodule) samples.

The sample recovered was CCZ15-B17 a box-core taken in TOML Area B1. The sample comprised mixed volcanic breccia fragments and nodules on top of several decimetres of mud (Figure 3-55). The fragments often have brown glassy rinds and appear altered and should be relatively young as they have only minor (<3 mm) ferromanganese concretions on them. Box-cores B18 and B19 were taken to the west onto shoaling carbonate, and near the knoll, with poor results in terms of nodule abundance (Figure 3-55).

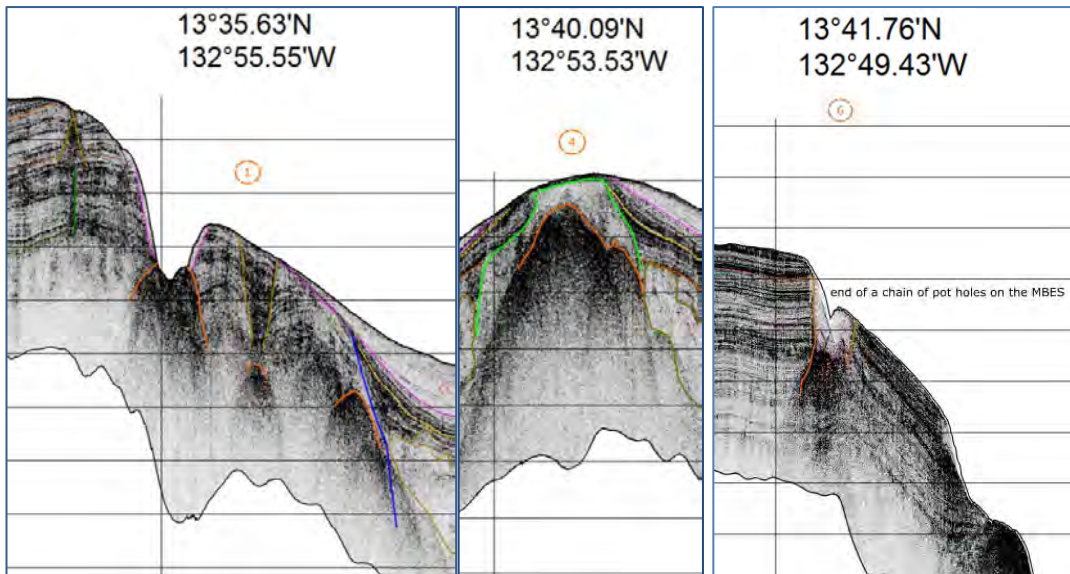


Figure 3-53: Example SBP through the TOML B1 dykes
 exaggeration = 10x, horizontal lines 25 m apart; interpretation legend at Table 3-3

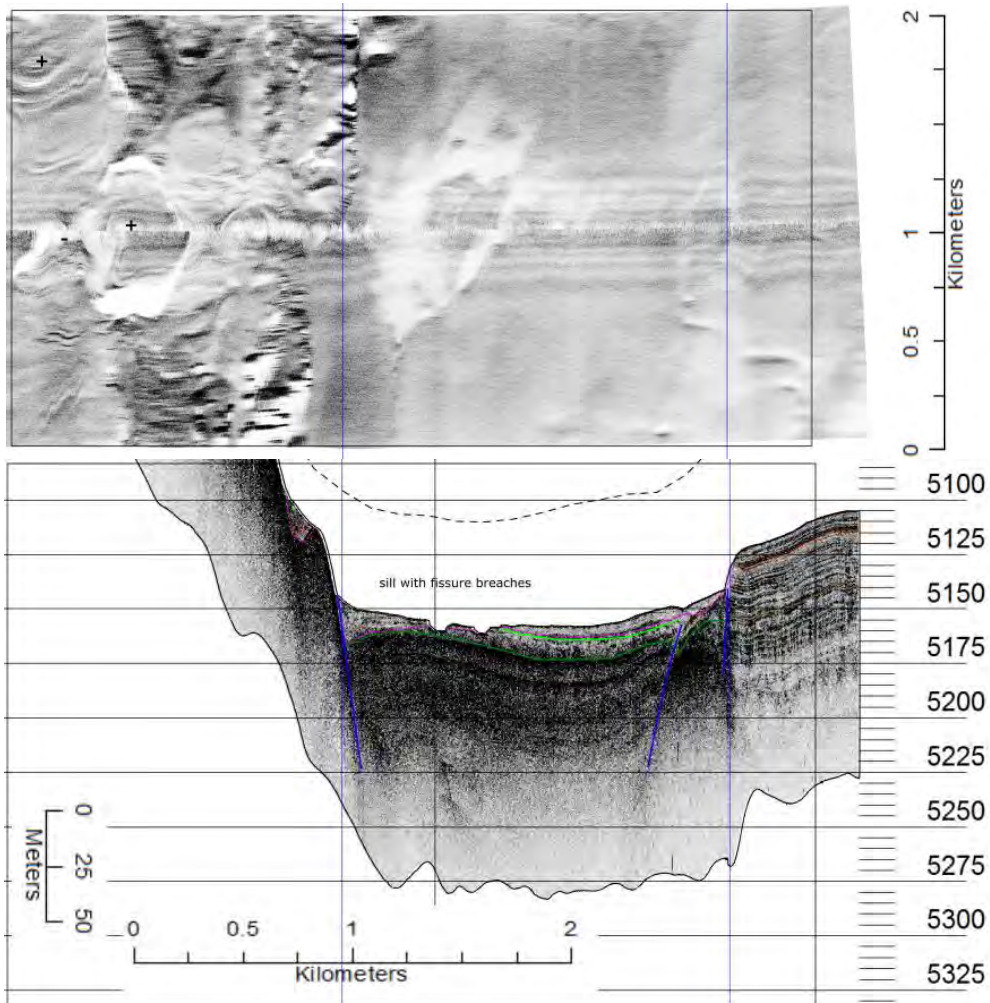


Figure 3-54: SBP/SS through a sill located 4.5 km south and in the same valley as B17

Note side-scan swath ensonification scale is roughly opposite to the SBP (and MBES) i.e. lighter areas are those of higher reflectance.

The sample from B17 is from a valley located 1,200 m from the nearest fissure/dyke feature resolvable by MBES, but 4.5 km to the south there is a sill located just below surface with what appear to be breaches or vents in the clay-ooze (Figure 3-52; Figure 3-54). Unfortunately, the seabed camera on the box-core failed to operate on that particular deployment. Thus, it is not clear what type of volcanic breccia is sampled by B17, but similar scoriaceous fragments associated with a nearby outcropping dyke are shown in Figure 3-56. Nonetheless, lava autobreccia can be expected in areas also containing coherent lavas, even if block mass waste (as seen on the steeper slopes of Knoll B4046 above), hyaloclastite, and local density current flows are not considered likely.

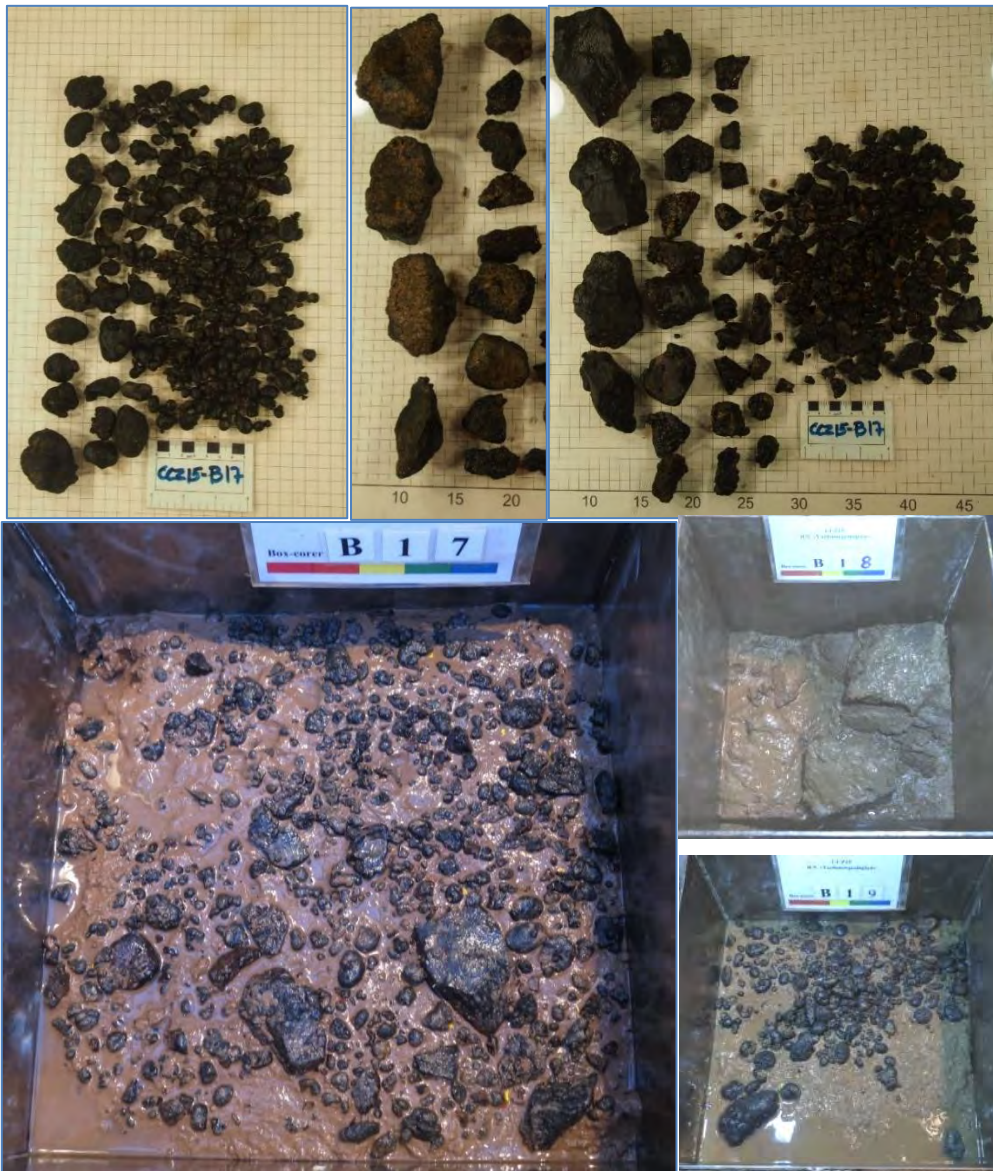


Figure 3-55: Mixed sample collected in B17

Top are photos after washing of sample; left is nodules right is topside of volcanic fragments centre is base side of larger volcanic fragments; grid is 1 cm. Bottom is samples as received; corer is 50 cm a side. Box-cores B18 and B19 were taken 7 km and 14 km to the west into shoaling chalk.

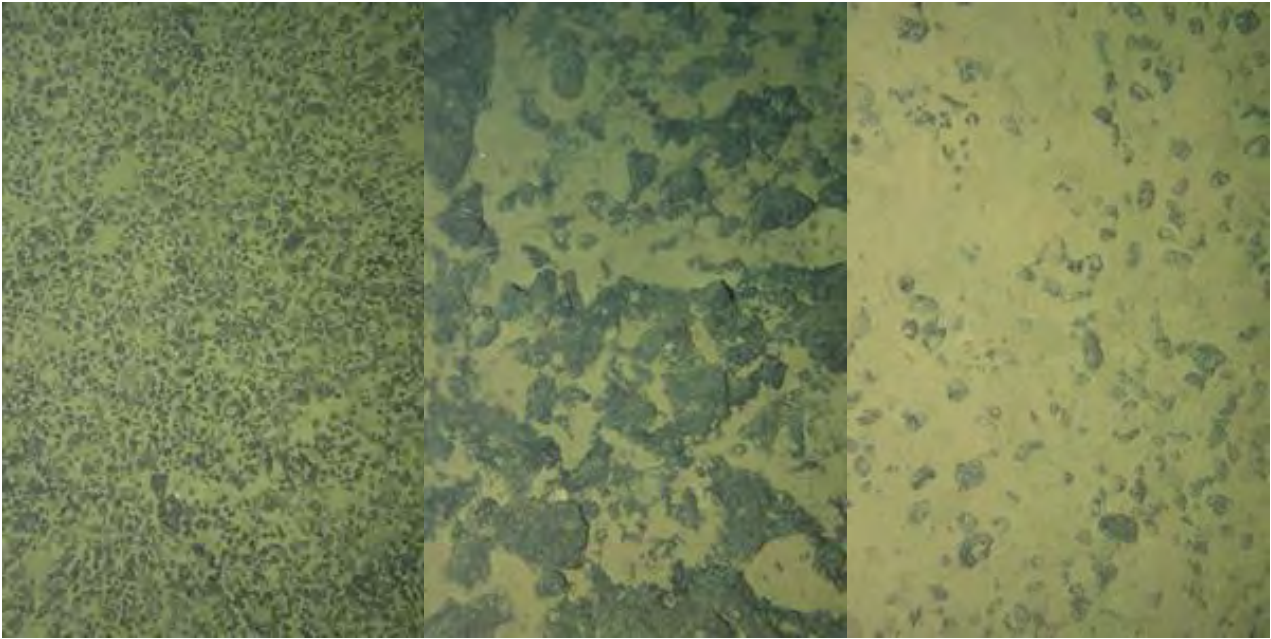


Figure 3-56: Seabed photo sequence across an outcropping dyke TOML B1

All photos are ~1.6 x 2.4 m and were taken approximately 30 m apart. From left to right (WSW to ENE) mix of volcanic fragments and nodules similar to B17 (CCZ15-F02 2015_08_17_023028); coherent lava (2015_08_17_023135); coarser volcanic breccia and clay-ooze (2015_08_17_023220). Full resolution images in Section 9.13

3.4 Commentary by area and sub-area

This commentary seeks to inform the reader/worker about the combination of geological units that defines each area/sub-area. Note that these areas are not necessarily representative of the CCZ. They were selected (from data available at the time) by commercial developers as offering the best chance of hosting polymetallic nodules, in high abundances, and containing rich metal grades. Nonetheless, each of the seven mapped areas is distinctly different in terms of surface geology, and thus likely illustrate much of the geological variety present in the CCZ. The areas are described here from west to east and from north to south.

As mentioned prior at the start of this chapter, section 10.2 has 1:250,000 scale maps of all the area covered by MBES (Figure 3-57). At the start of each section below a simplified version of this map is presented (which with scaling and pagination, are at slightly smaller than 1:1,000,000 scale).

Eleven exploration contract sub-areas were completely or partially covered by MBES survey and these can be grouped into seven areas, namely: NORI A; NORI B + TOML B; TOML C; TOML D + E; Marawa 19 + 20; NORI C and TOML F + NORI D. Additional commentary is given on other sub-areas covered with more detailed data, namely TOML B1, TOML C1, TOML D1, TOML D2, TOML F1 and NORI D DSAO (Detailed Survey Area). These sub-areas are all shown in Figure 3-57.

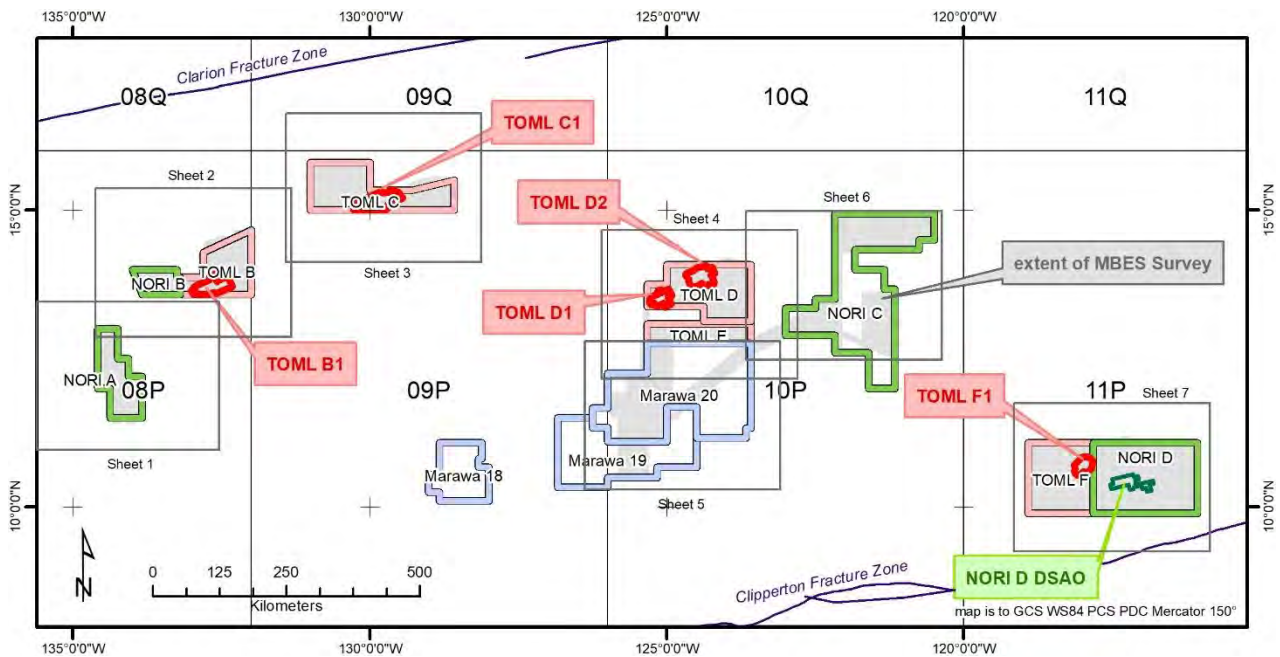


Figure 3-57: Sub-areas, MBES survey coverage and Map sheets (section 10.2)

Coded blocks are WGS84 UTM zones

3.4.1 NORI Area A

This area is covered by Sheet 1 in section 10.2 and a simplified map comprises Figure 3-58.

Like NORI B and TOML B this area was returned to the ISA by the Russian Pioneer contractor Yuzhmorgeologiya in 2001 (International Seabed Authority, 2020a) before being taken up by NORI in 2011. Like the other ex-Russian areas, historical sampling is fairly closely spaced compared to other returned areas (Figure 3-59). The underlying crust is 40 to 41 Ma in age (Mid Eocene; Figure 3-2), sediment thickness is poorly constrained but likely to often exceed 100 m based on the closest DSDP/ODP drill sites (located ~300 km to east and southwest).

Typical abyssal hills (5-10 km wavelength, 100 to 300 m amplitude; striking 345-350°) form the central-southern part of the area (Figure 3-17), and are distinctly different to a much flatter northern part (Figure 3-58). This change mostly correlates with a topographic break at about 4,820 mbsl (section 9.11.2). This flatter morphology extends into the adjacent exploration contract area held by Yuzhmorgeologiya (Melnik and Lygina, 2010) e.g, Figure 2-20.

The northern part of NORI A is the only part of the survey areas located on a regional geomorphic rise (Eastern Rise per Chapter 2), the only other MBES data on the rises is from ship-tracks, and these often indicate that abyssal hills are poorly formed or absent. While the Line Islands and Cooper Rises clearly include abundant volcanic knolls, seamounts and massifs, it would be interesting to learn if the more subtle, often sediment covered, pancake type knolls in northern NORI A were to be more widespread on Eastern and Central rises.

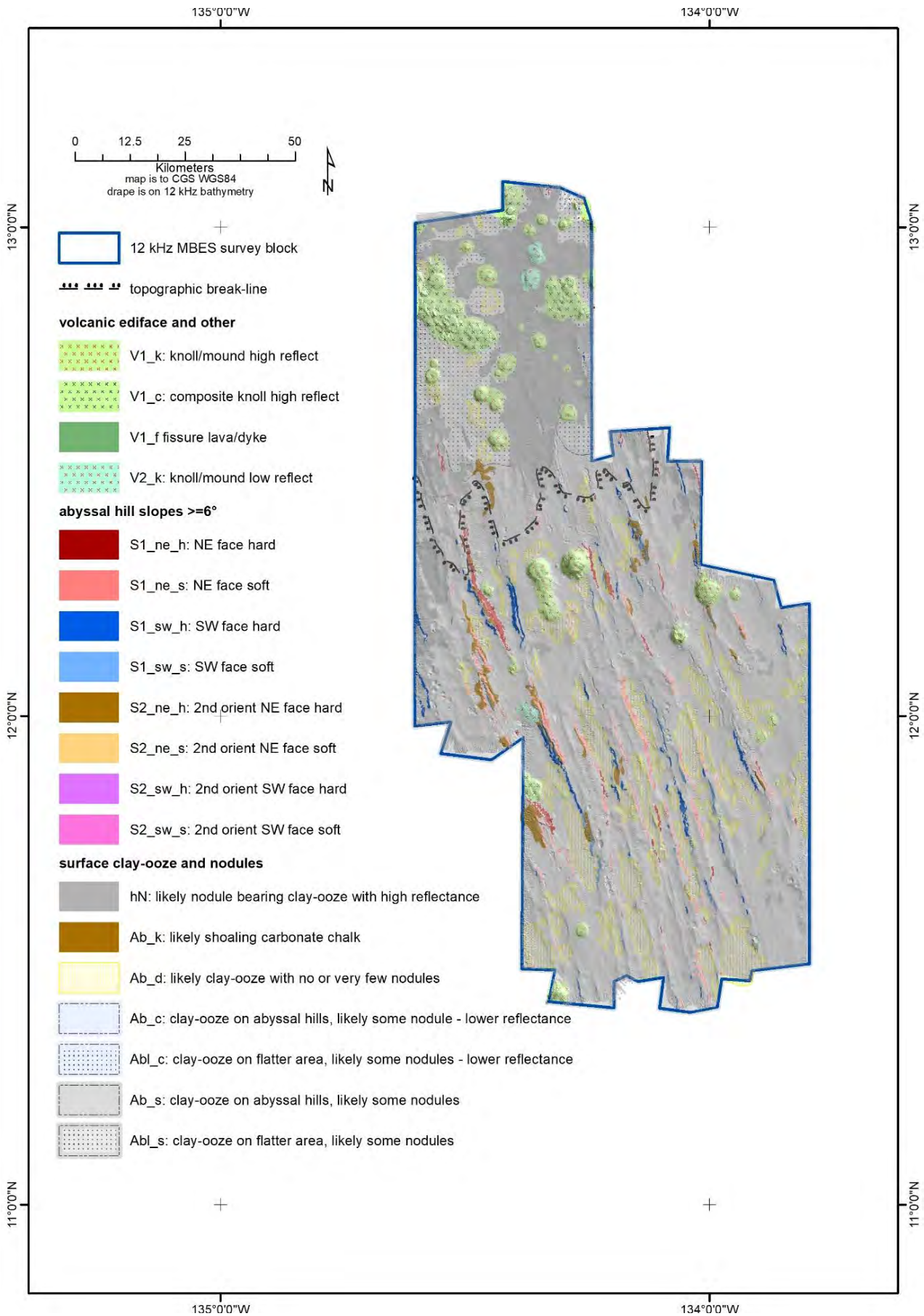


Figure 3-58: Simplified and draped surface geology map - NORI A

As noted above, the northern part of NORI A corresponds with the SE tip of Eastern Rise (Section 2.4.2.2). This area is unusual in that there are no abyssal hills and valleys to speak of and small irregular volcanic edifices are common. Within the relatively restricted survey area of this part, the volcanic knolls do not seem to align, and this may be because they are associated with a rise rather than a low as seen elsewhere (e.g. TOML B, C NORI C, D). There is also sediment cover on some of the knolls indicating that they are very old (Figure 3-59). This includes thick clay ooze on pancake knolls in the north and carbonate on knolls in the centre and south.

The northern part of NORI A also has extensive unit hN. In this part, the reflectance is atypically high i.e., often only -20 to -23 dB and well within the range of volcanic units (Figure 3-6). The occurrence of abundant nodules is supported by historical sampling (Figure 3-59). A relationship between flatter areas and high backscatter related to nodules is supported by the fact that priority mining areas at TOML B1, TOML D2 TOML F1 and NORI DSAO are all located on such a setting.

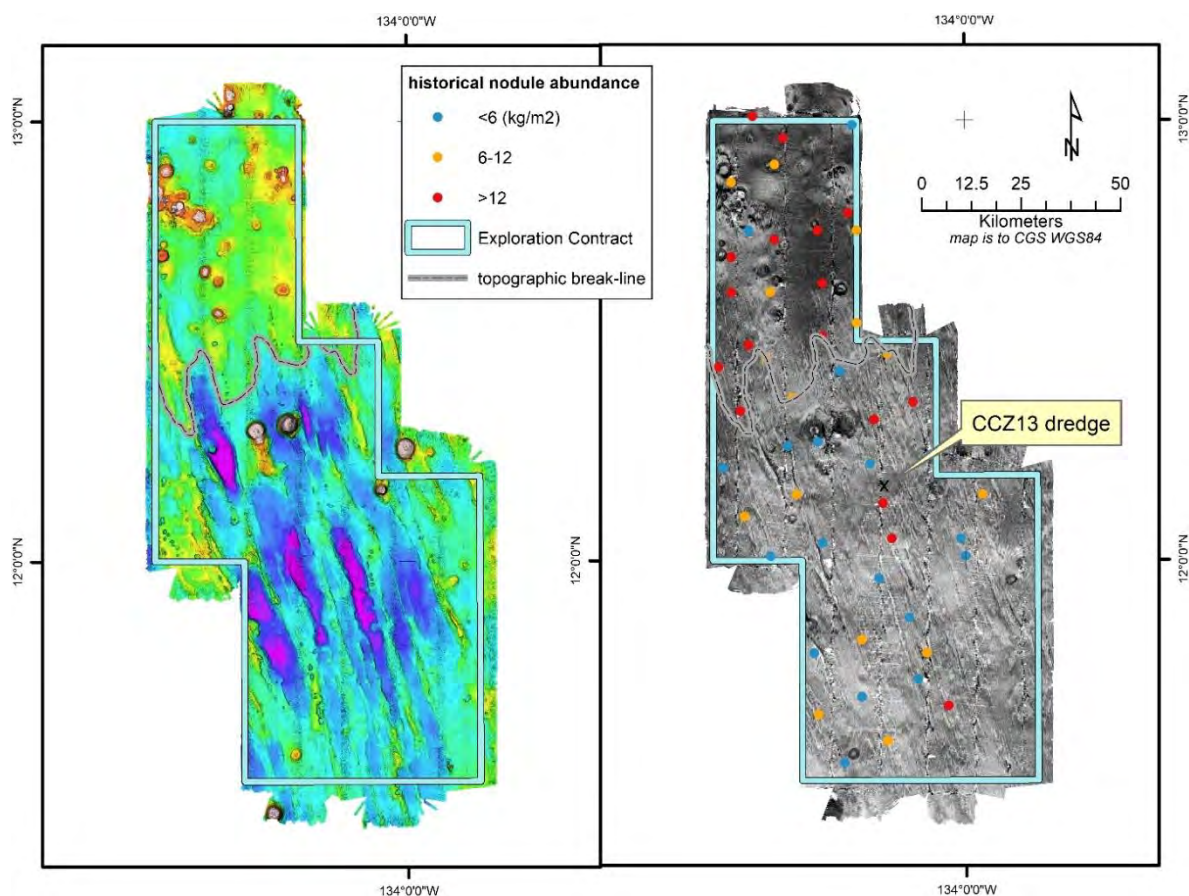


Figure 3-59: Other data on bathymetry and backscatter - NORI A

The southern part of NORI appears less prospective than the north, with extensive beds of likely low nodule coverage clay-ooze units (Ab_d) (Figure 3-58). Abyssal hills and valleys are oriented around 345°, are 2 to 10 km in wavelength and up to 300 m in amplitude. Unlike in the northern part, volcanic edifices in the central part of the area are aligned roughly NW to WNW.

Compared to the other survey areas, potholes are well developed in southern part of the area often forming chains along the abyssal hills in the south, developing into long narrow trough like features (Figure 3-23).

Historical sampling in the area (Figure 3-59) also shows that the northern parts have consistently higher abundances than in the south. Nodules collected by dredge (from a high backscatter reflectance area) in the central part of the area during the CCZ13 expedition (Figure 3-59) were very large (>10 cm across, Figure 3-60).



Figure 3-60: Very large nodules from a CCZ13 Dredge in NORI A

3.4.2 NORI Area B and TOML Area B

This area is covered by Sheet 2 in section 10.2 and a simplified map comprises Figure 3-61.

NORI Area B and TOML Area B are adjacent and so are considered together here. These are both Russian returned areas in the central part of the CCZ (International Seabed Authority, 2020a). TOML took up the exploration contract that includes Area B in 2012. The underlying crust is between 38 and 40 Ma in age (Mid Eocene; Figure 3-2). Sediment thickness from SBP profiles in western TOML have on average about 9 m of clay ooze over at least 100 m of chalk (Figure 3-2), although the clay-ooze thickness varies from absent to over 30 m (Table 3-11).

Abyssal hills generally strike to 350°, except for a secondary set to ~010° in western TOML B that extend from the Russian contract area located immediately to the south. The portion of TOML B located within Hotel Low appears to have generally higher and broader hills (5-10 km wavelength, 200-300 m amplitude) than areas to the west (e.g. NORI B with 1-5 km wavelength 100 m amplitude; Figure 3-17). There is a topographic break at about 4,990 mbsl, between the north-eastern parts of TOML B and the south-west corner of TOML B+ NORI B (section 10.2; Figure 3-61; section 9.11.2).

In the northern part of TOML Area B, there is an unusual line of irregular volcanic knolls and composite knolls (Figure 3-61). These are V2 type units with relatively moderate backscatter values compared to normal volcanic knolls (Figure 3-62). The volcanoes are probably covered with thin sediment as historical samples from the area often show fairly good nodule abundances (Figure 3-63), but low Ni, Cu and Mn grades and high Co grades indicate a more significant hydrogenetic component in their formation. This is a signature atypical of the central-eastern CCZ, and certainly within the other contract areas studied here. These nodules are of distinctly different chemistry to other lower Ni grade nodules from within the TOML B1 sub-area (i.e., box-cores CCZ15-B08, 12, 13, and 17) which all also have low Co, but elevated elements associated with volcanogenic or carbonate components (section 4.5.2.4).

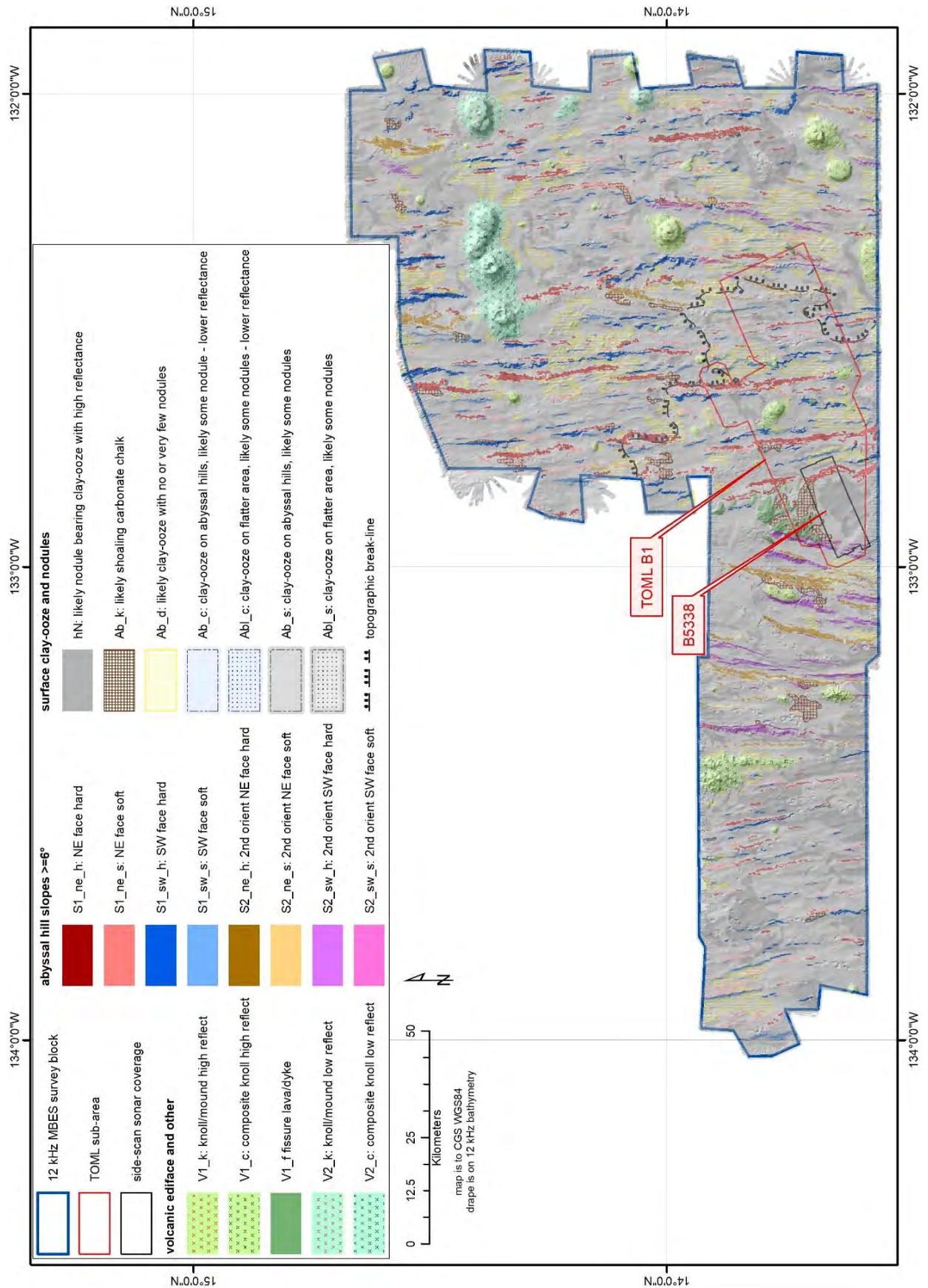


Figure 3-61: Simplified and draped surface geology map – NORI B and TOML B

Higher reflectance nodule bearing units are found in both contract areas but are proportionally higher in NORI B (Figure 3-61). TOML B, and to a lesser extent NORI B, have distinctive sediment drifts. Shoaling carbonates are interpreted to be relatively common in both areas especially in association with the secondary abyssal hills (Figure 3-63). Both areas were dredged once each as part of the CCZ13 expedition.

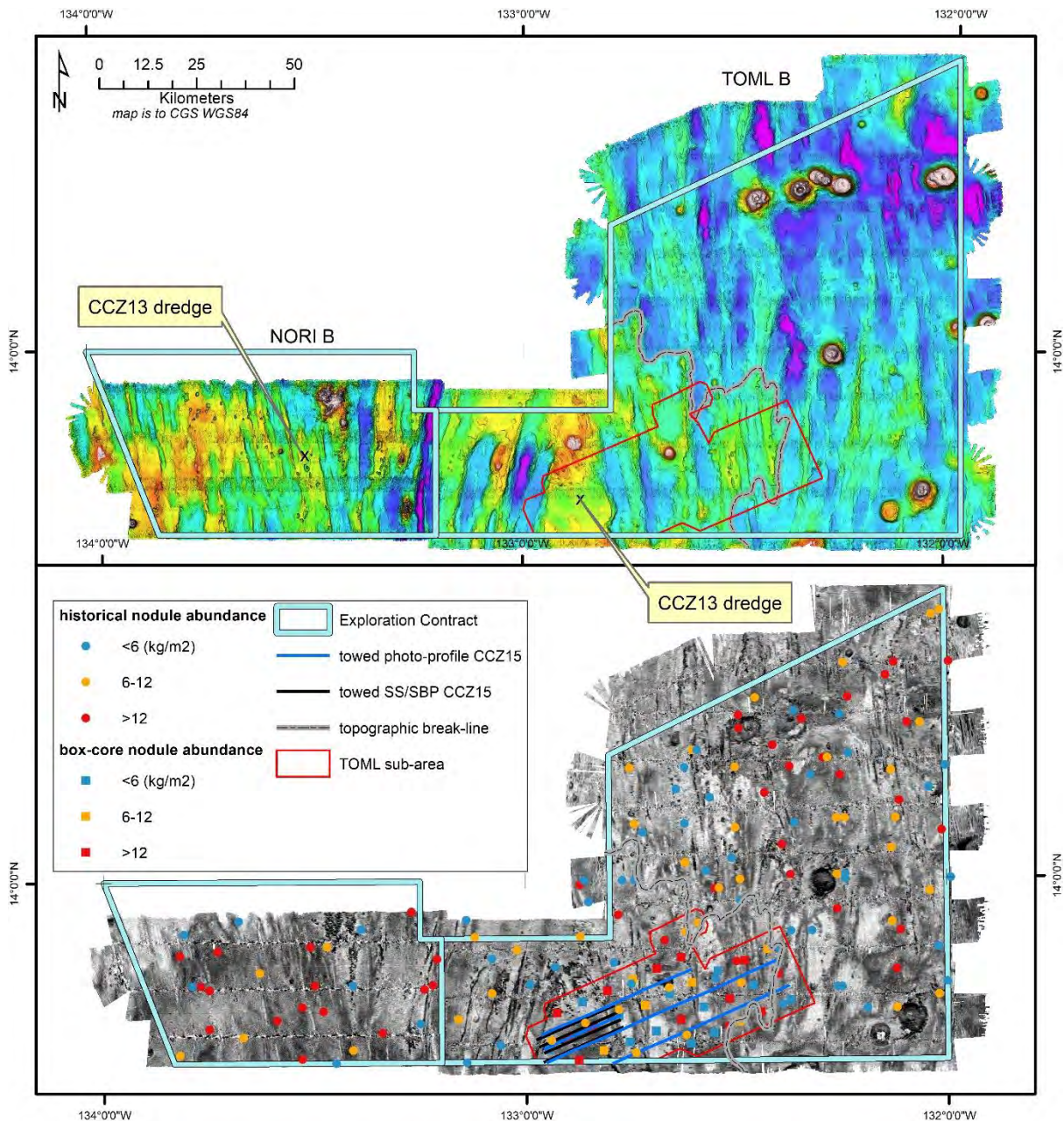


Figure 3-62: Other data on bathymetry and backscatter - NORI Area B and TOML Area B

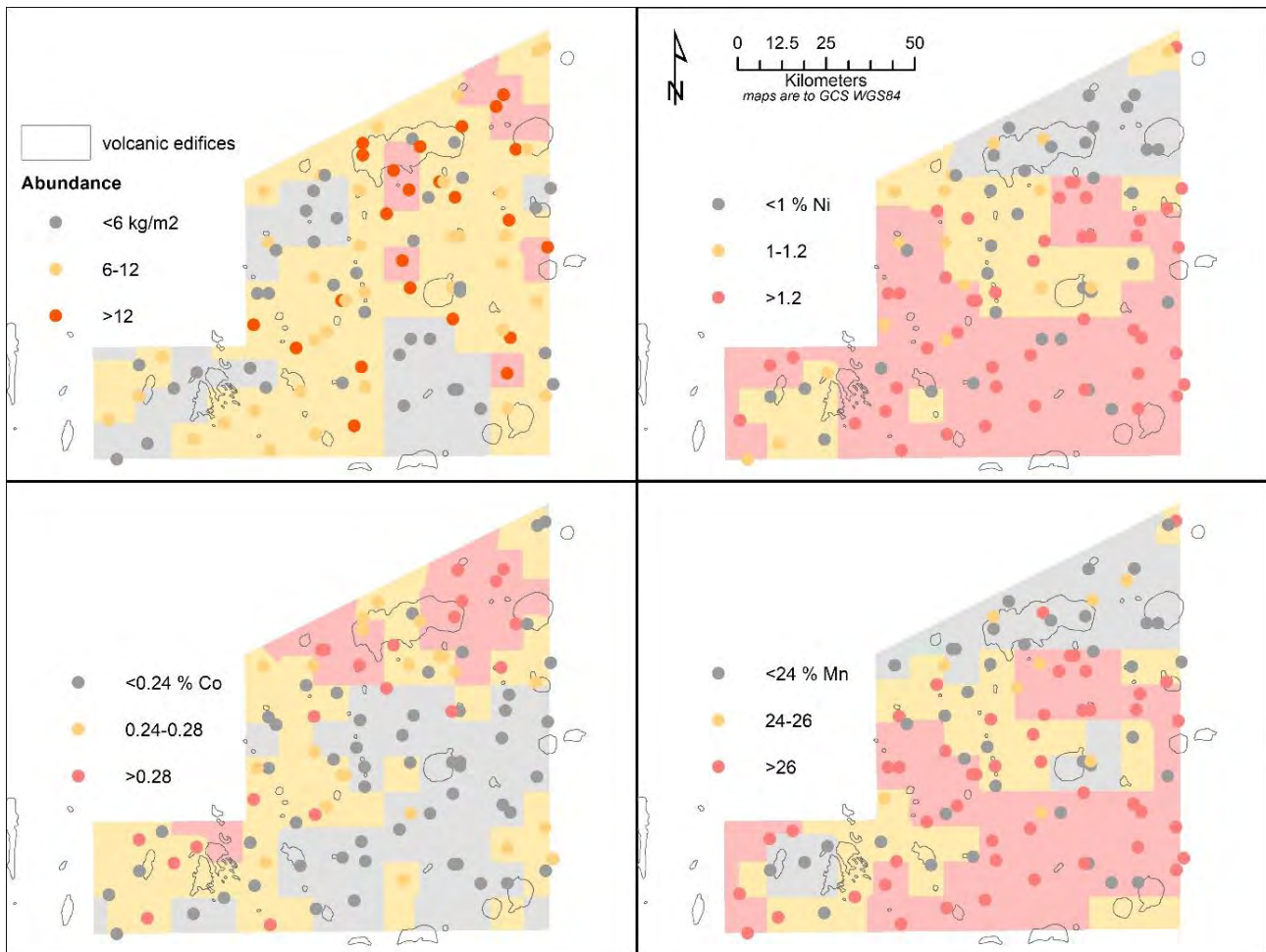


Figure 3-63: Grade trend in historical samples – TOML Area B

Background is 2013 Mineral Resource block grades matched by hue to samples (Nimmo et al., 2013)

3.4.3 TOML Area B1 and B5338

TOML area B1 is a 1,620 km² sub area within TOML area B (Figure 3-62) that was explored in 2015 sufficient to allow the definition of an indicated mineral resource (Lipton, Nimmo and Parianos, 2016; Chapter 5). This work included box-cores, and photo-profiles. Like most of the other TOML sub-areas, this area was selected for exploration from a combination of bathymetric (few volcanic edifices and some broader abyssal hills); backscatter (common high reflectance areas which have an improved chance for having high abundances of nodules) and historical sampling data (high grades and abundances).

B5338 is a ~150 km² 'field' at the western end of B1, that was explored sufficient to allow for the definition of a measured mineral resource as well as to allow for more detailed estimation of some modifying factors for a mineral reserve. This work added an additional photo-profile and side-scan sonar/sub-bottom profiling sonar (Figure 3-61, and Sheet 8 and Profiles 1-4 in section 10.3). The name B5338 relates to the combination of TOML area B and the minutes of longitude and latitude at the centre of the field. Such a naming convention (as used in some operations on land) is extendable and internally scalable, is but not known to been adopted by other workers in the CCZ.

The central part of B1 comprises wide abyssal hills (5 to 10 km wavelength, 200 to 300 m amplitude) with discrete sediment drifts in the valleys and along the western sides of the hills (Figure 3-39; Figure 3-62). This

indicates a component of local east to west clay-ooze transport from seabed currents, although evidence for lateral currents long the hills also exists (section 4.3.1.3). There is a small seamount on the northern side of the area (B4046) described in detail in section 3.3.4.1. In the eastern part of B1, the abyssal hills are of shorter wavelength (~5 km) and sediment drifts are absent. This is up to a topographic break, they are then found further east again (Figure 3-62).

Within B1, nodules are generally of the rough-smooth type (section 4.3.1.2) in a range of sizes; less common are minor amounts of rough nodules within the sediment drifts and some smooth types on hard substrates. Mixed sizes are relatively common here with 5 out of the 30 box-cores collected during the CCZ15 expedition returning mixed size nodules. The area's average abundance of 14.3 wet kg/m² (for samples >6 kg/m²), is quite good compared to other areas (the 2013 NI43-101 inferred mineral resource estimate for the TOML areas has an average abundance of 9.4 kg/m² (Nimmo et al., 2013).

B5338 is in effect a very wide (~15 km) abyssal 'hill', with abyssal valleys east and west but bracketed with complex hills to the north and south (Figure 3-62, Figure 3-64, Figure 3-65). The complex to the south is unmapped but the one to the north (B5347) is clearly a large composite volcanic knoll that has been recently active. This includes intrusion of several dykes into/onto the sediments in the area. B5338 is bound to the east by a fairly conventional normal fault escarpment striking to 350° (or 170° using British right hand strike convention), but the western side comprises a series of echelon fault scarps striking to 020° to 030° for an overall strike closer to 010°. This is part of a locally common secondary abyssal hill strike (Figure 3-61).

Sub-bottom profiles show that the area has over 90 m of chalk with variable clay-ooze cover (up to 20 m thick; Figure 3-66). Carbonate strata breccias are common in the sub-bottom profiles extending up to 3 km along the section. Most of the clay ooze is smooth and homogenous with changes in the side-scan relating to nodule cover (Figure 3-64). There are however a range of surficial features that can be correlated with information from sub-bottom profile and/or photo-profiles. This includes a breaching dyke, incipient and more developed potholes (the later in the area being small and related to underlying dykes), and dome structures in the chalk sequence affecting the clay-ooze. There are also local slumps and development of some ripples (scale of metres to tens of metres). At the northern end of the side-scan coverage in B5338, the clay-ooze thins and chalk starts to outcrop in small patches, especially on the eastern side.

The dykes and a sill located in the valley to the east of B5338 area described in detail in sub-section 3.3.4.3.

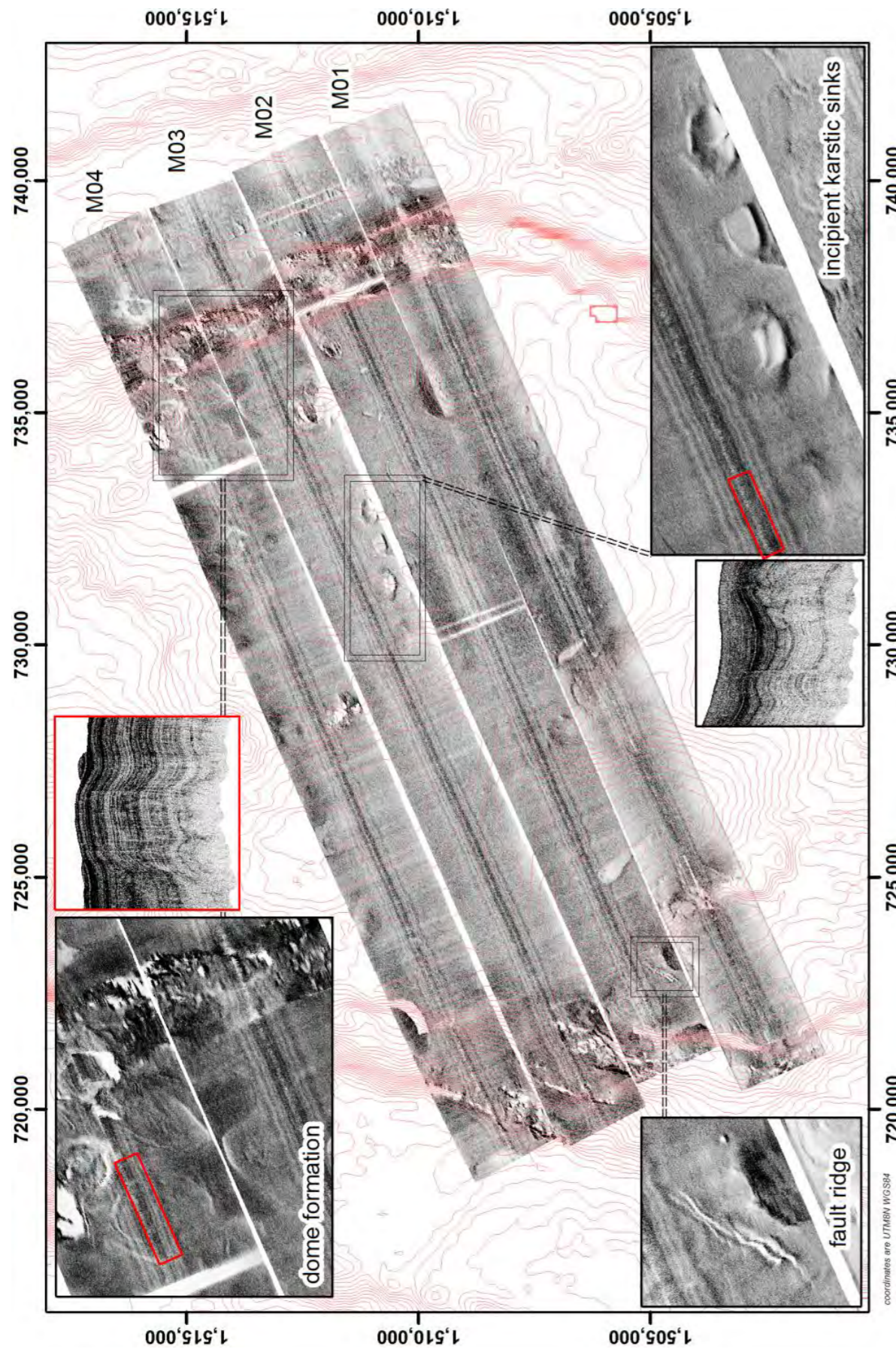


Figure 3-64: MAK side-scan in B5338, Area B1

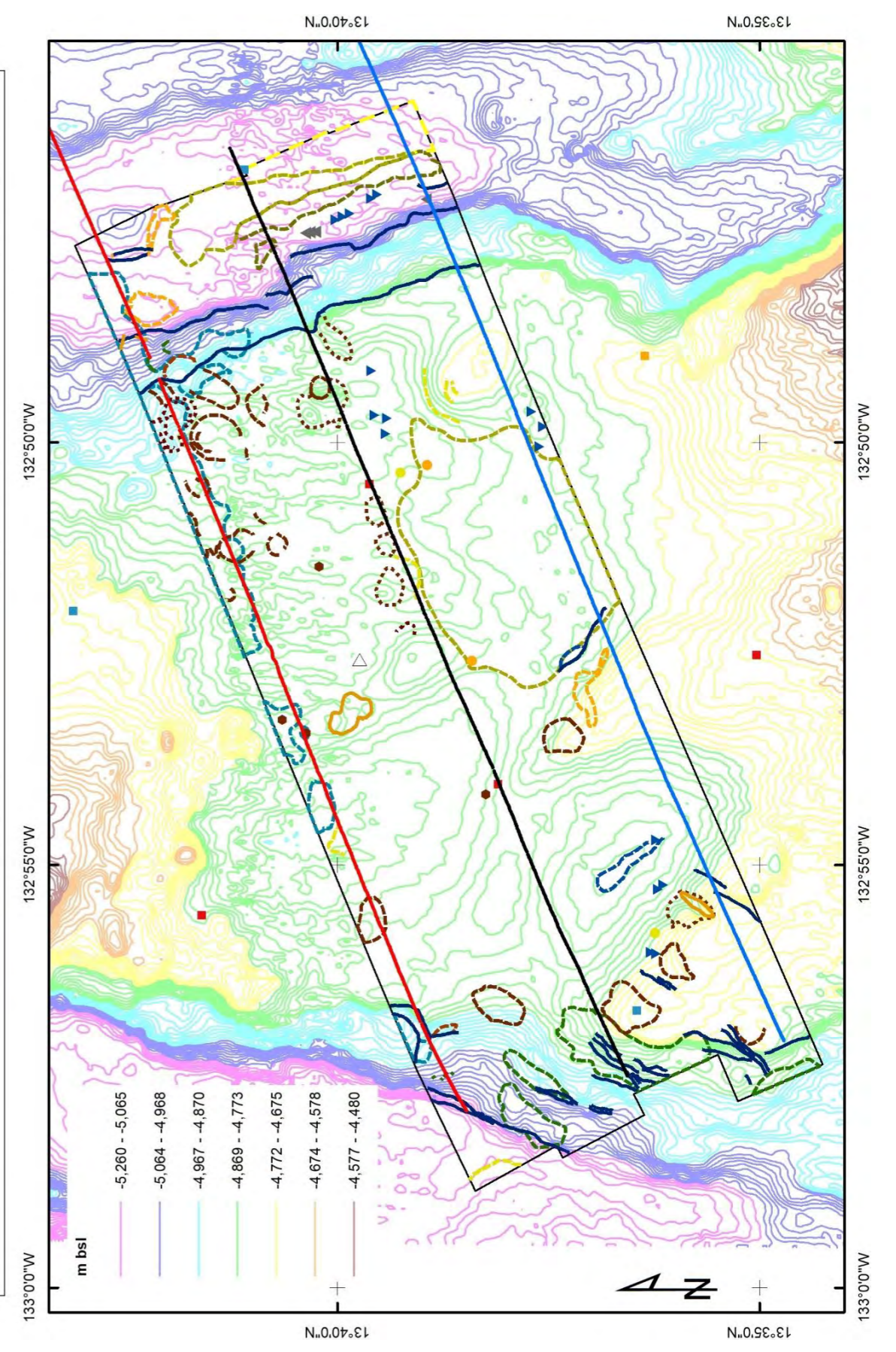
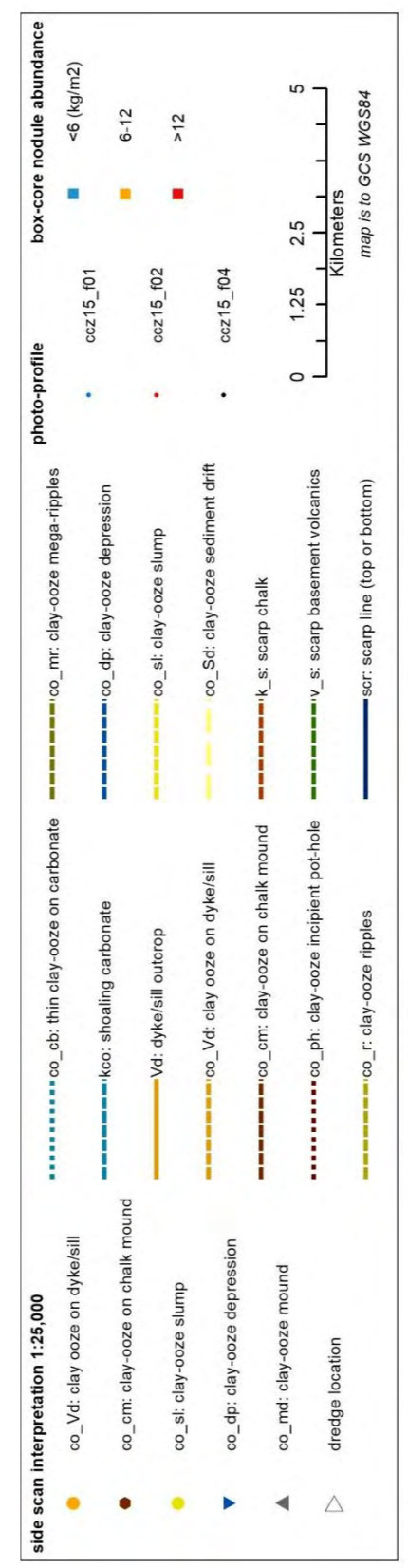


Figure 3-65: Side-scan interpretation B5338, TOML B1

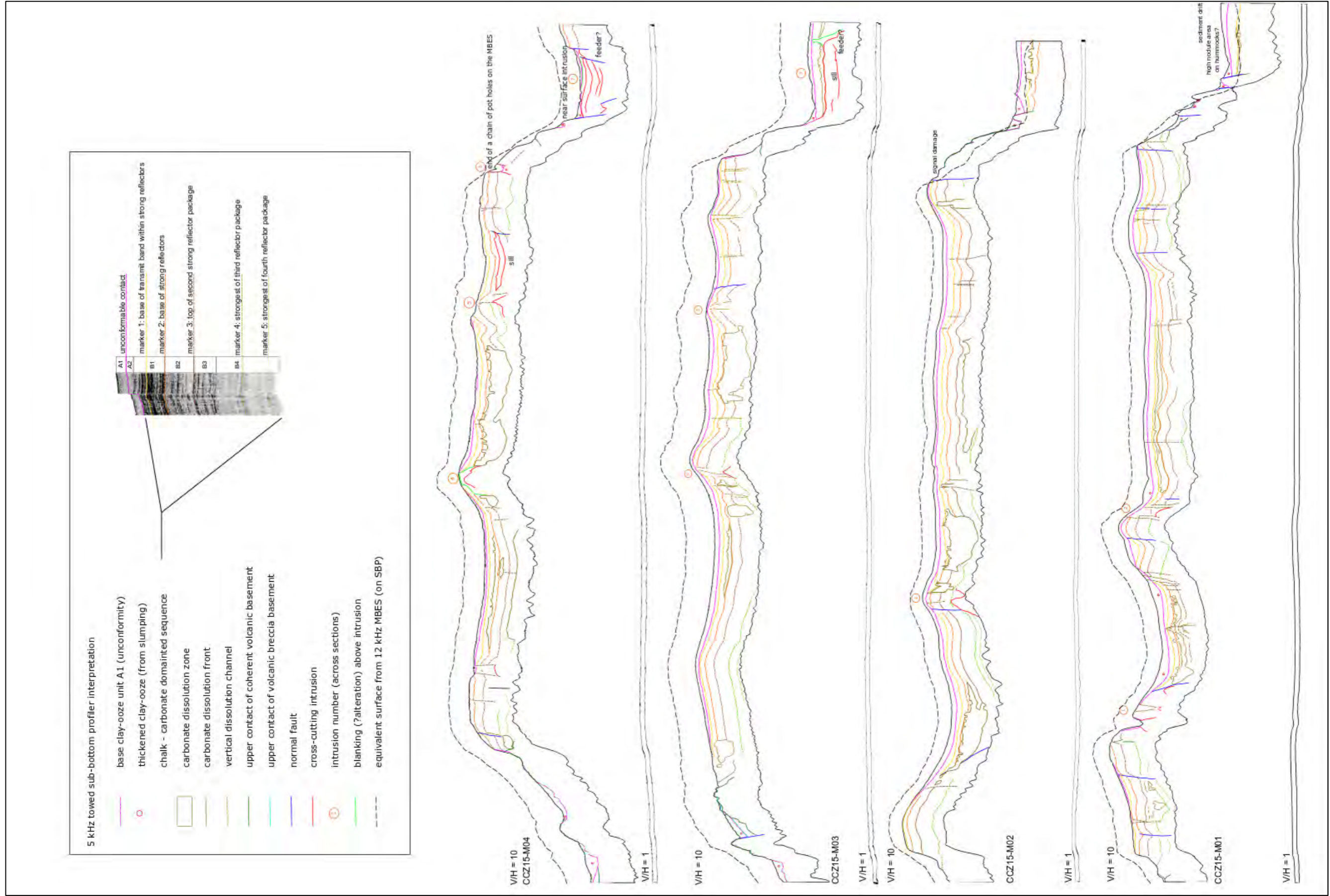


Figure 3-66: SBP in B5338 (TOML B1) refer to section 10.3 for detailed SBP sectional interpretation

3.4.4 TOML Area C

This area is covered by Sheet 3 in section 10.2 and a simplified map comprises Figure 3-67.

TOML Area C is located near the central part of the CCZ, and is the northernmost block mapped here (latitude $\sim 15^{\circ} 30' N$). Its NW corner is 200 km from the Clarion Fracture Zone (Figure 3-57). It was an exploration area of the French pioneer contractor Ifremer, before return to the ISA in 2001 (International Seabed Authority, 2020a). Ifremer retained the area immediately to the south. The underlying crust is between 33.5 and 36 Ma in age (Late Eocene; Figure 3-2).

The western part of the area, located in Hotel Low, is distinct from the eastern – central part, located in India Plain (Figure 3-67, Figure 3-68). While the central-eastern part is comprised of fairly regular abyssal hills (2-10 km wavelength for 100-150 m amplitude), the western part:

- is mostly a little deeper, with a distinct topographic break at about 4,970 mbsl (section 9.11.2) and a correlation with the eastern side of Hotel Low (section 2.4.3.4; Figure 3-68);
- has often wider and more pronounced abyssal hills (about 5-15 km wavelength and 150-300m amplitude; Figure 3-17), that can sometimes strike slightly more westerly ($\sim 330^{\circ}$ vs the more typical 350°) with some changes across the topographic break;
- includes many more volcanic edifices, in part associated with ENE to NE striking areas of subdued abyssal hills.
- includes common hilltop areas with low backscatter interpreted to be shoaling carbonate.

Potholes are common throughout Area C (Figure 3-67) and this may reflect a greater depth below the lysocline here than for many of the other areas. Areas with higher backscatter return (interpreted as high potential for nodule coverage; hN), are uncommon in Area C, with the best such area being along the southern edge, along with a small area on the eastern side (Area C1). This is reflected in generally lower nodule abundances compared to many of the other mapped areas (Chapters 4, 5).

Figure 3-68 compares the total area of sub 5,000 m bathymetry collected by 12 kHz MBES with equivalent depth contours from the 2014 GEBCO dataset. Given the extremely coarse resolution of the GEBCO data set (30 seconds), it corresponds remarkably well with the MBES depths.

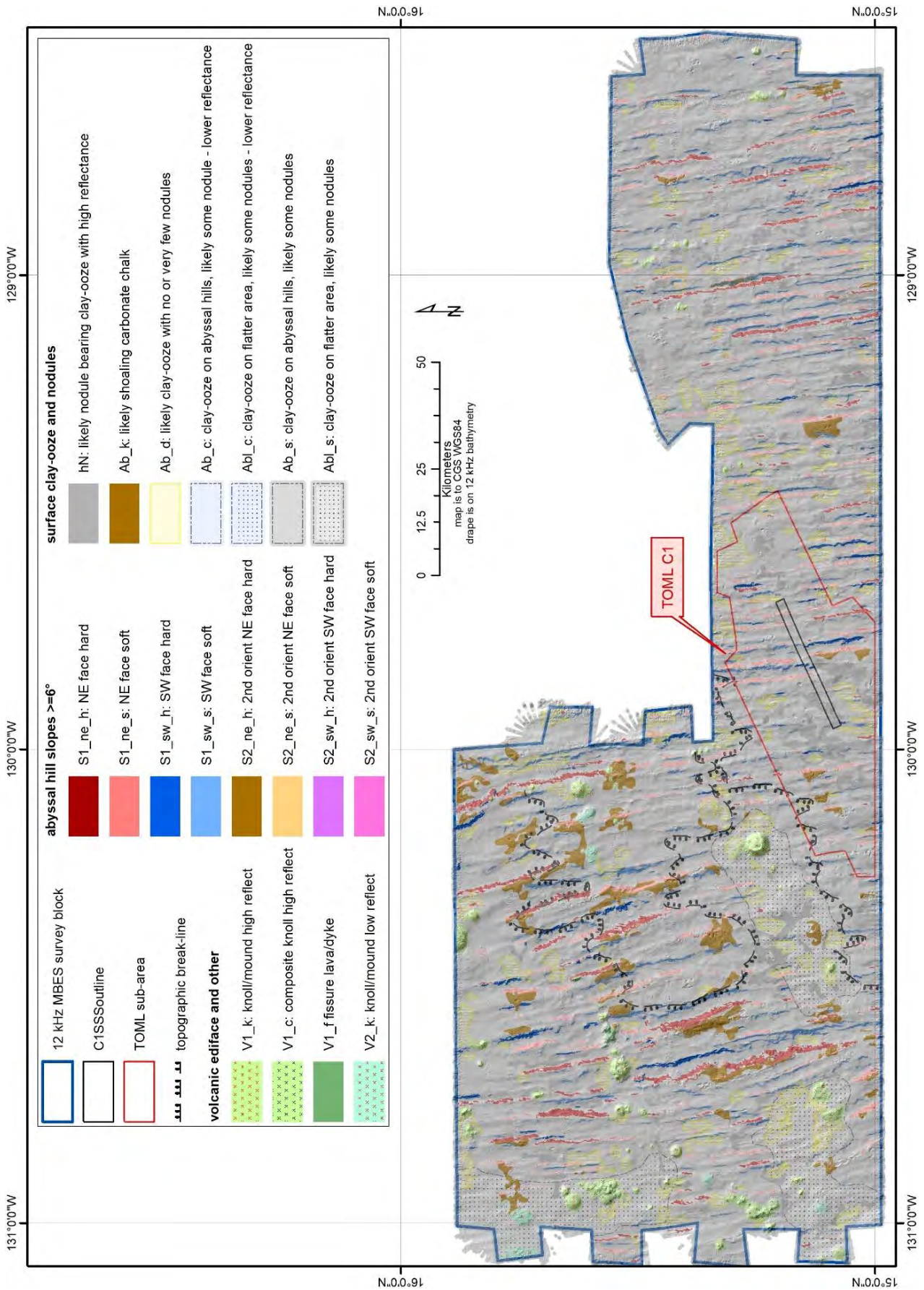


Figure 3-67: Simplified and draped surface geology map – TOML C

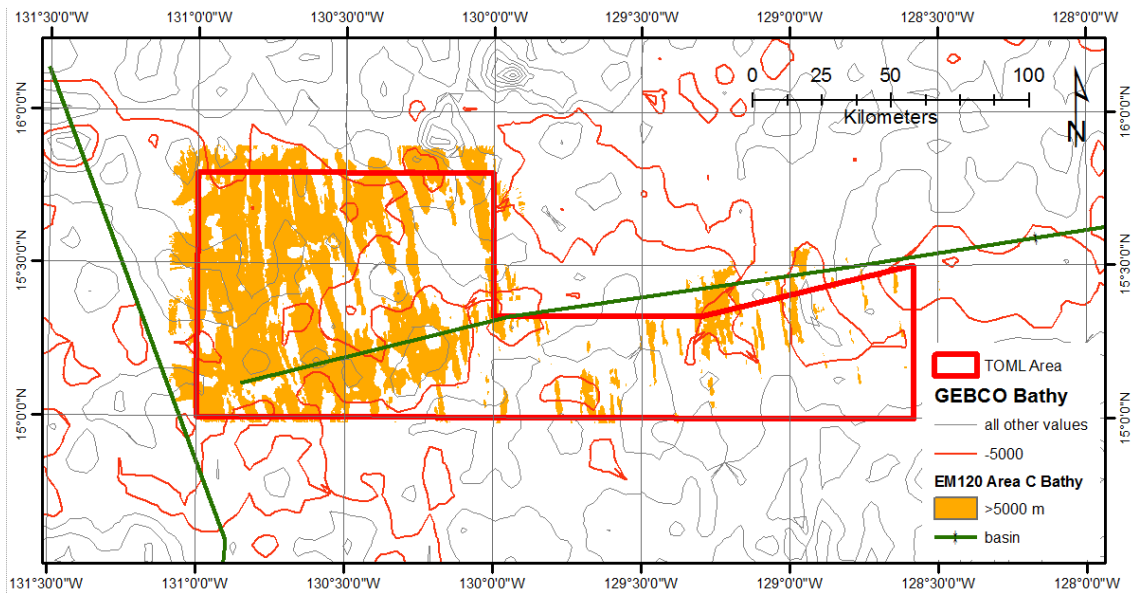


Figure 3-68: Comparison of Gebco and Bathymetry – TOML Area C

3.4.5 TOML Area C1

TOML area C1 is a 1,950 km² sub area within TOML area C (Figure 3-67) that was been explored in 2015 sufficient to allow the definition of an indicated mineral resource (Lipton, Nimmo and Parianos, 2016; Chapter 5). This work included box-cores and photo-profiles, and is partly covered by side-scan sonar (Figure 3-67) and sub-bottom profile per Sheet 8 and Profile 5 in sections 10.2 and 10.3. Like most of the other TOML sub-areas, this area was selected for exploration from a combination of backscatter (some high reflectance areas which have an improved chance for having high abundances of nodules) and historical sampling data (high grades and abundances).

A single line of side-scan sonar/sub-bottom profiling (CCZ15-M05B) was run along the CCZ15-F05 photo-profile. SSS/SBP line CCZ15-M05 was aborted due to technical issues shortly after deployment and the entire line re-done as CCZ15-M05B. Rather than mapping the area in detail as was done in Area B5338, the objective with the SSS/SBP was to characterise the area and try to extrapolate any relationships into the MBES survey data.

TOML C1 generally comprises abyssal hills (2 to 5 km wavelength, 100 to 200 m amplitude). However, at its western side there are areas up to 15 km across with only gently undulating hills (50-70 m elevation change over 1 – 2 km). There are no mapped volcanic edifices within C1. Sediment thickness from the SBP profile indicates mostly consistent 10-15m of clay ooze over about 80 m of chalk (Figure 3-2; Figure 3-69). The clay-ooze thickens in the valleys and can thin to only a few m on the steeper slopes. Carbonate strata breccias are less common than in B5338, but nonetheless are present in most valleys crossed by the SBP (Figure 3-69). The CSBs can be up to 50 m thick and up to 300 m wide. The MBES indicates common potholes in the area although none were crossed with the photo-profiles or SBP/SSS. Discrete sediment drifts are only found in the south and far east (Figure 3-67), although the seabed photo-profiles find smaller patches of nodule free sediment (Figure 3-69).

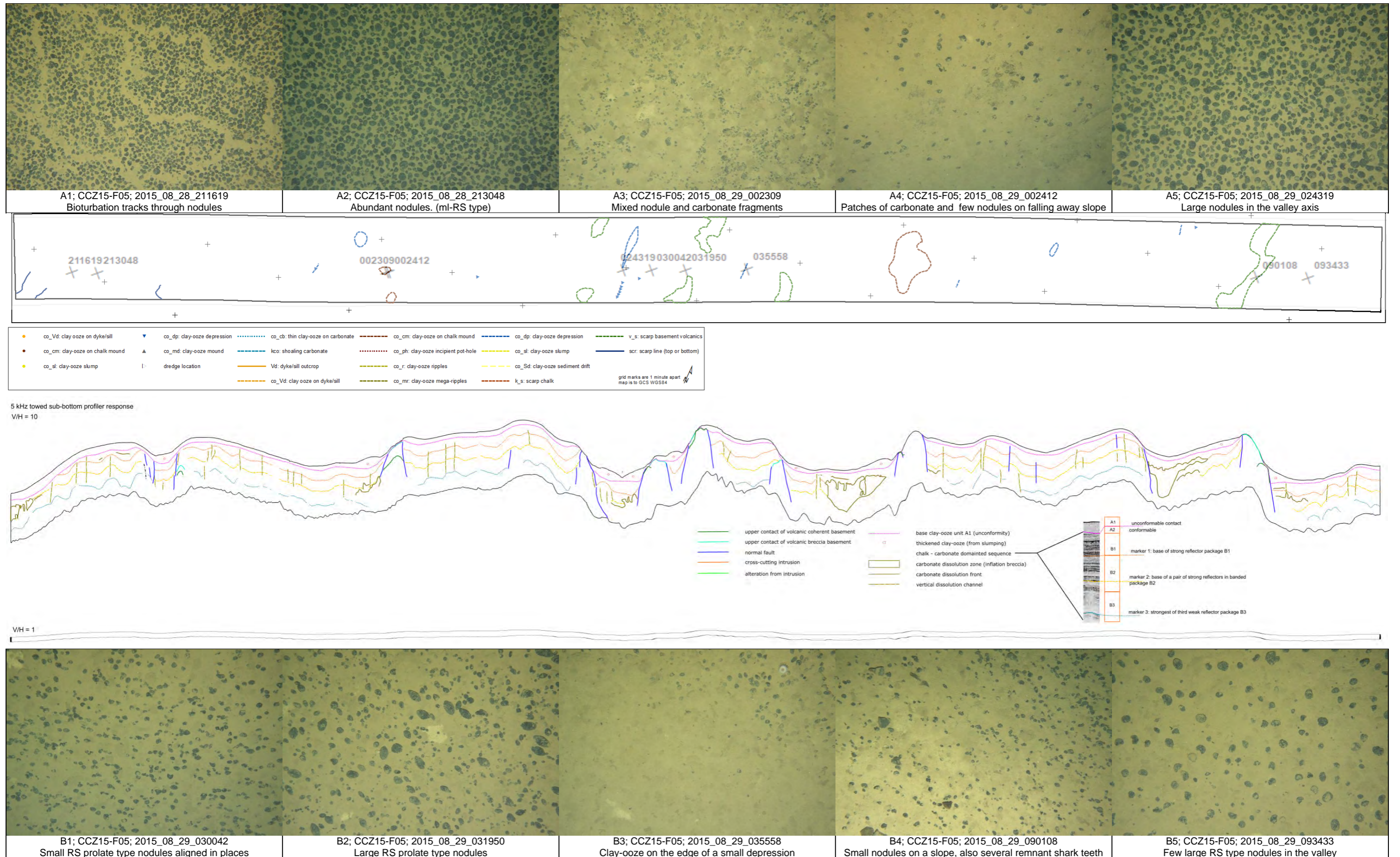


Figure 3-69: Side-scan and SBP interpretation CCZ15-M05B

All photos are 2.4 x 1.6 m in view. Full resolution images in Section 9.13

Nodules are generally, consistently medium to large smooth-rough type (ml-SR). TOML C1 abundances average, 11.4 kg/m² (for samples >6 kg/m²), which is generally lower than the other sub-areas, although still higher than the overall TOML NI43-101 mineral resource.

3.4.6 TOML Areas D and E

This area is covered by Sheet 4 in section 10.2 and a simplified map comprises Figure 3-70.

TOML Areas D and E are effectively adjacent and so are considered together here. Area D was explored and then returned by the Japanese government research group DORD in 2001 and Area E was explored by the government of the Republic of Korea, and also returned in 2001. The underlying crust is between 27 and 29 Ma in age (Oligocene; Figure 3-2).

Abyssal hills occur through the area are generally 5-10 km wavelength, 100 to 300 m amplitude and strike 350-360°. Deeper valley-“troughs” (~400 m amplitude) are found in several places. There is a small area of secondary slopes in the centre-eastern part of the area near the tectono-volcanic features within north-eastern Marawa 19.20 and south-western NORI C. A broad 20 km wide ‘plateau’ comprises the TOML D2 area (see below), part of a generally higher area within the north and eastern parts of TOML D above 4,550 mbsl (section 9.11.2).

Volcanic edifices such as knolls and fissure lavas are found throughout the area, but are most common on the eastern side of the area. Located in the northeast is the only true seamount within the TOML areas. Informally named Mt Mo during the 2013 expedition (identification code is KW-16121 per Kim and Wessel (2011)), it appears to be composed entirely of lava and rises almost 2000 m above the seafloor with slopes often reaching 20° and in some places 30°. The seamount is located within a topographic low with subdued abyssal hills, that can be seen extending to the WSW (i.e. Juliatt Low in section 2.4.3.6).

SBP profiles from TOML D1 and D2 (sections 3.4.7, 3.4.8) show ~80 m of chalk overlying the basement basalts, but the thickness of uppermost clay-ooze varies widely. Both TOML D and E have some very well-defined sediment drifts within some of the abyssal valleys, with an indication in TOML D that stripping of clay-ooze from higher ground around the TOML D2 sub-area may have been re-deposited at lower ground located to the south. Potholes are also common away from the higher ground.

Higher than normal re-deposition of sediment may also be supported by the fact that the nodules in TOML D1 and D2 have much higher rates of cover (Figure 3.36 - Figure 3.38) than any of the other TOML and NORI areas that have so far been photographed (i.e., TOML B1, C1, F, NORI D). This implies greater influence of currents which may in turn have significant environmental implications (e.g. faunal assemblages better suited to recruitment in a relatively high natural re-sedimentation regime that might be closer to expected conditions near an future mining operations).

Despite the higher rate of sediment cover, TOML D has relatively extensive areas of high backscatter reflectance, indicating that it generally has more (or larger) nodules than TOML E.



Figure 3-70: Simplified and draped surface geology map – TOML D,E

3.4.7 TOML Area D1

This 850 km² area is partly covered by side-scan sonar (Figure 3-70) and a sub-bottom profile per Sheet 9 and Profile 9 in section 10.3. It was selected as a priority area based on high backscatter reflectance and was explored in the CCZ15 cruise sufficient to define an indicated mineral resource ((Lipton *et al.*, 2016); Chapter 5). As at Area C1, a single link of deep-tow sonar was completed to help to characterise the area (Figure 3-71).

The area has clearly defined abyssal hills striking 350-355° with 5-10 km wavelengths and 100 to 150 m amplitudes. On the western side a ~ 12 km wide divergent horst relay defines a flatter area. Escarpment exposure of both basement basalt and carbonate is found in some cases, but generally clay-ooze cover of slopes is the norm.

Surface exposure of volcanic edifices are restricted to one knoll, distinguished from the MBES, but there is a swarm of small dykes at the western end of SBP line M09 and several sills in the centre of the line that stooped out the host carbonates for over 2 km (Figure 3-71).

Sediment thickness from SBP profiles, in the western part of the TOML D area, contain on average about 4-5 m of clay ooze over about 80 m of chalk (Figure 3-2), although the clay-ooze thickness varies up to over 20 m (Table 3-11). The carbonate sub-strata show numerous flexures and faults on the scale of m to 10s of m. Vertical features hint at either dykes or fluid alteration/dissolution up to 10 m across. Outcrop is found at horst margins (cliffs to 80 m) and sometimes on flat surfaces of hills. Karstic sinkholes are uncommon in this area, but are found elsewhere in Area D.

The clay-ooze in the west displays distinctive, complex, and hummocky “mega-ripples”, which are tens of metres in wavelength and hundreds of m to km in strike. From the photo-profiles, nodules on these ripples look similar to those elsewhere in the area (Table 3-14). Subarea D1 was delineated to try and avoid the sediment drifts located in the vicinity, but there are several smaller mapped units in the north of the subarea.

Nodules are generally medium to large smooth-rough type (ml-SR), although other types exist (e.g. Table 3-14), abundances average 16.2 kg/m² (for samples >6 kg/m²) which is very good compared to the other areas and the published mineral resource (Lipton *et al.*, 2016).

Diagenetic crusts are present (e.g. Table 3-14), as also found in TOML D2, and as also collected in three dredge samples elsewhere in TOML D in 2013 and TOML A in 2015 (sections 4.3.3, 4.5.2.6).

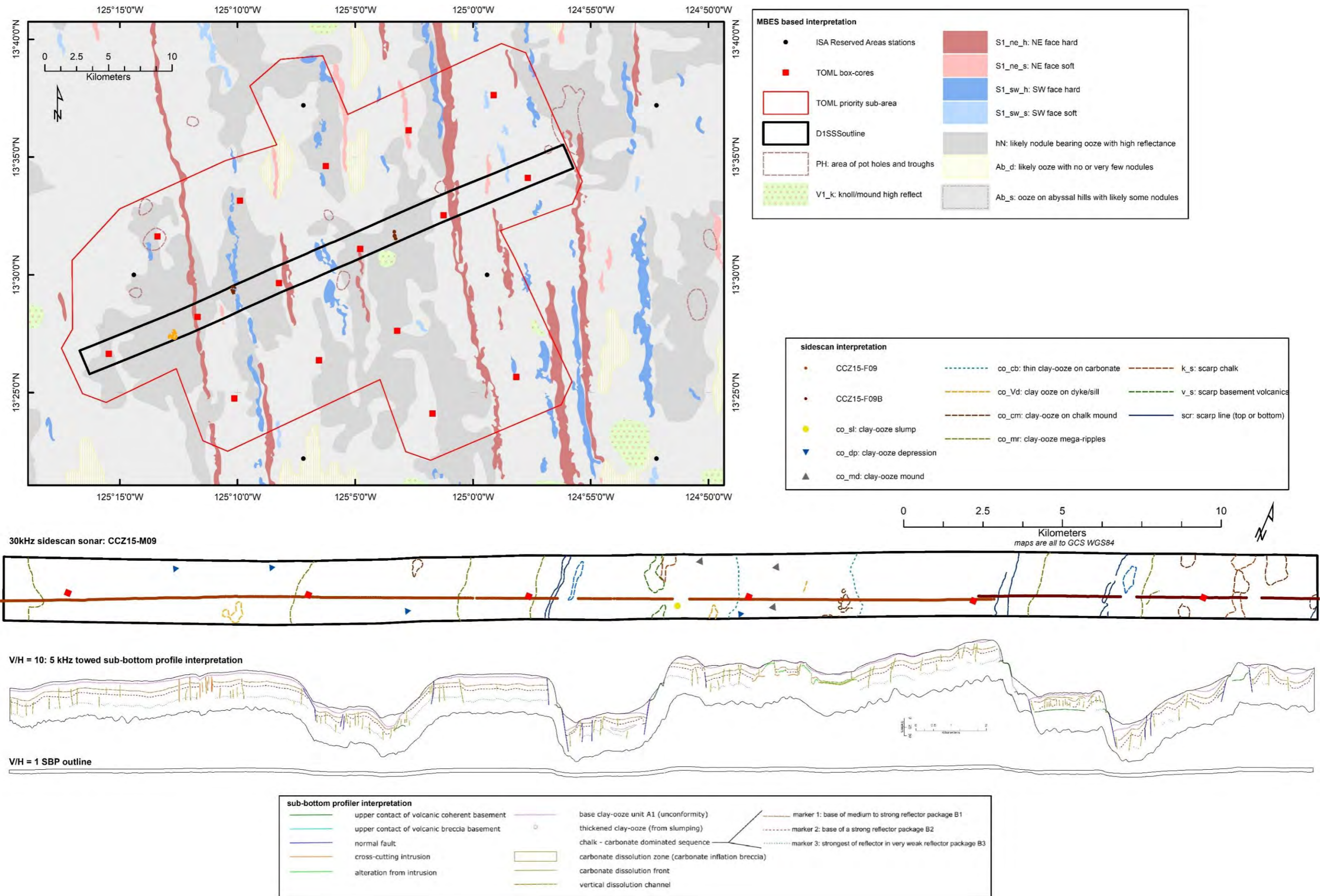


Figure 3-71: TOML Sub-area D1 summary

Table 3-14: Example seabed photographs from TOML D1 and TOML D2

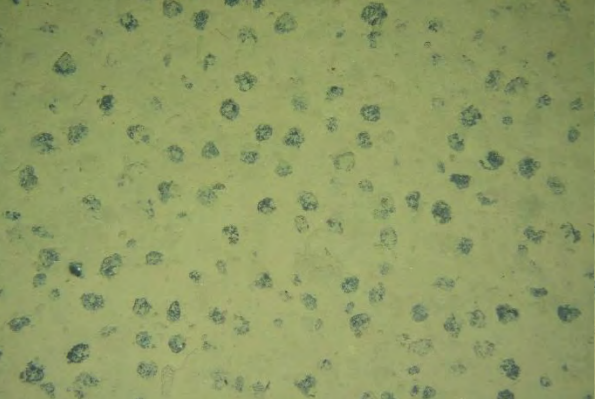
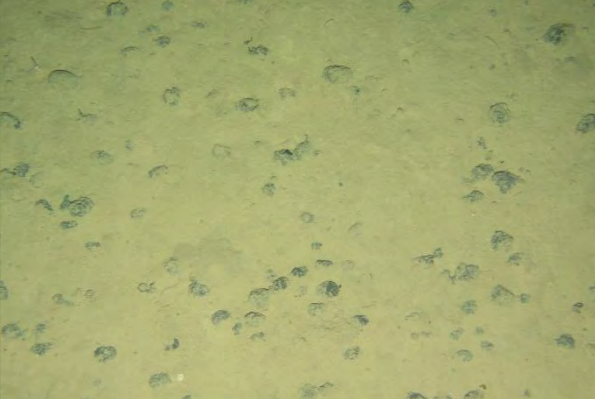
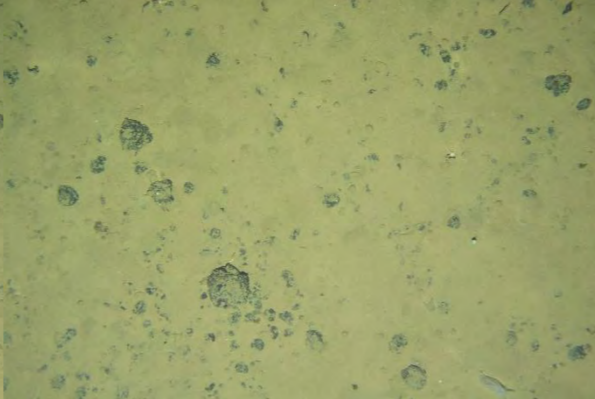
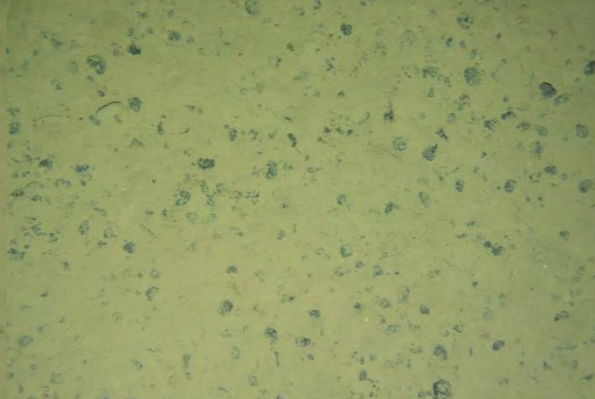

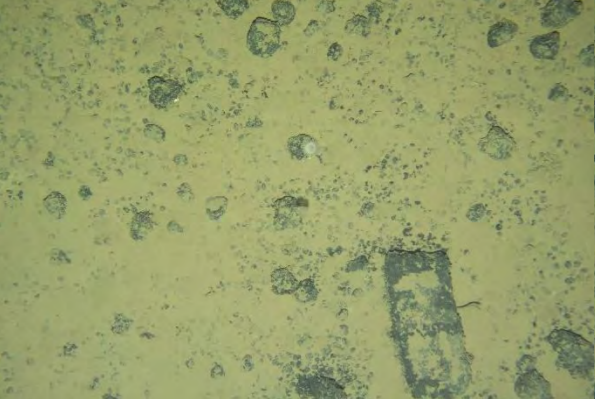
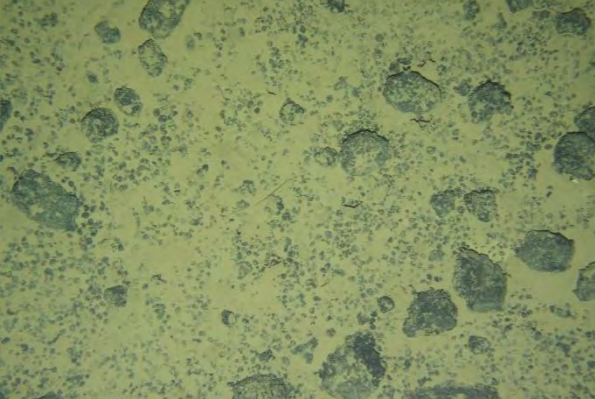
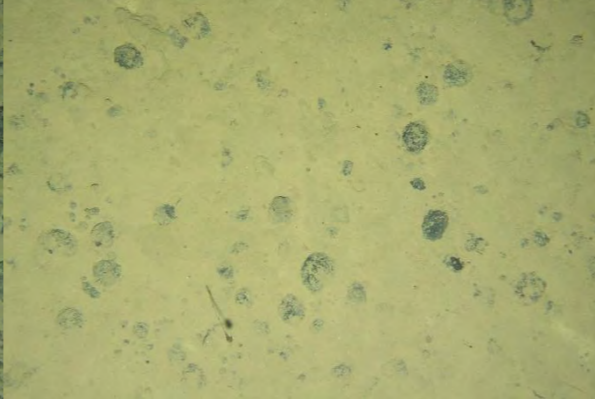
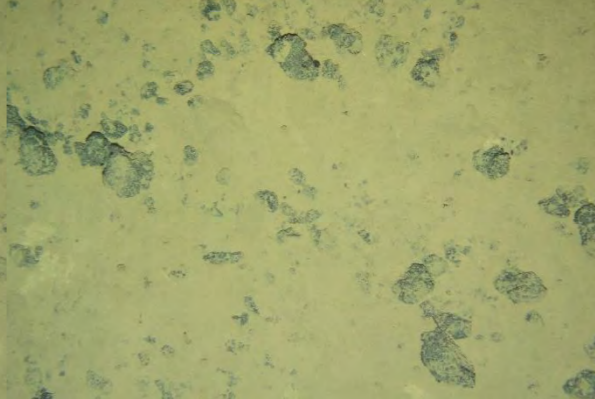
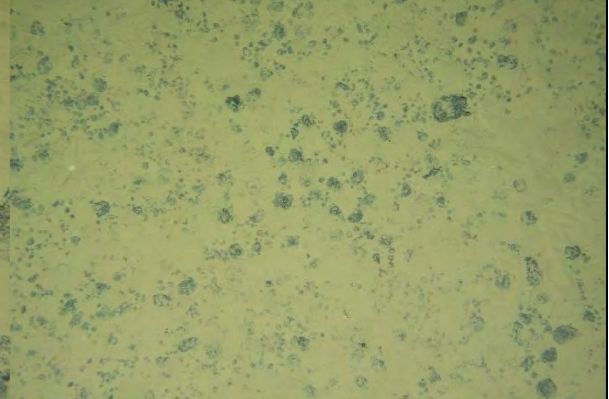
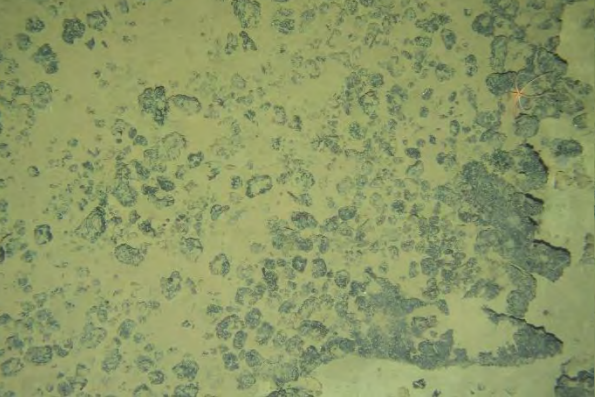
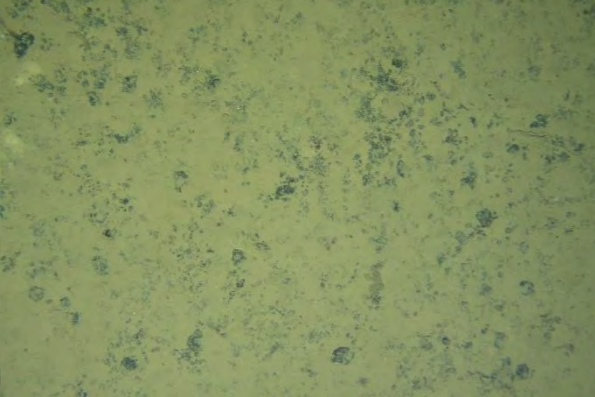
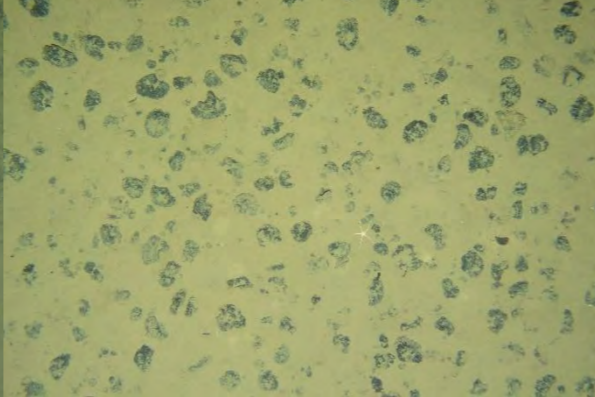
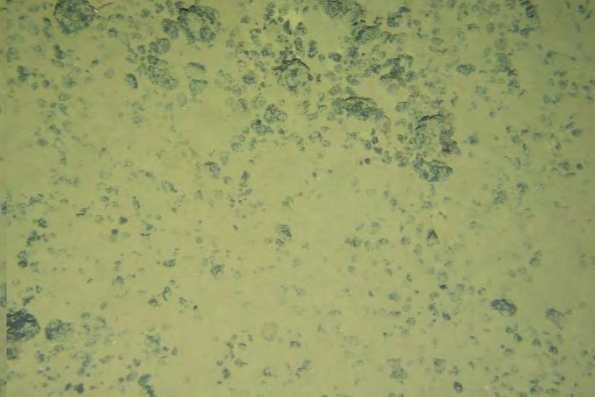
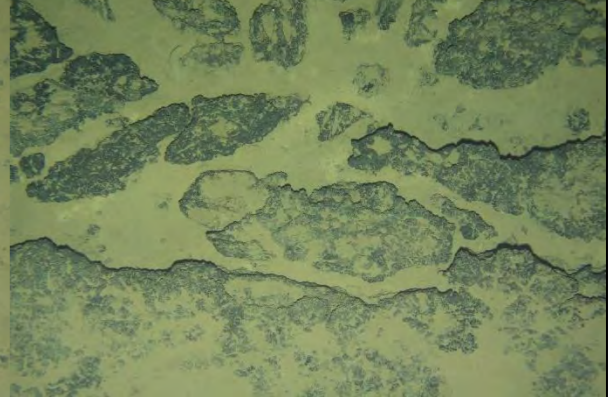
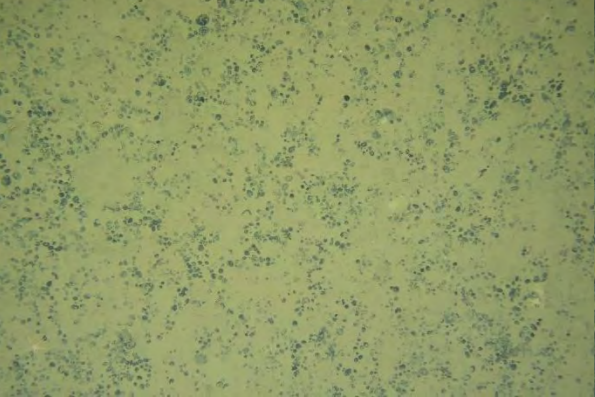
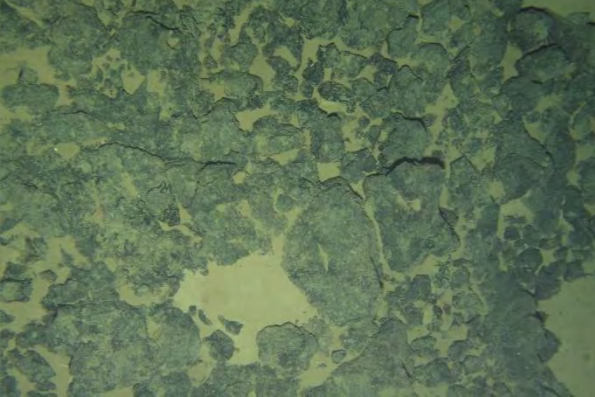
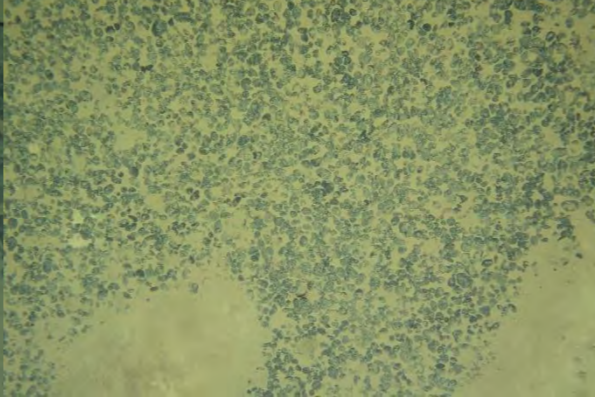
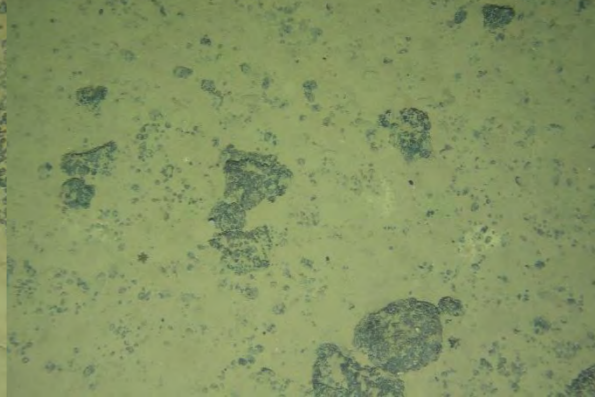
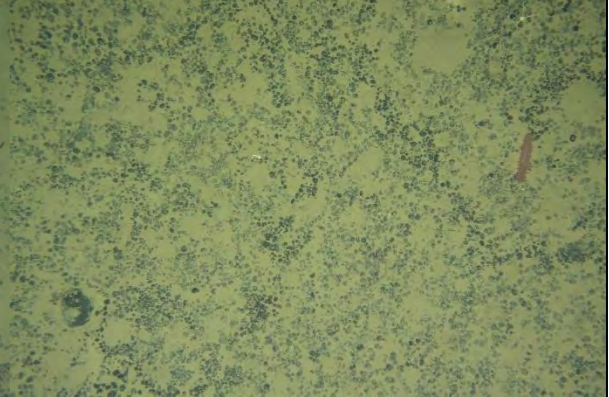
				
A1; CCZ15-F09 (TOML D1); 2015_09_13_132542 Large RS nodules from clay-ooze with mega-ripple texture	A2; CCZ15- F09 (TOML D1); 2015_09_13_160020 Large RS nodules from clay-ooze on a 6-14° slope.	A3; CCZ15- F09 (TOML D1); 2015_09_13_195232 Occasional very large nodules (~20 cm Ø) extending ~300 m	A4; CCZ15- F09B (TOML D1); 2015_09_14_062042 Atypically small nodules approaching an escarpment	A5; CCZ15- F09B (TOML D1); 2015_09_14_064102 Basement lava escarpment in "the triangle"
				
B1; CCZ15- F09B (TOML D1); 2015_09_14_101053 Disaggregated diagenetic crust	B2; CCZ15- F09B (TOML D1); 2015_09_14_101149 Disaggregated diagenetic crust	B3; CCZ15-F09B (TOML D2); 2015_09_15_110113 Very large RS nodules in thick sediment off the plateau	B4; CCZ15- F09B (TOML D2); 2015_09_15_111256 Partly disaggregated diagenetic crust	B5; CCZ15-F10 (TOML D2); 2015_09_16_014745 Mixed sized nodules
				
C1; CCZ15-F10 (TOML D2); 2015_09_16_025313 Diagenetic crust	C2; CCZ15-F10 (TOML D2); 2015_09_16_043652 Small nodules and Fe-Mn coated fragments on breaching dyke	C3; CCZ15-F10 (TOML D2); 2015_09_16_052727 'Typical' large RS type nodules	C4; CCZ15-F10; 2015_09_16_075042 Yet more diagenetic crust	C5; CCZ15-F10 (TOML D2); 2015_09_16_094354 Carbonate exposure in an escarpment
				
D1; CCZ15-F10 (TOML D2); 2015_09_16_104634 Less common small nodules example	D2; CCZ15-F10 (TOML D2); 2015_09_16_121433 Lava blocks associated with large breaching dyke	D3; CCZ15- F10 (TOML D2); 2015_09_16_155718 Relatively well exposed small-medium RS type nodules	D4; CCZ15-F10 (TOML D2); 2015_09_16_170841 Giant nodules/crust amongst small RS nodules	D5; CCZ15-F10 (TOML D2); 2015_09_16_185621 Holothurian track on small nodules – Final image

Photo selection is not of typical seabed exposure with an emphasis on more unusual formations. All Photos: 2.4 x 1.5 m. Full resolution images in Section 9.13

3.4.8 TOML Area D2

This 1,460 km² area is partly covered by side-scan sonar (Figure 3-70, Figure 3-72) and sub-bottom profile per Sheet 9 and Profiles 6-8 in section 10.3.

The subarea was noted as having high minerals resource potential during the CCZ13 cruise, based on the high backscatter reflectance and encouraging dredge hauls, then was explored during the CCZ15 cruise sufficient to define an indicated mineral resource ((Lipton *et al.*, 2016); Chapter 5).

There are almost no abyssal hills in the western and central parts of D2, over an area of ~ 35 x 35 km NE-SW. The eastern part has 'normal' abyssal hills striking 350-355° with 2-5 km wavelengths and 100 to 200 m amplitudes. The western side of D2 is bounded by a distinct 50 km long valley, up to 300 m deep and 6 km wide. D2 occurs above a topographic break at about 4,550 mbsl (Figure 3-70).

One unusual feature of the SBP in the central western part of D2 corresponds to singular and swarms of interpreted dykes +/- hornfels and associated diffraction patterns (Figure 3-46). The side-scan and especially 12 kHz backscatter also indicates that they breach the surface in places (Figure 3-72; Table 3-14). While dykes are found on all three SBP lines, correlating these features from line to line was not possible indicating that they have short strike, the MBES also indicates that they may strike NW and thus at a low angle to the SBP lines. Also of note is a second layer visible in the basement (profiles 6-8, rightmost Figure 3-46), something never seen on the other SBP sections. This is tentatively interpreted to be a deeper sill and it is noted that an outcropping dyke occurs at one limit of this feature in CCZ15-M06. It is suspected that these more recent volcanic features are the reason why D2 is so flat and elevated.

The complete (i.e. not stopped by volcanic units) chalk sequence is usually about 80 m thick. The strata is mostly intact, with warping/flexures (domes) and faults, numerous small normal faults and growth faults of several m to tens of m. Carbonate outcrop is found at horst margins (cliffs to 40 m) and in shoaling domes. There are minimal signs of sub-surface carbonate dissolution and no carbonate strata breccias in evidence in the SBP. However, interpreted potholes (from the MBES) are roughly as common as elsewhere in TOML D, and two at least are located on or adjacent to interpreted dykes/fissure lavas (Figure 3-72). This supports the hypothesis in sections 3.3.2.3.1 and 3.3.2.3.4 that particular stress fields may influence the formation of pot holes on hills versus CSBs in valleys. Surficial carbonate fragments are relatively common at the eastern end of on the flatter area covered by photo-profile CCZ15-M10.

Siliceous clay-ooze is generally very thin (< 5 m) in D2 but still present over the entire area. There are a very wide range of textures in the side-scan with examples in Table 3-4 and Figure 3-44. With reference to the SBP, these are often thought to relate to variations in sub-surface carbonate structure (e.g., domes) or presence of near surface dyke swarms. Other textures likely reflect sediment transport (e.g., the 100-200 m scale mega-ripples in unit co_mr). Some of these textures can just be recognised at the resolution of the MBES backscatter. There is no apparent relationship between these textures and nodule type or abundance.

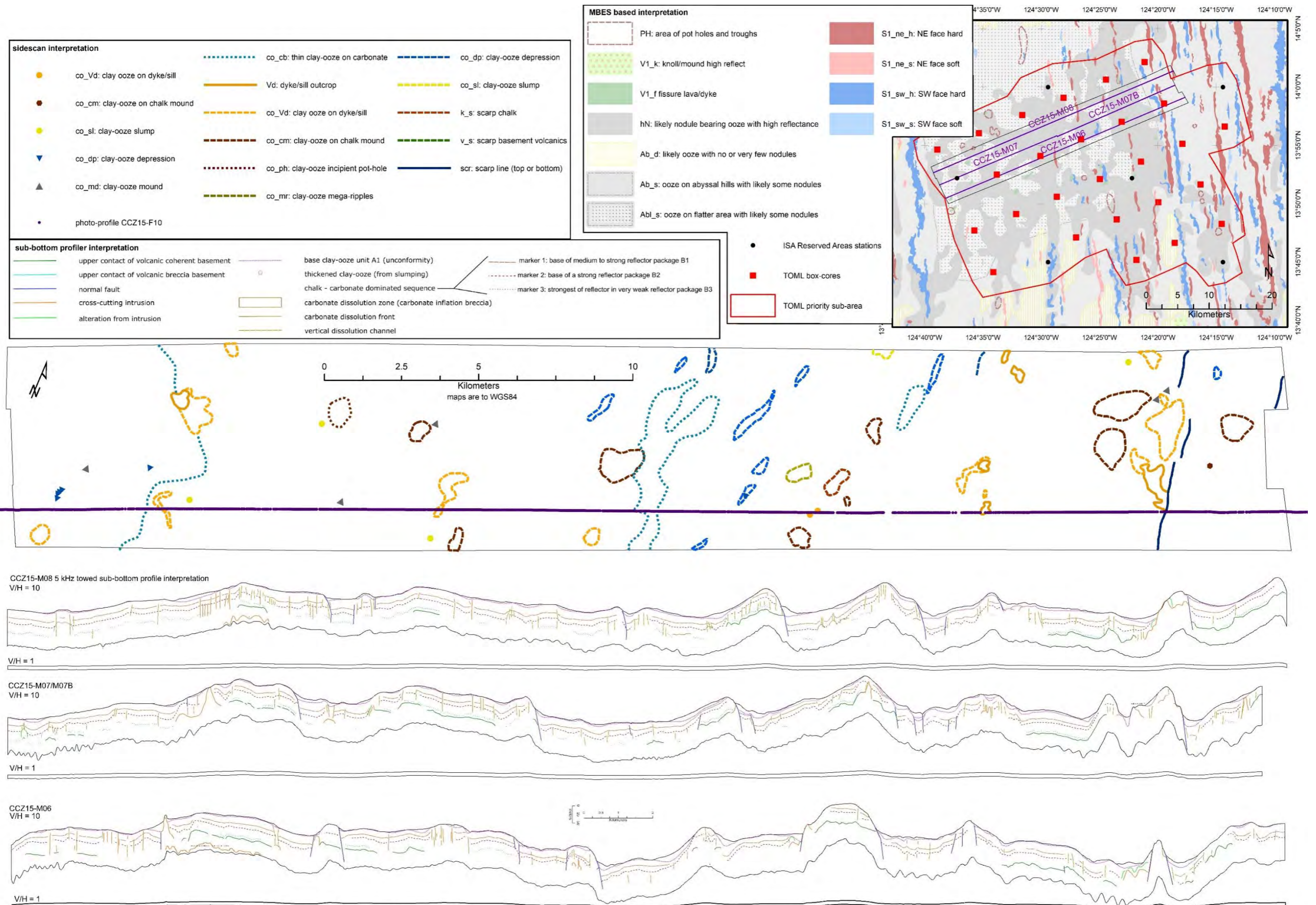


Figure 3-72: Area D2 summary

Nodules are generally large smooth-rough type (I-SR; Table 3-14), abundances average 13.3 kg/m² (for samples >6 kg/m²), which is good compared to the other areas and the published mineral resource. TOML D2 occasionally hosts some very large (>10 cm ø) and even in some cases “giant” (20-40 cm ø) nodules (Table 3-14). Diagenetic crusts are also seen (as at other locations in TOML D).

It is significant that, despite the thin siliceous clay-ooze in the area, the nodules have a higher degree of cover than seen in the other areas (except Area D1; Figure 3.38, Figure 3.36, Figure 3.37). As mentioned above this may reflect more active sub-sea currents in this area.

3.4.9 Marawa Areas 19 and 20

This area is covered by Sheet 5 in section 10.2 and a simplified map comprises Figure 3-73.

The three Marawa exploration contract areas (18, 19, 20) were returned to the ISA by the government of the Republic of Korea in 2001 and taken up by Marawa in 2015 (International Seabed Authority, 2020a). The underlying crust to Areas 19 and 20 is between 27 and 31 Ma in age (Early Oligocene; Figure 3-2). MBES survey in 2012 only partly covered the area (i.e., ~18% of area 19, ~50% of area 20).

Abyssal hills generally strike 350-355°, with minor secondary development across to 010° in the SW side of the survey area. In the NE corner a transit MBES swath also indicates a local more northerly strike. Hill wavelengths are 2-10 km and amplitudes generally 100 – 200 m (Figure 3-17). Part of the central-southern part of the survey area is above a topographic break at about 4,640 mbsl (section 9.11.2).

Volcanic edifices (knolls) are very rare within the survey area, increasing only towards the northeast (and the NORI C area).

Almost nothing is known about the sedimentary stratigraphy in this area, however the backscatter response indicates extensive clay-ooze cover with small nodules or small amounts of nodules (supported by nodule abundance in sampling to date). Discriminating any shoaling carbonate is thus really not possible. DSDP site 159 located over 150 km to the east but at similar latitudes has 18 m of clay-ooze over 90 m of chalk (Figure 3-2). Potholes are common especially in the southern part of the survey area.

Logged nodule types from this area (section 9.18) are a combination of RS types and much more unusual medium to large sized R type nodules. R type nodules are interpreted to be diagenetic only type nodules and more typical of high sedimentation environments like the Peru Basin than the CCZ (von Stackelberg and Beiersdorf, 1991; Von Stackelberg, 1997). In the Marawa area, the R type nodules were logged from sites in the central-eastern side of the contract area (and off the multibeam survey; Figure 3-73), the samples were of low abundance (<3 kg/m²) and of unusually high Mo and Cu content (section 4.5.2.4).

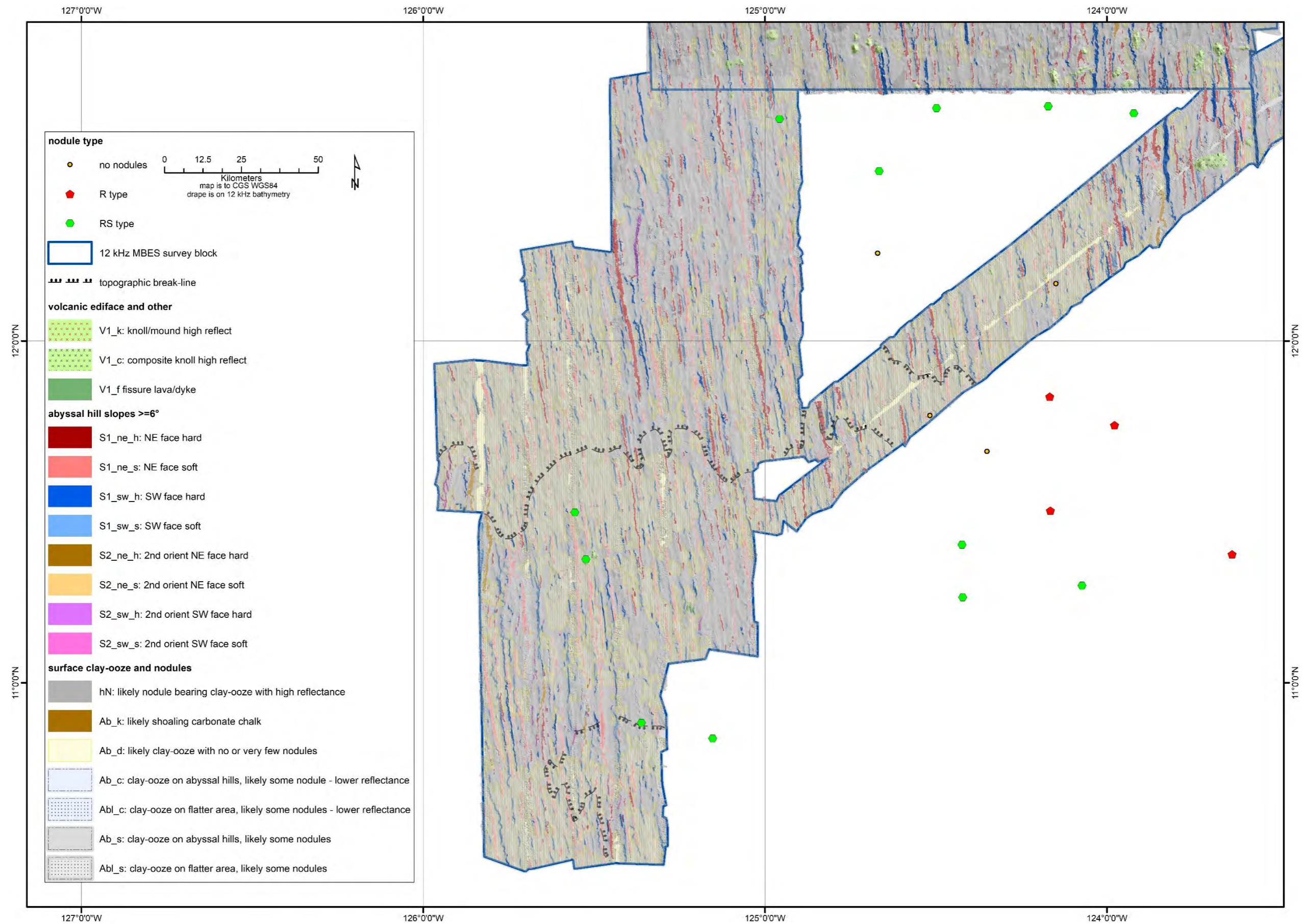


Figure 3-73: Simplified and draped surface geology map - Marawa 19,20

3.4.10 NORI Area C

This area is covered by Sheet 6 in section 10.2 and a simplified map comprises Figure 3-74.

The NORI C exploration contract area was returned to the ISA by the InterOceanMetals (IOM) consortia in 2001 (International Seabed Authority, 2020a). The underlying crust is between 22 and 26 Ma in age (Late Oligocene to Early Miocene; Figure 3-2). MBES survey in 2012 covered ~67% of the contract sub-area.

Much of the surveyed area within NORI C is flatter areas with common volcanic edifices (~13% or double the proportion of any of the other survey areas; Figure 3-74, Figure 3-33), and the NE corner has an unusual tectono-volcanic setting. This is because the area is in effect the NW extensions of the Victor and Yankee regional geomorphic lows (Chapter 2, Figure 2-22). The remaining area comprises abyssal hills albeit in fairly erratic orientations (wavelengths are 1-10 km and amplitudes up to 400 m (Figure 3-17)).

Most of the volcanic edifices are single or composite knolls. They can be very significant in terms of size often exceeding 600 m height above the surround seafloor and largest composite being over 32 km across and 1,200 m high (i.e. technically a seamount; southern part of KW-16119 per Kim and Wessel (2011)). In the NE corner is located an igneous complex of rifts, sills/laccoliths, sheet lavas and a seamount (KW-16116) that are interpreted to represent the tip of a propagating seamount chain. This is discussed in more detail in section 3.3.4.2.

As for the Marawa area, almost nothing is known about the sedimentary stratigraphy in this area. The backscatter response indicates a fairly typical proportion of sediment drifts within the 'normal' abyssal hill areas. DSDP site 159 located almost immediately to the south has 18 m of clay-ooze over 90 m of chalk (Figure 3-2). Potholes seem to be quite rare, most being among the abyssal hills in the SW corner of the survey area closest to TOML D and E.

Areas with very high backscatter, interpreted to be nodule bearing, are common in the area (Figure 3-74) especially in some of the flatter areas amongst the volcanic knolls (*cf* the northern part of NORI A).

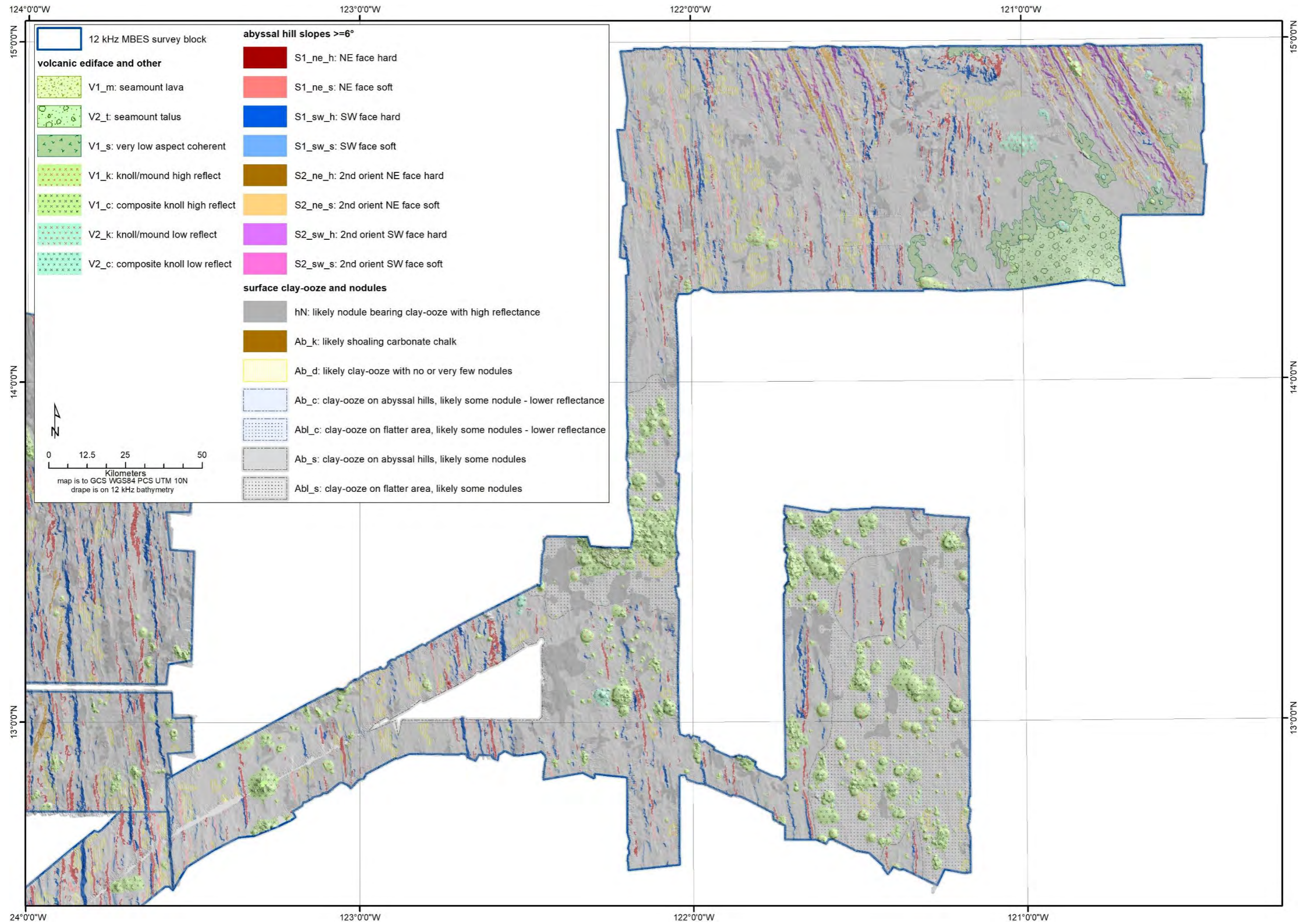


Figure 3-74: Simplified and draped surface geology map - NORI C

3.4.11 TOML Area F and NORI Area D

TOML Area F and NORI Area D are adjacent and so are considered together here. This area is covered by Sheet 7 in section 10.2 and a simplified map comprises Figure 3-76.

The areas are located in the eastern part of the CCZ. They were returned to the ISA by the German government research group BGR in 2006, based on pioneer exploration done in the region by Ocean Management Inc/Arbeitsgemeinschaft Meerestechnisch Gewinnbare Rohstoffe (Derkmann *et al.*, 1981; Lipton *et al.*, 2016), who originally held an exploration license under the reciprocating states regime with the then West German Federal Republic of Germany (Lipton *et al.*, 2016; International Seabed Authority, 2020a). The underlying crust is between 18 and 21 Ma in age (Early Miocene; Figure 3-2).

Both TOML F and NORI D have extensive areas of abyssal hills of 5-10 km wavelength, but in TOML F they tend to be of distinctly higher amplitude, 100-200 m, compared to 70 – 150 m in NORI D (Figure 3-17). Both areas include some flatter areas without much abyssal hills, but they are much more extensive in NORI D (e.g. NORI DSAO area in Figure 3-76). A deep (450-500 m) graben in the SE corner of NORI D is associated with a change in abyssal hill direction and proximity to the Clipperton Fracture Zone (refer also Figure 2-11). There are two topographic break levels, one at about 4,290 mbsl and another at 4,180 mbsl (section 9.11.2).

Volcanic edifices are mostly knolls that trend WNW and that are often associated with flatter areas. Several fissure lavas were mapped in TOML F, some look quite recent based on very high backscatter reflectance. Knoll 3627975 per Yesson *et al.*, (2011) is located just north of the NORI D area, and the NORI 12 kHz multibeam indicates a height of ~ 1270 m above the surrounding seabed (as opposed to the 966 m measured by Yesson *et al.*, (2011)).

Sediment cover from AUV-SBP in the central NORI D area (see below) indicates up to 23 m of clay ooze over about 70 m of chalk (Figure 3-2), although the clay-ooze can be absent in places. A generally lower level of backscatter reflectance in the southern and eastern parts of the area (Figure 3-75), is interpreted to reflect either a slightly higher level of carbonate in the clay-ooze or the influence of a near surface carbonate unit (see 3.4.13). The idea that there might be a higher level of carbonate in the clay-ooze is supported by the calcium content of box-core sampled nodules and sediments from the NORI D portion (Figure 3-75). This somewhat gradational contact could be re-interpreted at a closer scale and perhaps with additional supporting data. Clay-ooze sediment drifts are often lying on the eastern sides of abyssal valleys. Shoaling carbonate is mapped on some hill/ridge tops especially in the SE corner of the contract sub-areas. Potholes are rare in TOML F and NORI D.

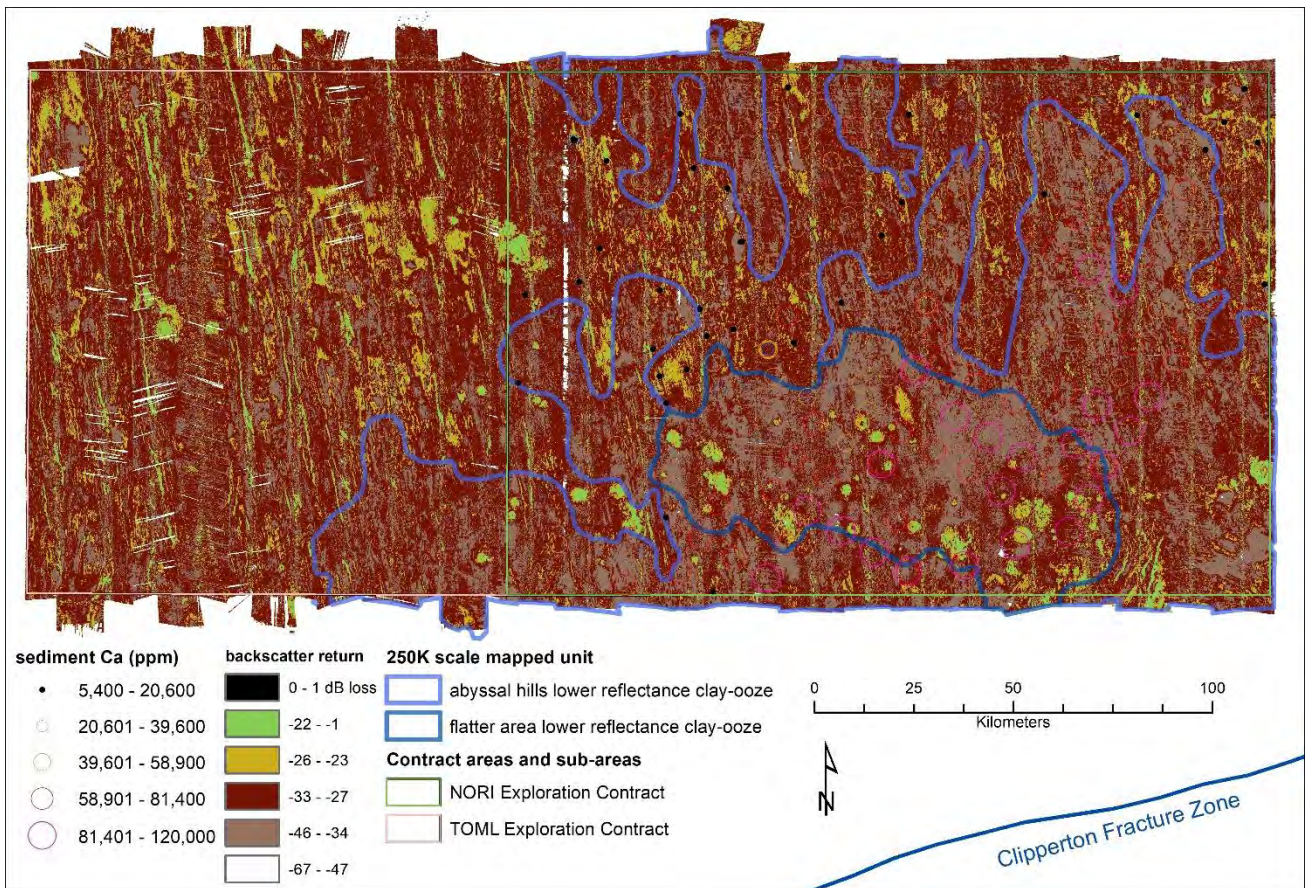


Figure 3-75: Changes in backscatter response across TOML F – NORI D

Nodule abundances in the area are often quite high ($>15 \text{ kg/m}^2$) and cobalt grades relatively low ($<0.2\%$; section 4.5.2.3). The level of sediment powder cover is intermediate between TOML B/C and TOML D (Figure 3-77 versus Figure 3-35). While a range of nodules types have been logged from the area, both NORI and TOML have noted two main types (Figure 3-77):

1. a typically small to medium sized S type (referred to as type 1 in Lipton *et al.*, (2019)), that comprise 60% of box core samples in TOML F and 71.7% of AUV photo coverage in NORI D; and
2. a typically large RS type (referred to as either type 2 ($>20\%$ coverage) or type 3 ($<20\%$ coverage) in Lipton *et al.*, (2019)), that comprise 40% of box-core samples in TOML F and 27.5% of AUV photo coverage in NORI D.

The two types have similar levels of many elements (e.g. Mn, Ni, Ca, Si, Al) but systematic differences in others (e.g. Fe, Co, Cu, Ba, Er, Nd) that support a higher hydrogenetic component to the S-types as discussed in section 4.5.2.4. Nodule abundances average 19 kg/m^2 for TOML Area F and 16.2 kg/m^2 for NORI D (for samples $>6 \text{ kg/m}^2$; note that the NORI estimate does not change between $>4 \text{ kg/m}^2$ and 6 kg/m^2), which is excellent compared to other areas.

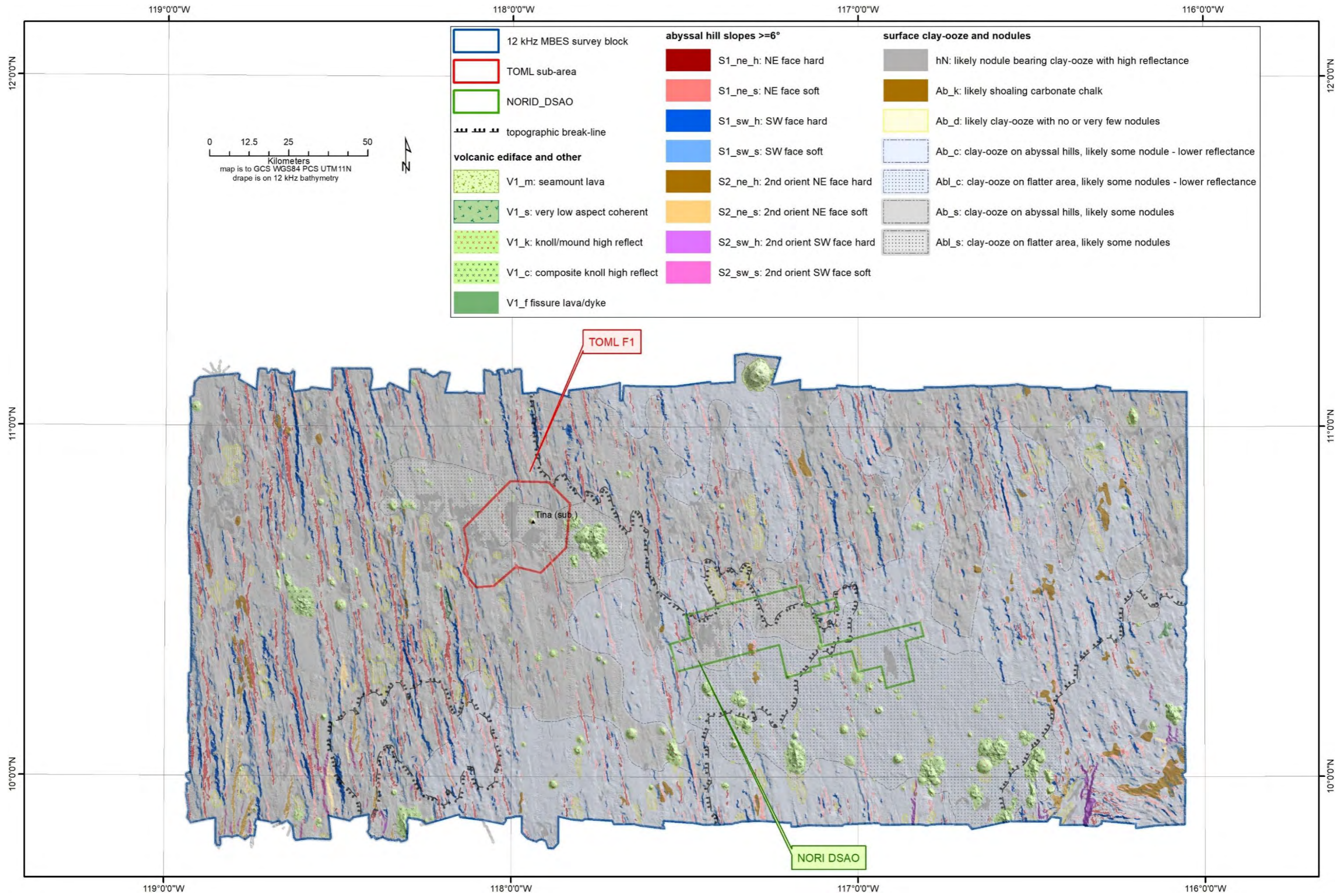


Figure 3-76: Simplified and draped surface geology map – TOML F and NORI D

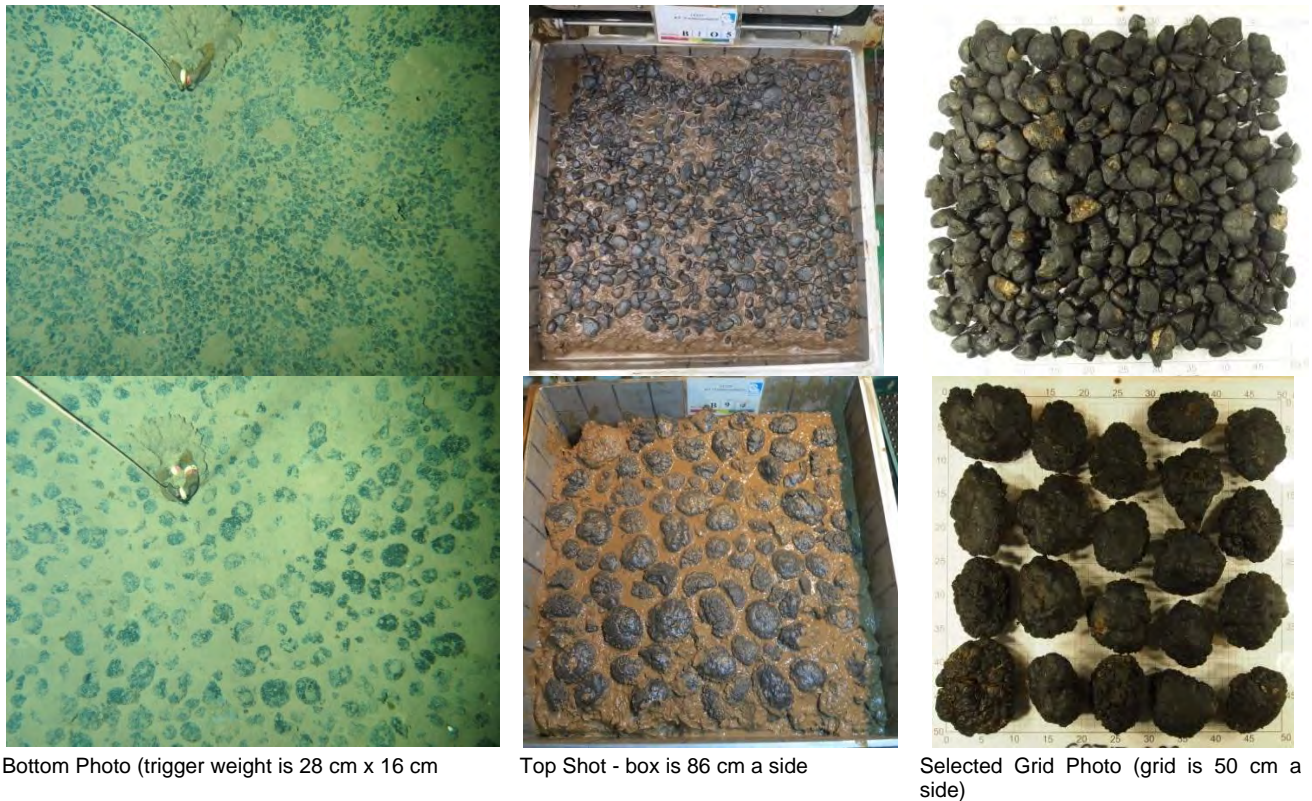


Figure 3-77: Example nodule types CCZ15-B99 and B105

3.4.12 TOML Area F1

Sampling of Area F during the CCZ15 expedition aimed to define an inferred mineral resource. With box-cores returning consistently good abundances, and the program slightly ahead of schedule, more box-core samples were taken in the 800 km² sub-area F1, at a spacing suitable to support an indicated mineral resource estimate ((Lipton *et al.*, 2016); Chapter 5).

The area was selected based on relatively high backscatter reflectance and relatively flat terrain. In effect there are no abyssal hills within F1 and two small volcanic knolls (including Tina Knoll) in the centre, and a larger complex just outside the eastern boundary.

Without SBP data, it is difficult to determine the underlying stratigraphy, although it is expected to be similar to that in NORI DSAO (below). There are no sediment drifts, shoaling carbonates or potholes within the area.

While type 1 S-type nodules comprise 15 of the 25 box-core samples collected in Area F/F1 during the CCZ15 expedition (60%), within F1 they only comprise 4 of the 10 that characterize the area. Nodule abundances average, 21.8 kg/m² for Area F1 (for samples >6 kg/m²), versus 19 kg/m² for Area F.

3.4.13 NORI DSAO

The NORI Detailed Survey Area (Lipton *et al.*, 2019) was explored sufficient to support an indicated and measured mineral resource during NORI expedition 3 (part of the April to June 2018 campaign). This included box-cores BC_001 to BC_045 and 2,286 line km of AUV data including MBES/SSS/SBP collected at 35 and 22 m altitude, and seabed photographs collected at 6 m. NORI expedition 6B in 2019 was instrumental in extending the indicated mineral resource to over 80% of the NORI D area (Lipton *et al.*,

2021). This included box-cores BC_47 to BC_280. The DSAO area is specifically mentioned here due to information collected by AUV during expedition 3. Its location relative to other areas of interest defined in the 2018 program is shown in Figure 3-78.

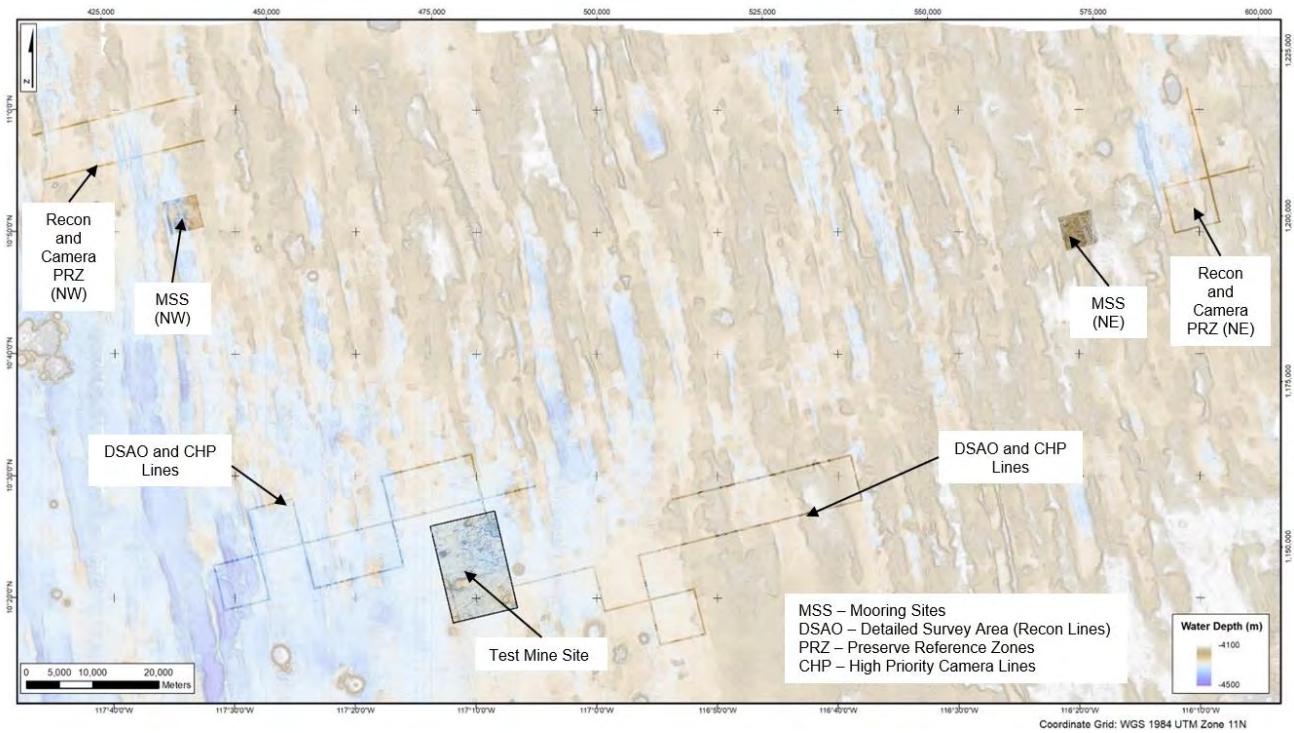


Figure 3-78: NORI D areas surveyed by AUV in 2018
 Modified from Lipton *et al.*, (2019)

The DSAO is located on a flatter area with only a few short (2-10 km) abyssal hills (Figure 3-80, Figure 3-81) on its margins and western end. These strike to about 350° and have erratic wave lengths of several kilometres and amplitudes of about 100 m. The 4,290 mbsl topographic break lies on its northern side and through the centre to the east of the collector test site. Similarly, there are few volcanic edifices within or marginal to the area, but there numerous more immediately to the south. One of the SBP profiles has a high reflectance unit in an abbreviated sediment stratigraphy that resembles the sill seen in TOML B5338 (Figure 3-82 (A), Figure 3-54 respectively).

The AUV SBP data for the NORI D area was only able to be viewed via several already produced example figures. These are reproduced below in Figure 3-82. Some comparison with the MAK SBP can be made but the responses look quite different (e.g., lower contrast in terms in internal structure, different vertical scale), and it is not certain if all of the differences are due to the system/processing software or if some is due to the geology. Nonetheless, with consideration of existing interpretation (Fugro Onboard Geoscience and Processing Team, 2018; Lipton *et al.*, 2019), some additional interpretation is presented here.

The profiles can be interpreted to have a stratigraphy of three sedimentary layers (Figure 3-82 (E)):

- Unit C starts above the basement lavas and often shows structure very similar to the Marquesas carbonate chalk discussed/defined in section 3.3.2. Its maximum thickness in the example profiles is

about 60 m. In some parts of the section the structure is degraded, perhaps due to dissolution similar to that which forms the carbonate strata breccias discussed in section 3.3.2.3.3.

- Unit B overlies Unit C, but shows weak to no internal structure. However, it may form a harder surface contact with overlying Unit A. Unit B is interpreted to be poorly consolidated carbonate chalk. Its maximum thickness in a valley is about 45 m, but in other areas, it is consistently closer to 30 m. The irregular surface of this unit may be a consequence of carbonate dissolution.
- Unit A: overlies Unit B and is unstructured and generally fairly thin (<5 m). It often has surface textures reflecting the contact with Unit B (much as the thin clay-ooze in areas like TOML D2 reflects the structure of the underlying chalk). These textures include hummocks and shallow depressions ranging from the metre to hundred-metre scale. This unit is interpreted to be siliceous clay-ooze (as sampled in the box-cores).

As indicated above, all of the units are of variable thickness, and shoaling carbonate has been noted in at least one AUV SBP profile (Figure 3-82 (B)), and is mapped from 12 kHz MBES in several places in or near the DSAO (e.g. Figure 3-80). Lipton *et al.*, (2019) discuss likely shoaling carbonate at box-core site BC_031 located ~13 km east of the DSAO, but at this locality the MBES backscatter is higher than normal for shoaling carbonate. Nodules at the BC_031 site are quite large, which likely drives the backscatter response rather than the sediment host. and indicating that mapping shoaling carbonate in areas of larger (type 2 and maybe type 3) nodules may not be possible using 12 kHz MBES.

Nodules mapped by AUV seabed photography are ~70% sm-S type (type 1 in Lipton *et al.*, (2019)) and ~ 30% ml-RS type (type 2/3). The ml-RS type is associated with the hummocky texture in the surface clay-ooze, which may indicate that this area supports a thicker geochemically active layer (Chapter 4). Nodule abundance within the DSAO area is 17.2 kg/m², i.e. only slightly less than in TOML F and quite a bit higher than other parts of the NORI contract area (Lipton *et al.*, 2019).

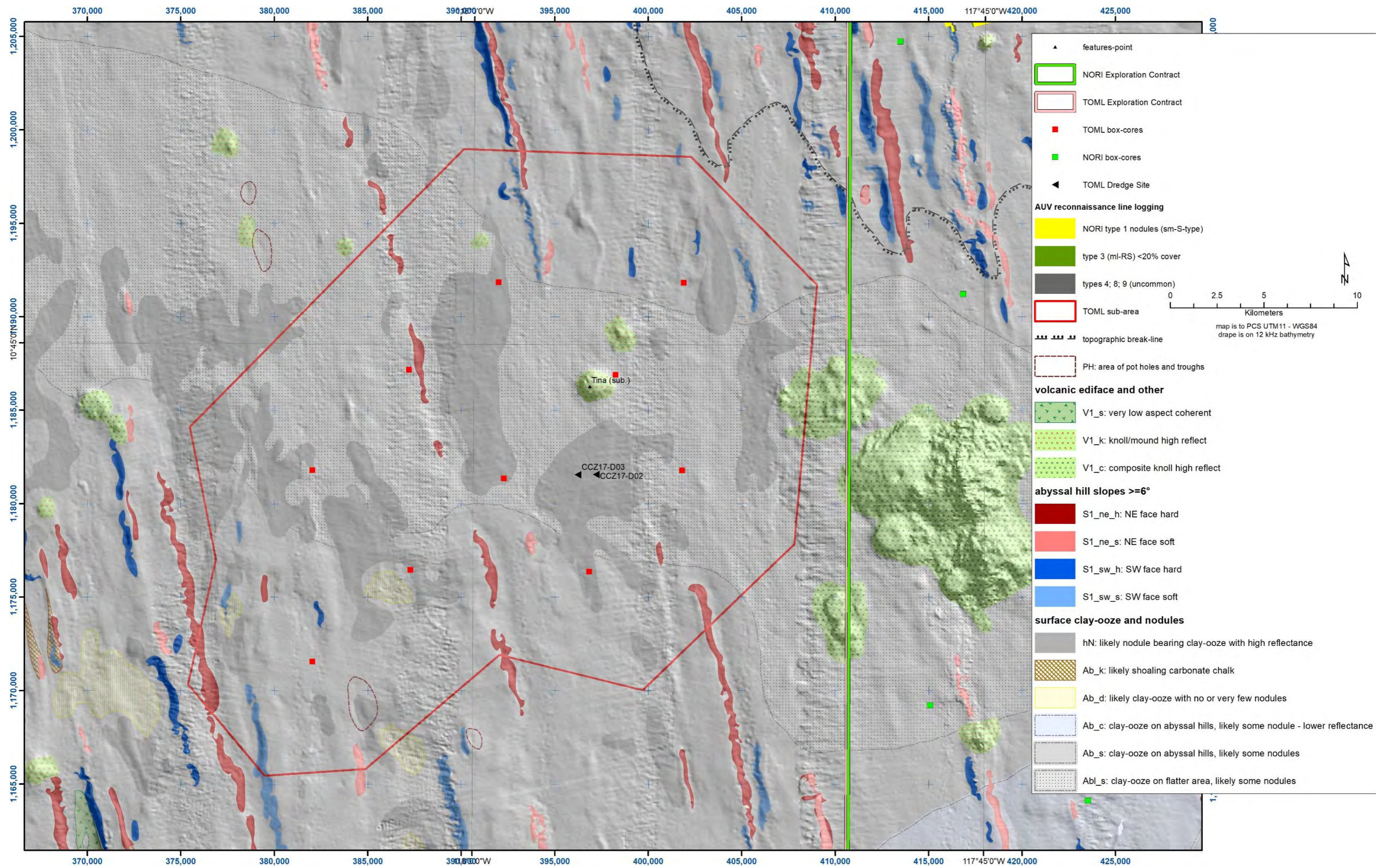


Figure 3-79: TOML F1 geological map at 1:150,000 scale

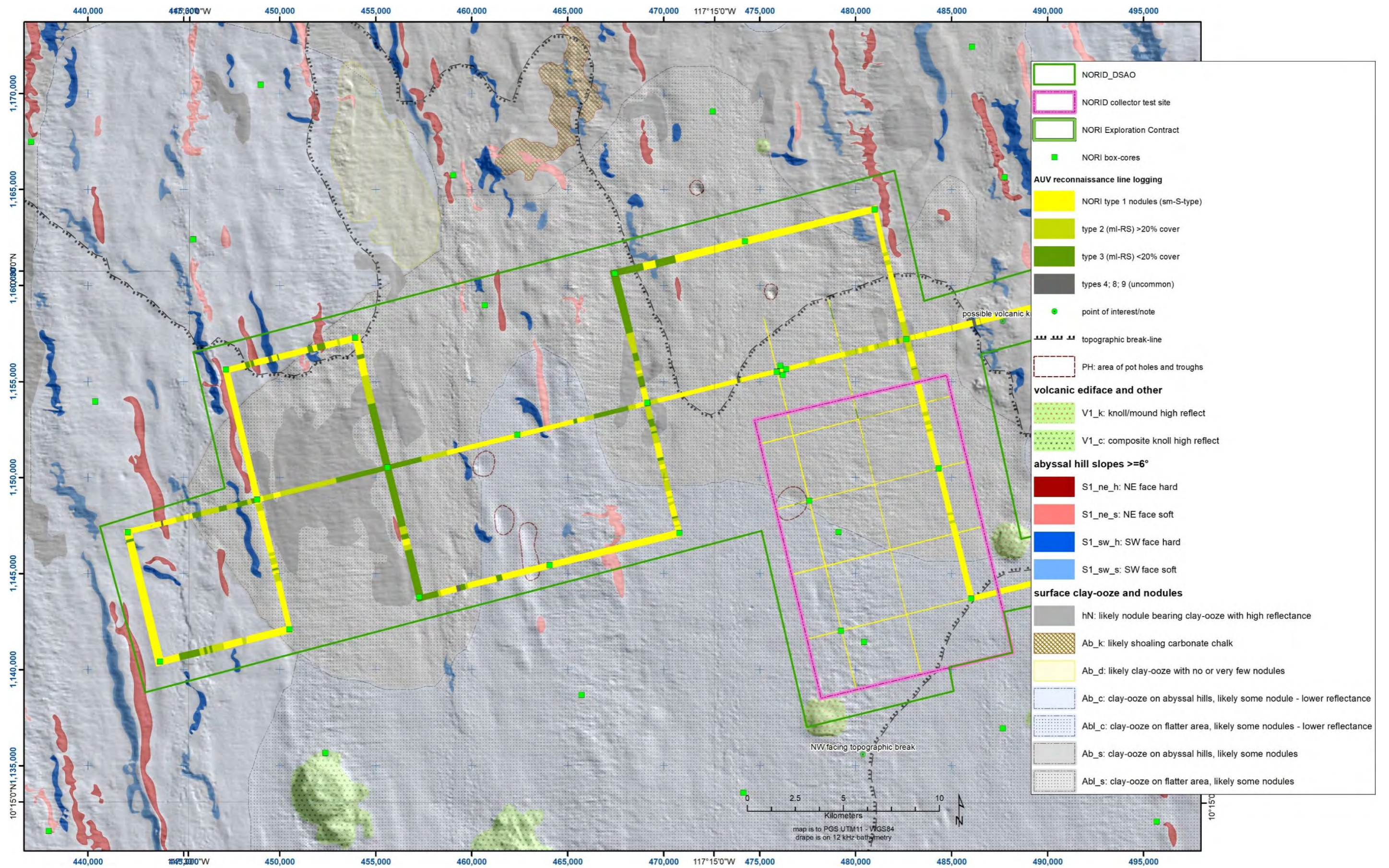


Figure 3-80: NORI D – DSAO west side geological map at ~1:150,000 scale

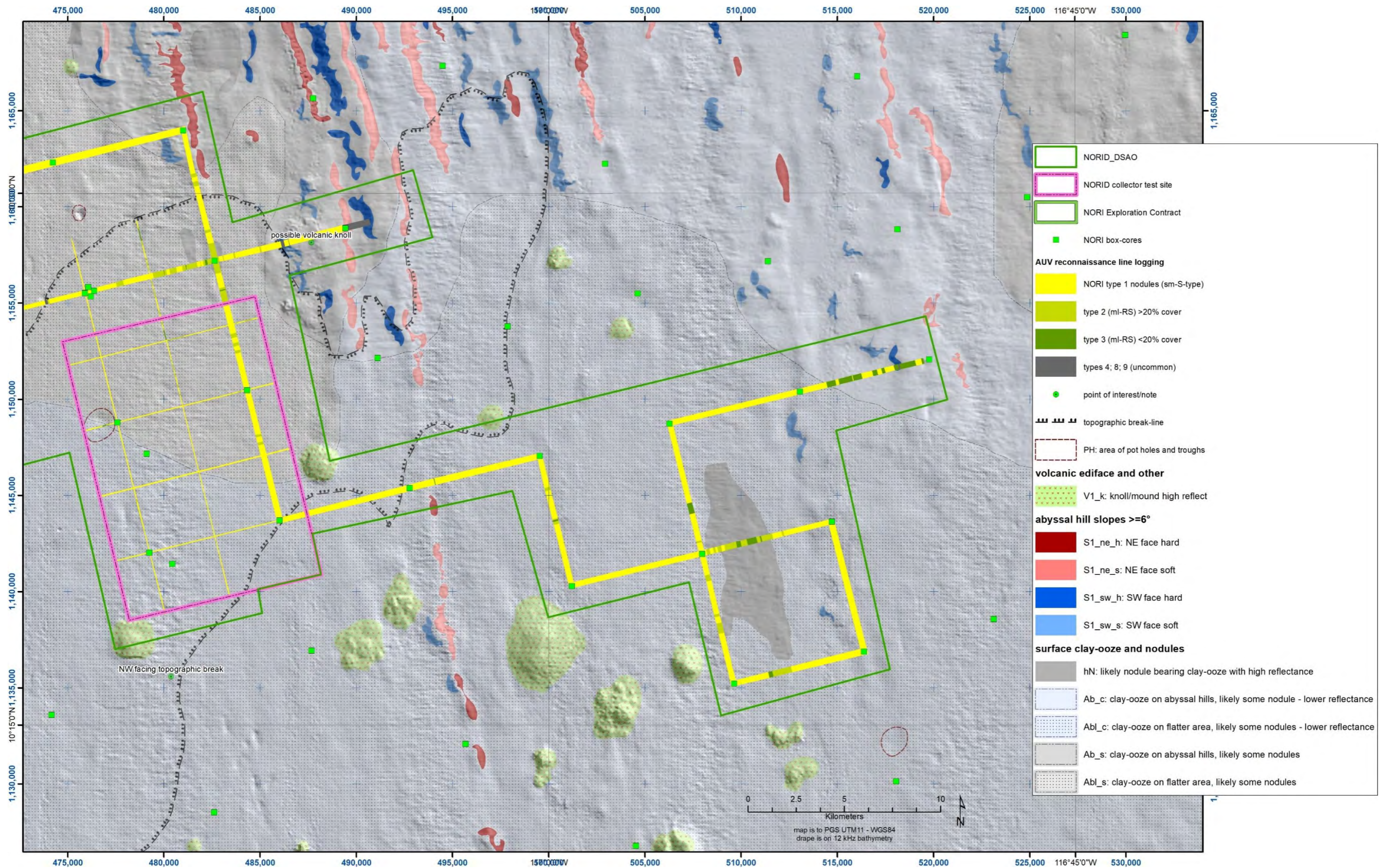
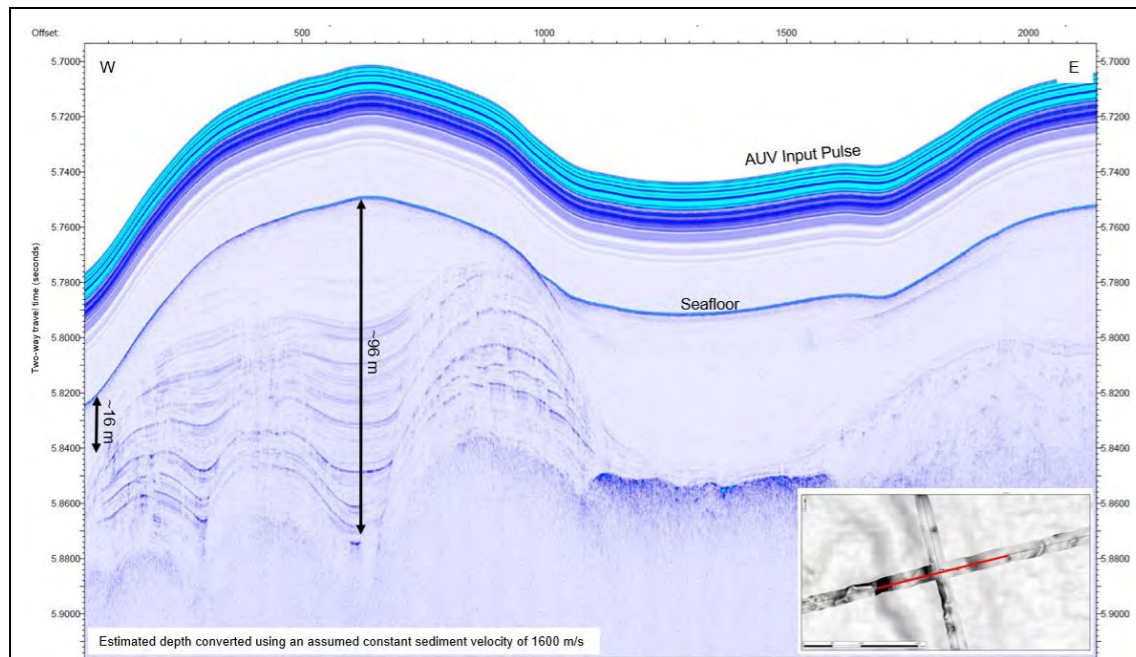
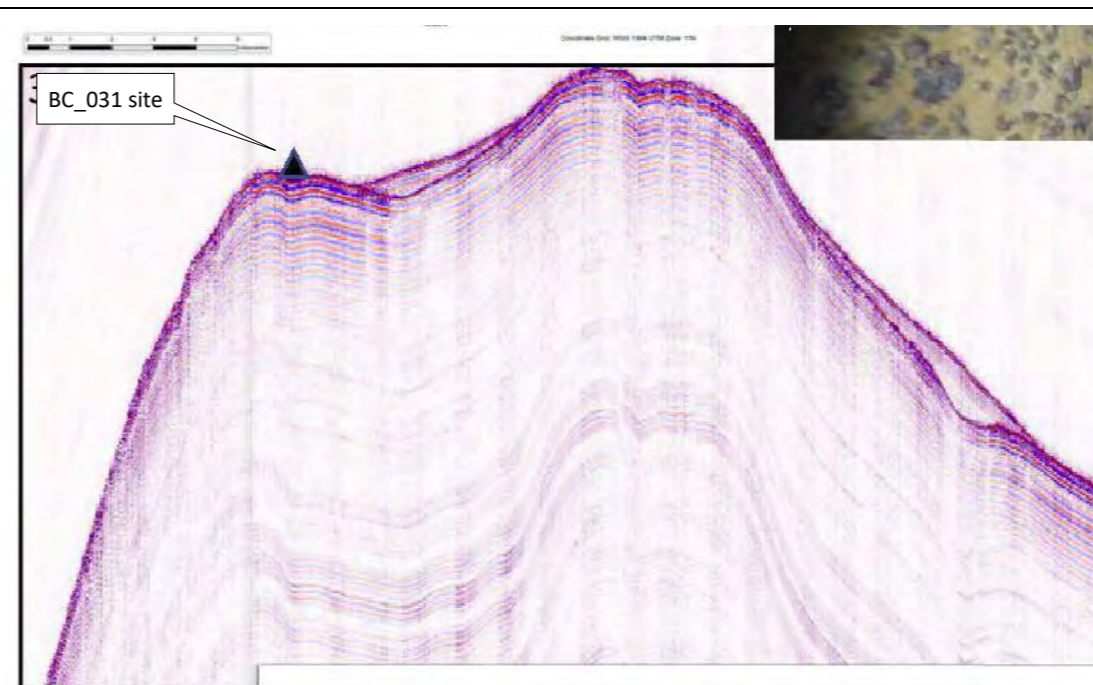


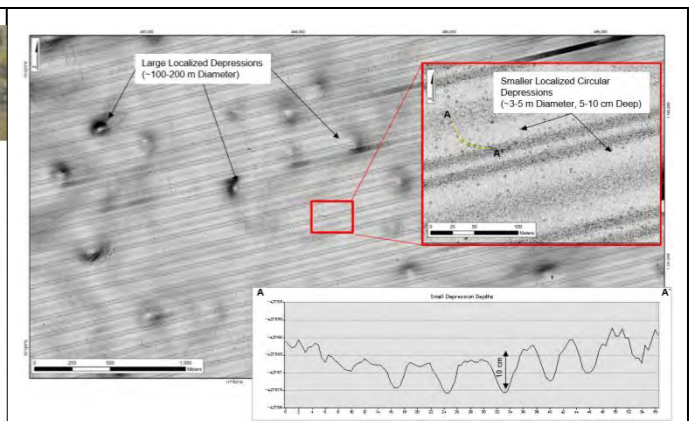
Figure 3-81: NORI D – DSAO east side geological map at ~1:150,000 scale



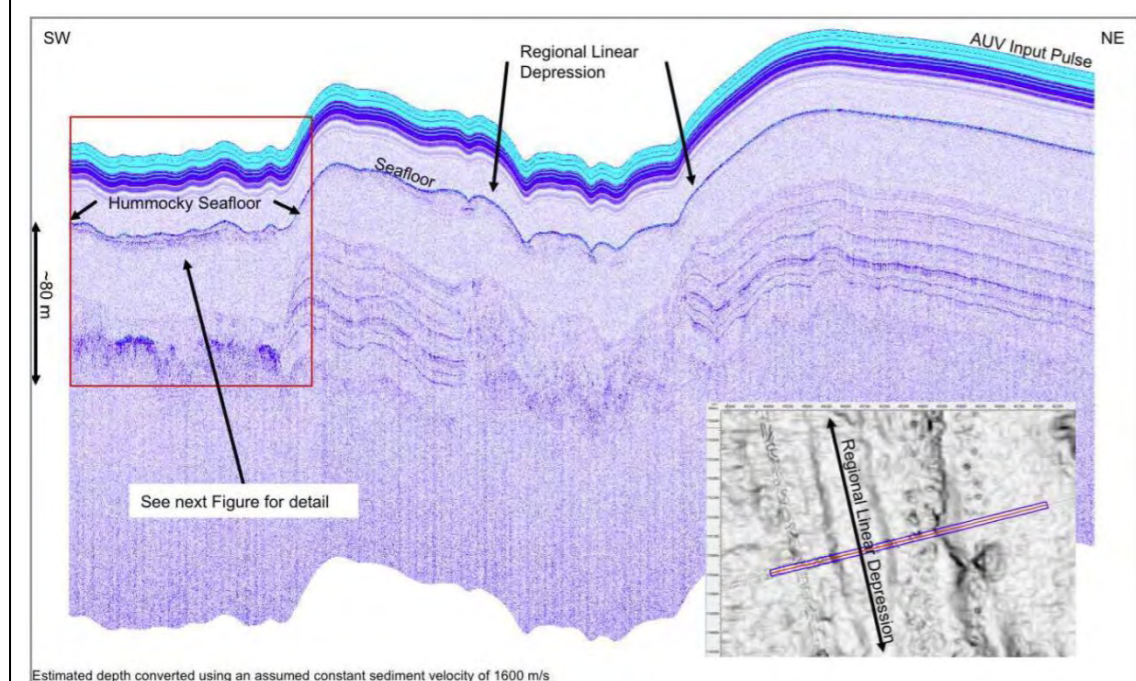
(A) example AUV SBP showing variable thickness sediment units A-C and possible sill or sheet lava in valley; section is 2.1 km across



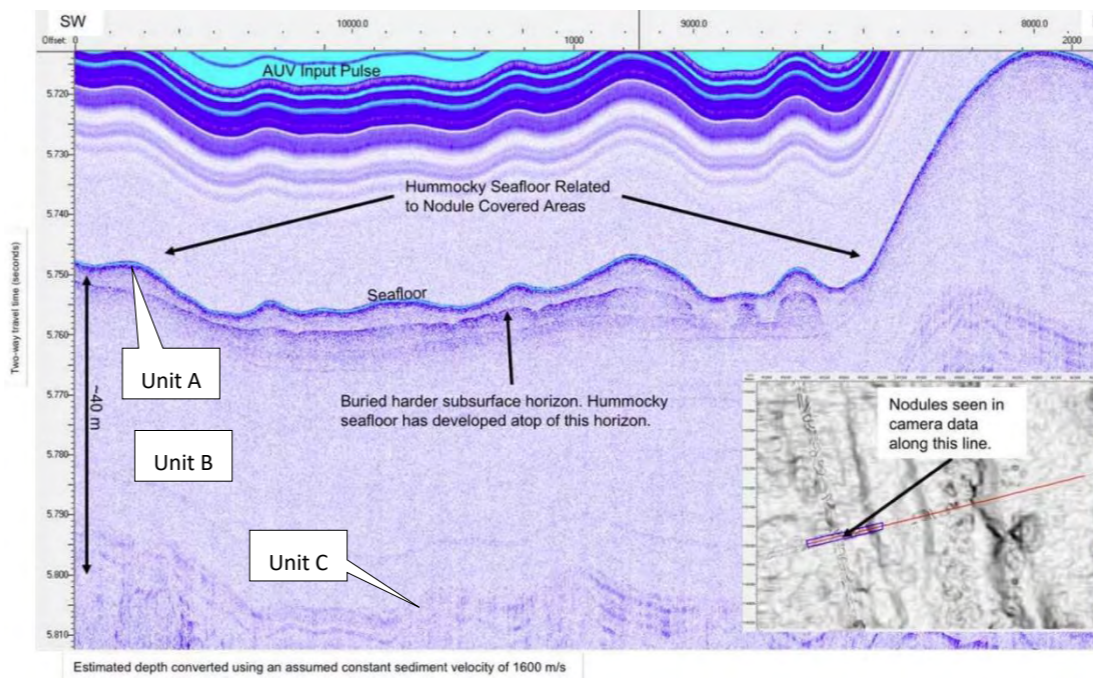
(B) example AUV SBP profile of shoaling unit C; section is approximately 8 km across



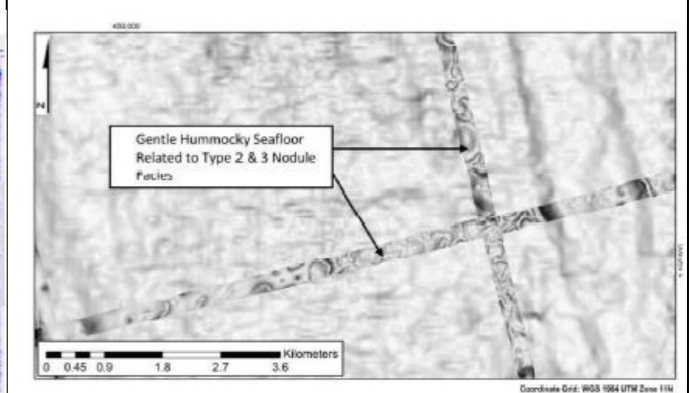
(C) AUV MBES of circular depressions in sediment unit A



(D) example AUV SBP showing hummocky A:B contact is approximately 10 km across



(E) detail of central part of red inset in (D) section is 2.1 km across



(F) AUV MBES of hummocky terrain

Figure 3-82: NORI D AUV SBP and related surface textures in AUV MBES

Sources: A, C (Fugro Onboard Geoscience and Processing Team, 2018); B, D, E, F (Lipton et al., 2019)

3.5 Conclusions and recommendations arising from Chapter 3

Ship-mounted 12 kHz MBES bathymetry and backscatter is the basis for mapping a significant part of the central and eastern CCZ seabed (~173,000 km²), via seven discrete survey areas. These areas span from 116° to 134.5° W (~2,000 km) and 10° to 16° N (~700 km). Mapped units include:

- abyssal hills and flatter areas covered with clay-ooze of the Clipperton Formation, with the flatter areas often related to emplacement of chains of volcanic knolls, or in one case at least, dykes;
- sub-units of the clay-ooze related to areas likely to host very few nodules (often sediment drifts) and areas more likely to host more or larger nodules. The sediment drifts can concentrate longitudinally along the sides of abyssal hills and around the bases of knolls;
- areas of shoaling Marquesas Formation chalk, with expression of pavement and residual breccia in seafloor photographs. Potholes that are located almost entirely on abyssal hill-tops rather than associated valleys and in some cases, formation related to emplacement of late stage dykes;
- steep slopes for ~ 5,000 abyssal hills that often include escarpments of underlying strata (crustal volcanic rocks and chalk), including the observation that slightly more hills face away from the East Pacific Rise (unlike classic illustrations of abyssal hills from seafloor spreading);
- a wide range of volcanic edifices, with forms and stratigraphic position indicating that ages likely ranging from near syn-crustal formation to present day. These edifices include single and composite knolls composed of lava and breccia (both seen in seabed photographs), seamounts composed on lava flows and of talus breccia, sheet lavas, fissure lavas, breaching dykes and associated surface breccia (photographed), and near surface laccoliths.

In one area (NORI C), the geological situation ahead of a propagating seamount chain progresses from rifting at a high angle to the abyssal hills; emplacement of intrusions; and eruption of sheet lavas from vents at the base of the seamount.

In use of the backscatter response for mapping, a comparison with towed photo-profiles showed that many units overlap in terms of their response. These include: sediment drifts and shoaling carbonate; areas with high abundances of small nodules and areas with a few large nodules and areas likely comprising volcanic breccia. Albedo off escarpments is also significant. Thus, use of backscatter in mapping is qualitative as best, and slightly better interpretations can be made if bathymetry is also considered.

As MBES backscatter is a comprehensive and very cost-effective data set to collect, future work to further apply it in mapping and thus mineral resource estimation, is well worth pursuing. A first consideration could be the scale of application, i.e., local scale correlations may be better than more regional ones as regional coverage includes a wider range of geological conditions. More specifically, studies could involve attempts to calibrate backscatter for key areas by using detailed photographic coverage of dominant nodule types (either by facies or by mineral resource domains). The process could involve resampling both datasets at different scales, including classification based on outcrop types (i.e. nodule types, volcanic facies, carbonate exposure). AUV collected MBES versus AUV photographs is a possible way to get more detailed and complete coverage for both data types. Once/if fundamental relationships are clear, then these may be able to be applied more widely (for example to the scale of an exploration contract).

Within the example type areas of this study, towed sub-bottom profiler (SBP), side-scan sonar (SSS) and photographs provide additional details.

- In conjunction with limited drilling from the Deep Sea Drilling Program, the SBP profiles show that the Eocene and younger carbonate stratigraphy thins from east to west and from north to south. This is in line with underlying plate movement away from the high primary productivity of the equatorial region. While the carbonates cement into chalk and internal strata can be correlated within each survey area, the siliceous clay-ooze that forms on them tends to be more mobile and thus highly variable in thickness. AUV SBP from NORI D indicates this region may also have a significant unconsolidated or poorly consolidated carbonate layer between the chalk and the clay ooze. The carbonates are often warped and can form domes, that sometime outcrop. A wide range of textures in the siliceous clay-ooze can be seen from SSS and AUV MBES, when it forms thin layers on the carbonate and/or volcanic rocks. Some of these are likely related to seabed currents.
- Potholes form in near-surface carbonate as reported by prior workers. These are more common in older more westerly crust, most likely due to a more extended period of time the rock has spent below the lysocline. In some cases, potholes are associated with near-surface dykes and details seen from a series of towed photos across such a feature are presented.
- While potholes have long been known to form on abyssal hills, other dissolution structures are described here from the abyssal hill valleys. The most striking are subterranean “Carbonate Strata Breccias” (CSB). These are stratabound zones where the structured SBP response of the chalk is mostly or entirely destroyed. These CSBs tend to form at several stratigraphic horizons but can also propagate vertically and horizontally much like vadose/phreatic cave breccias on land. They can be located in the centre or at the fault bound edges of the abyssal valleys, and often have dome shaped tops indicating some structural accommodation. Often the stratigraphic sequence replaced by the CSB is thickened or inflated relative to the original strata presumably to increased volume of breccia versus the original strata. CSBs can also be associated with thinner dissolution fronts and narrow vertical blanking of the SBP return.
- Volcanic units include sills that stope out stratigraphy (both in hills and valleys) and that in one case at least breaches. Dykes can be common and the larger ones have clearly visible alteration halos, beaching examples are also seen on the side-scan sonar and in one photo profile in TOML B.
- Regarding any future research, it is suggested here that a seafloor drilling rig may more readily study the CCZ stratigraphy than ship-based drill-rigs. These can operate off smaller cheaper expedition vessels and there are several spreads (MEBO, BGS Rockdrill 2, CRD100) able to reach the ± 100 m depth below seafloor needed.

Ultimately this study helps to understand the geological character of the different survey areas. The areas are remarkably diverse considering they are all fundamentally composed of abyssal hills made of volcanic basement overlain by chalk in turn overlain by nodule bearing clay-ooze. A few of the distinguishing features between them are:

- In NORI A, an extensive flatter area associated with a geomorphic High has common volcanic knolls and very high backscatter response is thought to relate to very large nodules;
- In NORI B and TOML B, there are a well developed secondary set of abyssal hills and associated volcanic complexes including dyke swarms and hyaloclastite volcanic breccia;
- In northern TOML B, there are lower grade nodules associated with a medium backscatter ?breccia-dominant volcanic chain;

- In TOML C, there appears to be abundant shoaling carbonate on the broader abyssal hills of the geomorphological Low in the west, versus the consistent clay ooze covered abyssal hills in geomorphological Plain in the east;
- In northern TOML D, there is a broad often sub-cropping carbonate plateau that may have formed due to reinforcing from abundant dykes and sills. Thin surficial clay-ooze hosts large nodules and sports a wide range of textures;
- In southern TOML D and E, there are large and distinctive sediment drifts that may have accumulated from sediment transport from the northern TOML D;
- In Marawa 19-20, there is a very high incidence of low reflectance clay-ooze and the very low incidence of volcanic edifices such as knolls;
- In the central and southern parts of NORI C, there are extensive flatter areas and chains of volcanic knolls;
- In the northern part of NORI C, the northern tip of the Acapulco seamount chain continues into a complex arrangement of tectono-volcanic units;
- In TOML F/NORI D, there are juxtapositions of rougher abyssal hills and flatter areas, of higher and lower reflectance clay-ooze, and of larger RS and smaller S type nodules, with both types frequently found in high abundance.



"At-sea trainees" prior mobilization on the R/V Yuzhmorgeologiya, Tarawa, August 2015.

Photo credit: Nicola Parianos.

4 Key properties of Clarion Clipperton Zone nodules

4.1 Introduction

Polymetallic nodules are being considered for commercial exploitation (Chapter 5). They would be mined, transported and metallurgically processed (e.g. Chapter 6) as a bulk commodity (i.e. with some similarities to iron ore, nickel laterite and bauxite; (McQueen, 2005)). This means they have various physical and chemical characteristics (key properties) that can be almost as important as metal endowment in terms of mine economics (i.e. modifying factors per the CRIRSCO codes for mineral resources conversion to ore reserves; e.g. (Joint Ore Reserves Committee, 2012; International Seabed Authority, 2015; CIM Mineral Resource & Mineral Reserve Committee, 2019; Committee for Mineral Reserves International Reporting Standards (CRIRSCO), 2019)).

This chapter addresses many of these key properties that have a geological basis. It does not (cannot) be completely comprehensive as this is an immense scope of work and beyond the reach of any individual and likely any individual organisation. The detail of the investigation also thus varies, in many cases according to the information accessible at the time of writing.

4.1.1 Chapter structure

There are nine sections to this chapter (plus references and conclusions).

1. As well as explaining this structure, the introductory section includes re-summarises, in more detail, the formation of Clarion Clipperton Zone (CCZ) polymetallic nodules. This is used to frame much of the assumptions and discussion in the subsequent sections;
2. The section on sampling methods explains the common methods used to collect the samples studied in subsequent sections and provides a summary table of sample type by analysis type. The subsequent sections all have methods and results sub-sections, but those methods sub-sections deal only with the methodology specific to that analysis;
3. The section on classification of seabed precipitates focuses on nodule classification (significant as the Tonga Offshore Mining Limited (TOML) nodule samples span a large portion of the CCZ), but also includes a discussion on diagenetic crusts. It also includes a conceptual analysis of how nodule growth forms and abundances may relate to their respective geochemically active layers;
4. The section on nodule mineralogy is mostly a review of published works by others and an attempt to provide a simple yet complete summary for reference in this thesis. It is accompanied by limited micro-analysis data accessible to the author that illustrates some fundamental mineragraphic relationships;
5. The section on nodule chemistry looks at the general attributes of samples from the TOML, Nauru Offshore Resources Incorporated (NORI) and Marawa Research and Exploration Limited (MARA) areas, compared with those published by other authors. It then focuses on some fundamental trends at the regional and local scales. It also includes a comparison of nodules and host clay-ooze from the NORI D exploration contract area (the only area with systematic and complete chemical analysis of the host sediment to the nodules);
6. The section on nodule and host clay-ooze densities looks at these properties and their variance between sample types and sampled sub-areas, as well as variance with depth (in the case of clay-ooze);

7. A somewhat comprehensive section on moisture content studies this largest single component of nodules, from several perspectives, and addresses several essential questions;
8. The section on generation of attrition fines versus cargo stability requirements is a first pass study at a potentially significant problem of safe transport of any future mined product;
9. A short section on packing factor provides some end-member values that would be required by developers for modelled ore storage calculations.

One key property that is not included in this section is nodule long-axis (major axis) measurements and analysis. This is because this property is included in Chapters 5 and 6, within a discussion on using seabed images to accurately determine nodule weights and hence mineral resource tonnage.

As alluded to above, the samples from the testing do not cover the entire CCZ, but they do span a considerable portion of it. TOML's exploration contract sub-areas B, C, D and F, span 16 degrees of longitude of ~ 35% of the CCZ and 5 degrees of latitude or ~ 60%. Some dredge data from TOML A increases the longitude range to 35 degrees of longitude (or ~80% of the CCZ). Samples from the NORI D sub-area extend the coverage over a degree further east, almost to the SE limit of the CCZ and the Marawa exploration contract sub-areas includes some of the most southerly contract areas within the central part of the CCZ.

The chapter often references 'scale' and four scales are usually used:

1. Facies scale: is at the scale of a given facies of polymetallic nodules, usually 10s of meters up to several kilometers;
2. Local scale: i.e., within a given TOML/NORI/MARA sub-area or a scale of 10s to 100s of kilometres range;
3. Regional scale: is across the TOML/NORI/MARA contract areas or a scale of 100s to 1000s of kilometres range and in effect the entire, CCZ as covered in International Seabed Authority (2010a) and Chapter 2 of this thesis; and
4. Inter-province scale: i.e., between the CCZ, Peru Basin and in some cases here Cook Islands and Indian Ocean Nodule Field (IONF).

Unless referenced otherwise, the test work presented here was either directly carried out or directly supervised by the author. Technical assistance is acknowledged as applicable in each section.

4.1.2 Summary of formation of nodules

Polymetallic nodules precipitate in and on mud, part of a range of ferromanganese rocks found on the seabed, e.g. (Glasby, 2006). They are distinguished from mounds, crusts and other coatings by:

1. forming discrete particles (nodules; classed as coarse gravels to occasional cobbles per ISO 14688-1:2002);
2. the nodules facies typically presenting as consistent ranges of size and aspect ratios (major/long axis: minor axis: thickness);
3. when cut open, the nodules show concentric layering.

Manganese precipitation in the deep ocean has probably been a widespread natural process since at least the Ediacaran period (~635 to ~548 Ma or late Neoproterozoic). This was when the deep ocean first oxidized (Fike et al., 2006), well after the start of oxidation at the surface and in shallow seas in the early Proterozoic

(~2,300 Ma). Fossil nodules of Jurassic age have been found in the European Alps (Jenkyns, 1977; Sabatino et al., 2011), but these are believed to have formed in a shallower sea than the nodules found in the CCZ. In the present day, nodules have been in all the major oceans (Horn et al., 1973; McKelvey et al., 1983), as well as in high abundance at 200 m depth in the Gulf of Bothnia (Boström et al., 1982).

About 90% of the manganese introduced into the oceans is interpreted to be from submarine hydrothermal sources (Glasby, 1988, 2006; Elderfield and Schultz, 1996), with the rest from terrestrial sources. This hydrothermal manganese is typically relatively slow to oxidise in seawater, with claims that vented anomalies can be detected over 1,000 km from the source (Burton and Stratham, 1988) and including an estimate that it would take of the order of 1,000 years to chemically oxidise 90% of the Mn present at any one time in seawater (Murray and Brewer, 1977). As actual residence time for manganese is estimated to be only 20-40 years (Glasby, 2006), a range of catalytic and bacterial oxidation processes have thus been proposed. In some locations at least, dissolved manganese contents in seawater decrease with water depth, while particulate manganese contents increase (Glasby, 2006), a notable exception being at the oxygen minimum zone (variably located between 500 and 1200 m depth; (Stramma et al., 2008)) where both dissolved and particulate manganese levels increase. Direct influence of hydrothermal ferromanganese into nodules (or crusts) is unlikely due to a distinctly different chemical signature (e.g Figure 4-38 - Figure 4-40; (Azami et al., 2018)).

Compared to other provinces, nodules in the CCZ have higher than average grades of Ni and Cu as well as relatively high grades of Mn and Co (Table 4-1). While nodules in the different provinces have broadly similar forms (compared to other types of ferro-manganese precipitates such as crusts and chimneys), it is apparent from the widely different physio-chemical conditions between the provinces, that different formative processes have been at work. For example: high Mn in the Peru basin is attributed to dominant diagenetic processes (Von Stackelberg, 1997), while in the Cook Islands EEZ high Co is attributed to hydrogenetic processes fed by Antarctic Bottom water (AABW) (Hein and Petersen, 2013; Hein et al., 2015), and the low metal grades for nodules in the Atlantic are impacted by the effectively deeper location of the lysocline and calcite compensation depth (CCD) i.e. effectively below most of the seafloor e.g. (Archer, 1996; Cronan, 2019). The higher metal grades between the CCZ and Pacific Ocean average and the IONF and Indian Ocean average are interpreted to be due to higher primary productivity and location near the CCD by (International Seabed Authority, 2010a; Mukhopadhyay et al., 2018).

Table 4-1: Summary of nodule grades from different oceans and provinces

Element	Pacific Ocean	CCZ	Peru Basin	Cook Islands EEZ	Atlantic Ocean	Indian Ocean	IONF
Mn wt%	20.1	26.3	31.4	14.9	13.3	15.3	25.4
Fe wt%	11.4	6.6	5.1	17.3	17.0	14.2	7.90
Ni wt%	0.76	1.20	0.73	0.36	0.32	0.43	1.12
Cu wt%	0.54	0.98	0.41	0.16	0.13	0.25	1.02
Co wt%	0.27	0.20	0.06	0.42	0.27	0.21	0.14

Indian Ocean Nodule Field (IONF). Sources (McKelvey et al., 1983) except Cook Islands-Aitutaki Passage (Glasby et al., 1983) , Peru Basin (Von Stackelberg, 1997)

Within the CCZ, most of the metals are thought to have been supplied from net export of deceased micro-organisms and fecal pellets. This is broadly supported by a correlation of grades with primary productivity and the interpreted position of the calcite compensation depth e.g. (Halbach et al., 1981; International Seabed Authority, 2010a). Metal release is probably mostly from dissolution of the micro-organisms as they reach the seafloor (and before lithification is possible), there might be some particulate contribution from metal enriched hydrogenetic Fe-Mn oxide coatings on foraminiferal tests as described by (Palmer, 1985). There is also likely regional variation in grade ‘fingerprints’ related to the type of primary production (Section 4.5.2.2).

Within the CCZ, nodules are found either totally buried within the clay-ooze sediment host, partly buried and partly exposed to the overlying sea (most typical), and fully exposed to the sea on top of hard substrate. Depending on the situation, their form is consistently different (Figure 4-1), indicating that the local environment has controlled their growth. Workers, including the author, have noted that the sediment recovered in box-cores often has a very soft, almost gelatinous upper clay-ooze layer that contains the nodules e.g. (International Seabed Authority, 2010a). Photos of the seabed also often show small amounts of sediment “powder” sitting on the nodules (Figure 3.36, Figure 3.37, Figure 3.38). Thus, the uppermost part of the sediment and immediate overlying water is often described as a “semi-liquid” or “geochemically active” layer (International Seabed Authority, 2010a), (Figure 4-1).

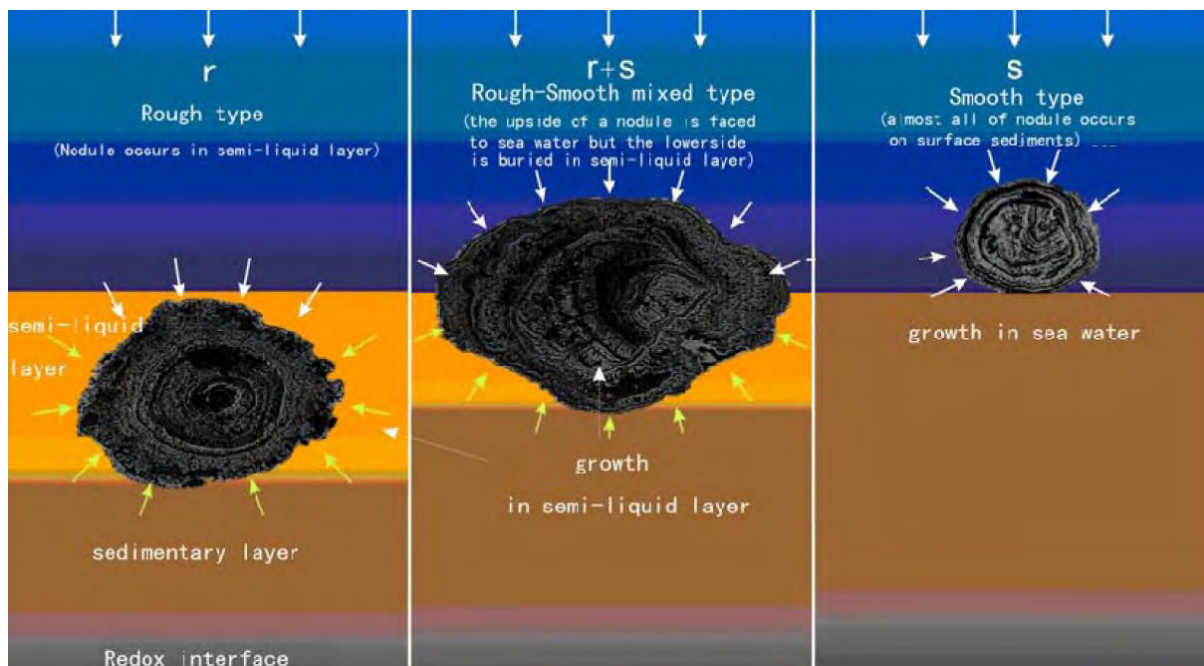


Figure 4-1: Types of nodules and their growth processes

Adapted from: International Seabed Authority (2010b); note that the so-called semi-liquid layer and immediately overlying waters can also be read as geochemically active layer (with regards to nodules).

CCZ nodules almost invariably show clear signs of semi-regular concentric layering (Figure 4-33 - Figure 4-37 in section 4.4.3.2), indicating that they have precipitated over time (e.g. Figure 4-2, Figure 4-3; (Chang et al., 2005; Yi et al., 2020)). The layers are composed of alternating amounts of Mn and Fe rich minerals as well as Mn minerals of different type and texture (section 4.4.3.2). Iron is one of the few metals that does not get accommodated within the manganese mineral structure, instead forming its own oxides that are finely intergrown with the manganese minerals.

Wegorzewski and Kuhn (2014) thus define are two main layer types: type 1 refers to dense “platey” textured layers relatively rich in iron; type 2 layers have dendritic texture and are relatively rich in manganese. Wegorzewski and Kuhn (2014) also separated out layers or zones intermediate between the two types (type 3, that are included here with type 2). Published information of the proportion of the two main layers is sparse, but type 1 is thought to be invariably less abundant. Within the TOML areas, (section 4.4.3), type 1 make up on average 24% of nodules versus 35-40% found by Wegorzewski and Kuhn (2014) in the BGR eastern contract area. Conversely type 2 within TOML samples average 68% (versus 50-60% in the BGR eastern contract area).

The type 1 and type 2 concentric layers are respectively interpreted to relate to changes between oxic and sub-oxic conditions, that in turn likely relate to changes in surface primary productivity and ocean chemistry, that in turn relate to interglacial/glacial periods respectively (Dymond et al., 1984; Wegorzewski and Kuhn, 2014). The hypothesis is that in glacial times, reduced ventilation or seawaters and/or higher primary productivity in the tropics leads to sub-oxic conditions in the upper ± 10 cm of sediment. The higher primary productivity events lead to an increase in organic flux to the seafloor, then oxidation/take-up of the organics results in local reduction of Mn^{4+} to soluble Mn^{2+} which can then adsorb onto any nearby surfaces (Dymond et al., 1984; Xiong et al., 2015). Both calcite-based and silica-based micro-organisms are thought to contribute materially, as discussed further below in section 4.4.

Microbes are the biggest component of biomass in the nodule fields. Wei *et al.*, (2010), Wang *et al.*, (2012) and UK Seabed Resources (2014) discuss how bacteria could play a role in the growth of nodules. Essentially, they may help in the formation of ancillary seeds for tiny (100 μm) micro Mn-nodules that agglomerate to form some nodule layers, as well as through what appear to be biofilms that lead to the formation of the manganese rich layers onto the iron rich layers. Microbial oxidation of Mn^{2+} can absorb and affect/disrupt the phyllo-manganate structure (Hinkle et al., 2016), in a manner very similar to that seen in type 1 layers. Blöthe *et al.*, (2015) use molecular 16S rRNA gene techniques to show that polymetallic nodules contain an abundant and diverse prokaryotic community dominated by nodule-specific Mn^{4+} -reducing and Mn^{2+} -oxidizing bacteria. These bacteria were not detected in the sediment hosting the nodules.

Nodules are also interpreted to grow under both hydrogenetic processes at the surface and diagenetic processes in the buried portion (Bender et al., 1966; Callender and Bowser, 1980). Most nodules in the CCZ formed under a combination of these two processes, but nodules that formed exclusively under one process or the other are also found (Figure 4-1). As all types of nodules are typically concentrically zoned e.g. (von Stackelberg and Beiersdorf, 1991; Chang et al., 2005; Menendez et al., 2018) it likely follows that both hydrogenetic and diagenetic nodules are subject to some measure of oxic and sub-oxic conditions. Note that it should be made clear that this is not implied in (Dymond et al., 1984; Wegorzewski and Kuhn, 2014); and that (Benites et al., 2018) report hydrogenetic nodules from the Mascarene Basin without zonation. However, within the CCZ, even hydrogenetic (or smaller smoother nodules found on hard substrates) can have broadly similar Ni, Cu, Co and Mn grades to diagenetic (or variably sized rough-smooth mostly buried nodules in/on soft substrates).

A further key point is that the mechanism for the growth of nodules is very likely different to the mechanism for the enrichment of metals such as Ni and Cu in nodules in the CCZ. This is the case simply because low metal grade nodules are found elsewhere – thus there needs to be particular conditions for the CCZ (and other higher-grade areas like the Indian Ocean Nodule Field and Central Pacific Basin). It is generally accepted (Chen et al., 1988; Broecker, 2003; International Seabed Authority, 2010a), that these metals are sourced from the same organic flux that is breaking down at the seabed where the nodules are growing,

although the dissolution is assigned to the actions of acidic CO₂, particularly below the lysocline and around the calcite compensation depth likely located several hundred metres below (Chen et al., 1988).

The age of the polymetallic nodules and other ferromanganese deposits can be constrained by their sizes vis a vis modelled growth rates of (0.5 to 3 cm per Ma; (Chang et al., 2005); Figure 4-2), suggesting ages of 1 to 5 Ma or more. (Yi et al., 2020) study in detail an 18 mm radius nodule from the western CCZ and find ¹⁰Be/⁹Be isochron ages up to 5-5.5 Ma and more precise magnetic reversal ages up to 4.7 Ma. Many polymetallic nodules from TOML B for example contain fragments of clearly older nodules encompassed with younger ferro-manganese growth.

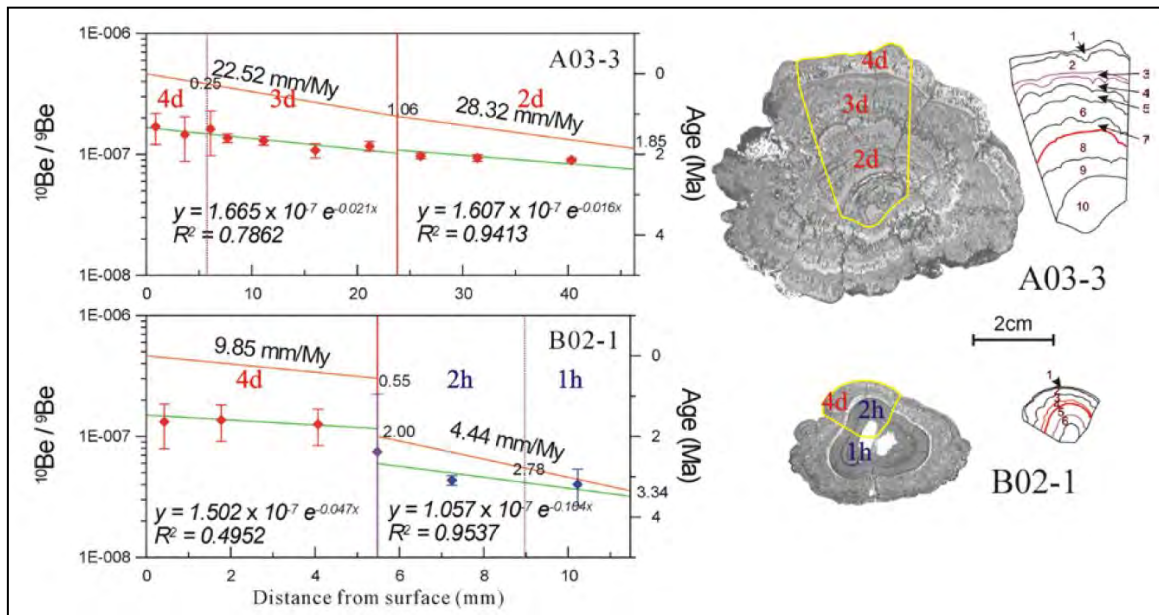


Figure 4-2: Growth rates and internal textures and depth profiles of two KODOS nodules

Source Chang *et al.*, (2005); Note the interpreted 1.45 Ma hiatus between hydrogenetic and diagenetic phases in the growth of B02-1 (step in red line).

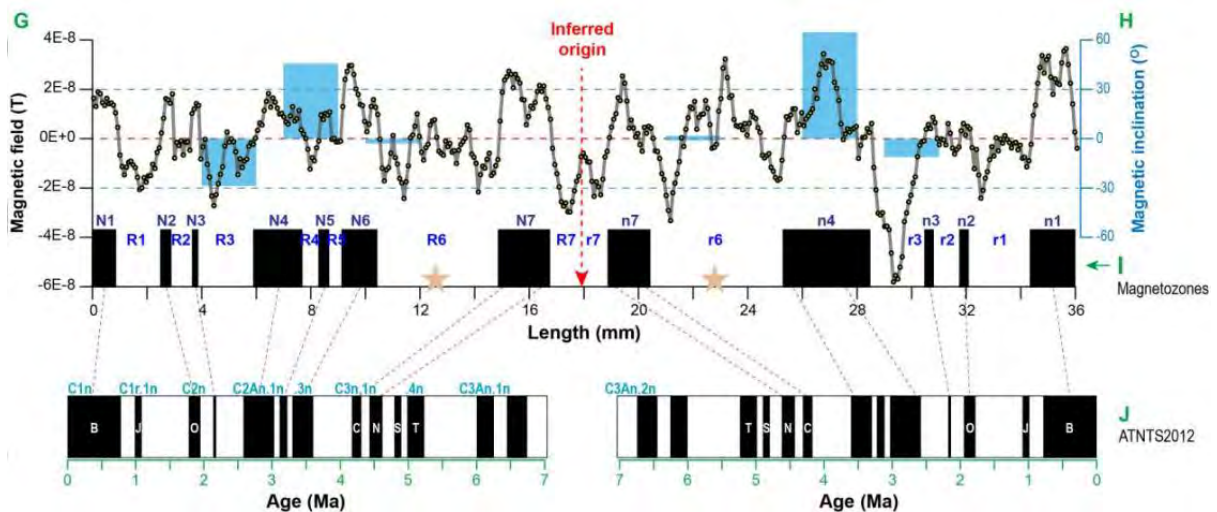


Figure 4-3: Polar reversal records across a single nodule from the western CCZ

Reproduced from Yi *et al.*, (2020). Derived via magnetic scanning using a Hall probe (G, H, I) and compared with the 2012 Astronomically Tuned Neogene Time Scale (J). B, Brunhes (C1n); J, Jaramillo (C1r.1n); O, Olduvai (C2n); C, Cochiti (C3n.1n); N, Nunivak (C3n.2n); S, Sidufjall (C3n.3n); T, Thvera (C3n.4n).

Within the ~40 cm depth reach of box-cores, nodules are mostly found at the surface, but as many as 23% by abundance may be buried (Kotlinski and Stoyanova, 2006; Lipton et al., 2016); these buried nodules undergo some chemical and mineralogical modification due to the move to permanently sub-oxic conditions (Wegorzewski et al., 2020). However, nodules are also found much deeper. Cronan (1973) reports on nodules found at depths of down to 244 m within the cores of DSDP Leg 16. These are as old as Mid-Eocene (± 40 Ma), although in some cases slumping of sediment into the drill-hole carrying nodules cannot be entirely ruled out. As nodules grow more slowly than the net sedimentation rate in the CCZ, there needs to be some mechanism by which most of the nodules remain at the surface (see also Chapter 3). Leading candidates are bioturbation (organisms selectively sweep and burrow/repack the sediment around the nodules) and seabed currents below the boundary layer (sweep sediment off the tops of the nodules but not often on to them...; see also section 4.3.2).

4.2 Nodule Sampling Methods

This section explains the common methods for collection of the samples studied in subsequent sections and provides a summary table of sample type by analysis type. Methods of analysis of samples are included in the each of the relevant sections below along with the results of that analysis.

A summary of analysis by sample type and location is also presented here.

4.2.1 TOML and NORI Sampling methods

Note that an outline of the methods, sufficient to compare and replicate the process is given here. Full equipment specifications, procedures and records of deployments are included in the relevant cruise reports. The methods to collect towed photos area have already been discussed in Chapter 3.

4.2.1.1 TOML dredging with an epibenthic sledge

Two devices were used for dredging, varying between the TOML CCZ13 and the TOML CCZ15/CCZ17 cruises. The intent of the sampling was to collect material for metallurgical test work, including chemical whole rock variance characterisation as presented in this chapter.

An epibenthic sledge or sled was designed and built for the TOML CCZ13 dredging by KC Denmark (Figure 4-4, Figure 4-5). The device was moderately successful, collecting ~2 t of sample in 14 deployments with up to 370 kg recovered per deployment. An epibenthic collector was chosen so as to:

1. Be able to be set up to skim the seafloor collecting epibenthic and inbenthic located nodules with minimum clay-ooze;
2. Hopefully thus, be more able to clean itself of clay-ooze;
3. Consequently, have less impact on the marine environment.

The sled was typically equipped with an attitude sensor. Data from this device were recovered and analysed at the end of each deployment to try and improve operation performance. An attached camera produced several seabed images prior to towing but was only able to be mounted behind the collector blade so was obscured by the sediment plume on towing.

Sample handling procedures essentially comprised weighing on recovery, followed by mesh screening (at approximately 6 cm) and photography of all nodule son a lay-down sheet, or if there was an excess of material for the photo, a typical sub-sample. Many of the nodules were broken, likely from the collection and time in the dredge.

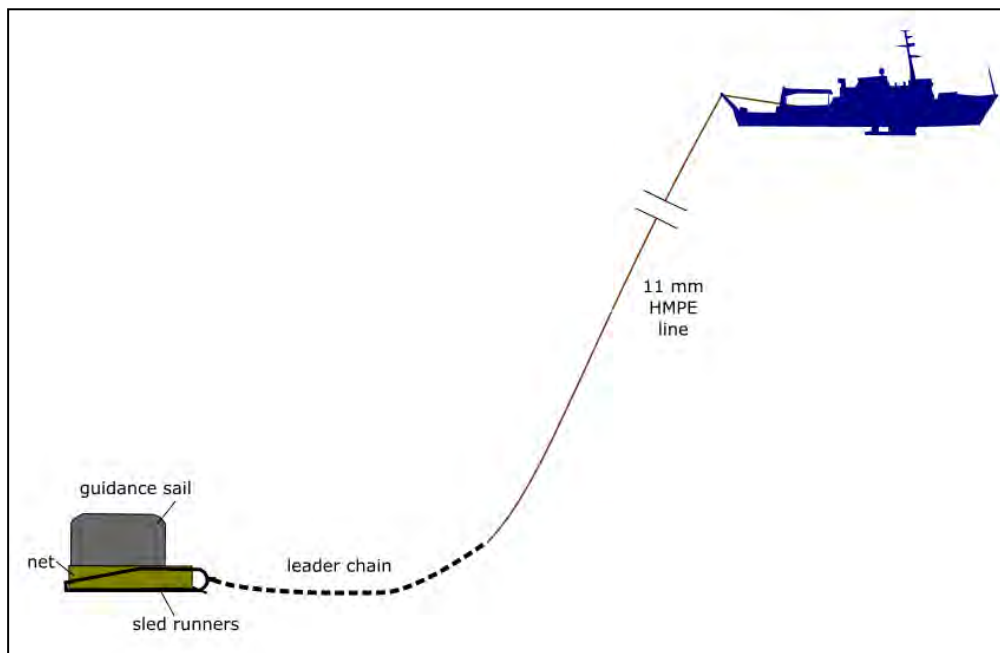


Figure 4-4: Epibenthic sled Deployment Schematic

After some trial and error, the approach generally taken to dredge was:

- About 1.5 km before the start of the target zone, steam into the wind at 1.5 to 2.5 knots paying out tow-line to 6-7 km;
- On reaching the bottom or the target slow line out to slowest effective forward speed (i.e. having available steerage). this was typically 0.3-0.8 kt speed over ground (SOG);
- Use line out to regulate load as transmitted to a load cell mounted on the A-frame sheave;
- Run the load between minimum (line slack) and maximum loads (lift off), decreasing the range around what was judged to be the effective towing load (this was typically a range of only about 40-80 kg due to line geometry over the loadcell);
- Several during the deployment lift and lower the sled using the vessel speed to wash out excess mud that might be filling the sled (termed a “tea-bag” manoeuvre). Care was taken to minimise use of the winch to avoid tipping the nose of the sled (due to weight of leader chain) and losing sample.
- End the dredge by starting line in and speeding up the boat to 2 knots

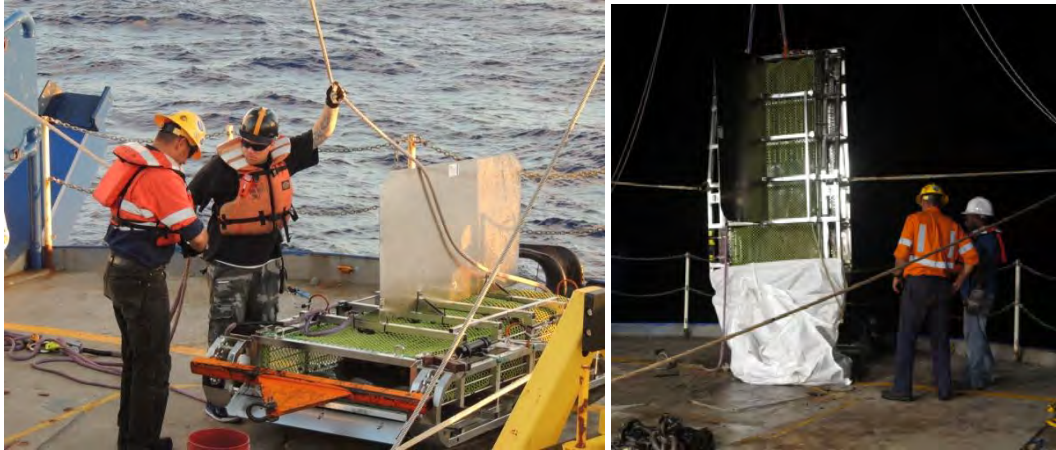


Figure 4-5: Epibenthic sled with sample on recovery and unloading into a bulker bag
Photos taken by A. Flinders and B. Powers

4.2.1.2 TOML dredging with TOML CCZ15, CCZ17 Galatea dredge

The dredging approach was changed in TOML CCZ15 and TOML CCZ17 for reasons of operational practicality and efficiency. The expedition vessel contractor had their own dredge and dredging system already on the survey vessel that promised much higher recoveries due to dredge size and more importantly the nature of the positioning/navigation system (pinger) that was included with the system. The haul per dredge proved significantly higher with 2.2 t in 4 deployments in TOML CCZ15 (up to 800 kg recovered per deployment) and 2.1 t in 3 deployments in TOML CCZ17 (up to 1,100 kg recovered per deployment).

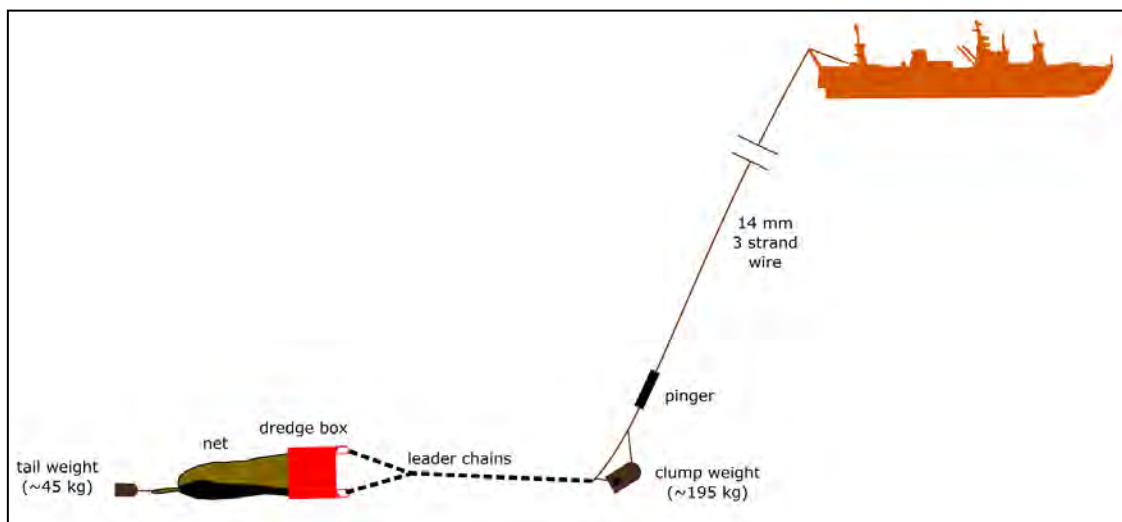


Figure 4-6: Galatea Dredge Deployment Schematic

The sample locations were picked to ensure that, between the sampling of these cruises and the TOML CCZ13 cruise, at least one dredge sample was taken in each TOML contract sub-area. Dredges were also the quickest and most effective way to sample TOML Area A, albeit in a non-quantitative manner.



Figure 4-7: Operations and details of the YMG Galatea-trawl dredge

Photos taken by the author, Mele Christina Pomee, Sisilia Kamila Faeamani, Victor Hugo Rocha Lopes.

The process of dredging involved:

- Dredge lowered at 0.5 m/s for first 200 m then 1 m/s to the bottom, then slowed to 0.5 m/s till touching the seabed;
- Recovery to surface all the way at 1 m/s (full speed);
- The vessel maintained forward speed into the weather at all times (~0.8-1.3 knot SOG was adequate, i.e. no change in speed needed);
- Winch speed slowed but not stopped and the pinger trace height (~10 m) used to estimate when the dredge touches;
- Leader chain and bridle were about 4-5 m long to ensure dredge is pulled parallel to the seabed;
- “Teabag” manoeuvres used to clean the dredge between landings (each landing is about 1 minute and after lifting at about 0.7 m/s to 100 m the cleaning taking about 2-3 minutes before return to the seafloor at 0.5 m/s);
- 3-7 “teabags” were carried out depending on weight of sample required.

4.2.1.3 TOML Box-coring

Box-corers have been used in the CCZ since the 1970s. As they collect a seabed sample effectively intact, they are seen by most workers as the best possible sampling device on which to base the estimate of nodule abundance in any given area. As such, the box-core samples were the most important deployment during the CCZ15 cruise results and by extension, contribution to the subsequent TOML mineral resource estimate. Chapter 5 includes a comparison of box-corers with the less accurate free-fall grabs, which were also used by other workers including the pioneer contractors who provided the reserved areas taken up by TOML, NORI and Marawa.

Box-corers come in different sizes: typically, 0.1 m² or 0.25 m² (plan area of sample box or tube), but box-corers of 0.75 m² and 1 m² have also been used.

Smaller box-corers are good for micro-biological sampling of the epibenthic zone and are adequate for the estimation of abundant nodule resources, especially those involving smaller nodules. For accurate estimation of the abundance of larger nodules, especially in lower quantities, larger box-corers are more accurate (Figure 4-8).

The largest box-corers used in the CCZ were 1 m² (Afernod’s Sympas system and one built by the OMCO consortium), but by all accounts, these were very large and difficult to handle. Kennecott built a 0.75 m² corer and used it extensively, deeming it to be an effective compromise (Felix, 1980).

It was the Kennecott experience that led the author to have two working 0.75m² box-corers built for TOML’s CCZ15 expedition (sold later to the operator of NORI and Marawa; section 4.2.1.4). A prototype was also tested during the TOML CCZ13 expedition.

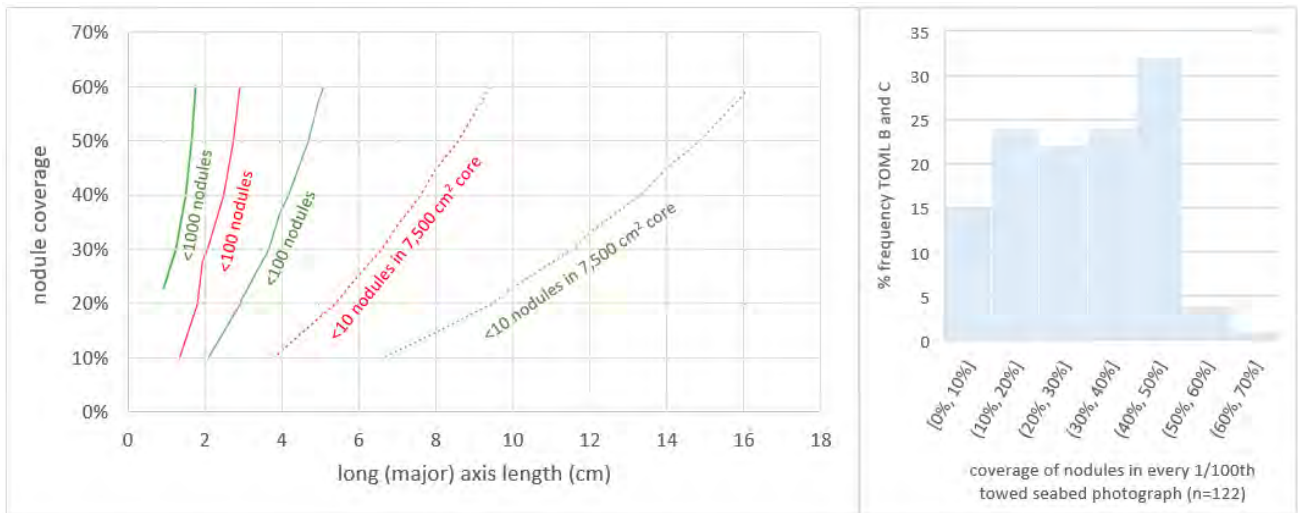


Figure 4-8: Nodule cover and count relationship by box-corer area

To estimate coverage, nodules are assumed to be slightly prolate i.e., x by y proportions of 1 x 0.75 per Figure 4-23. Estimation of coverage done from seabed photos using Image J software (image by image contrast adjustments followed by conversion to binary format and histogram measurement over clear and a representative area).

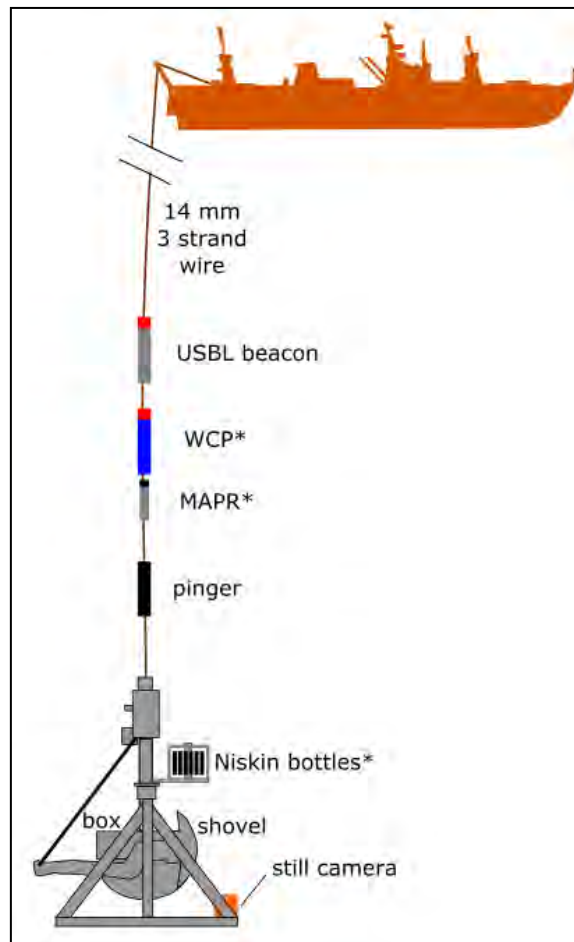


Figure 4-9: Box-corer Deployment Schematic

Ultrashort baseline (USBL) transponder used for navigation to the sample site; water-column profiler (WCP) and mini-autonomous plume recorder (MAPR) used on some deployments to collect temperature and turbidity from the water column (50 m above the corer); pinger used to accurately measure distance to seafloor so as to time the landing versus vessel speed; niskin bottles used to collect water column samples on some deployments.

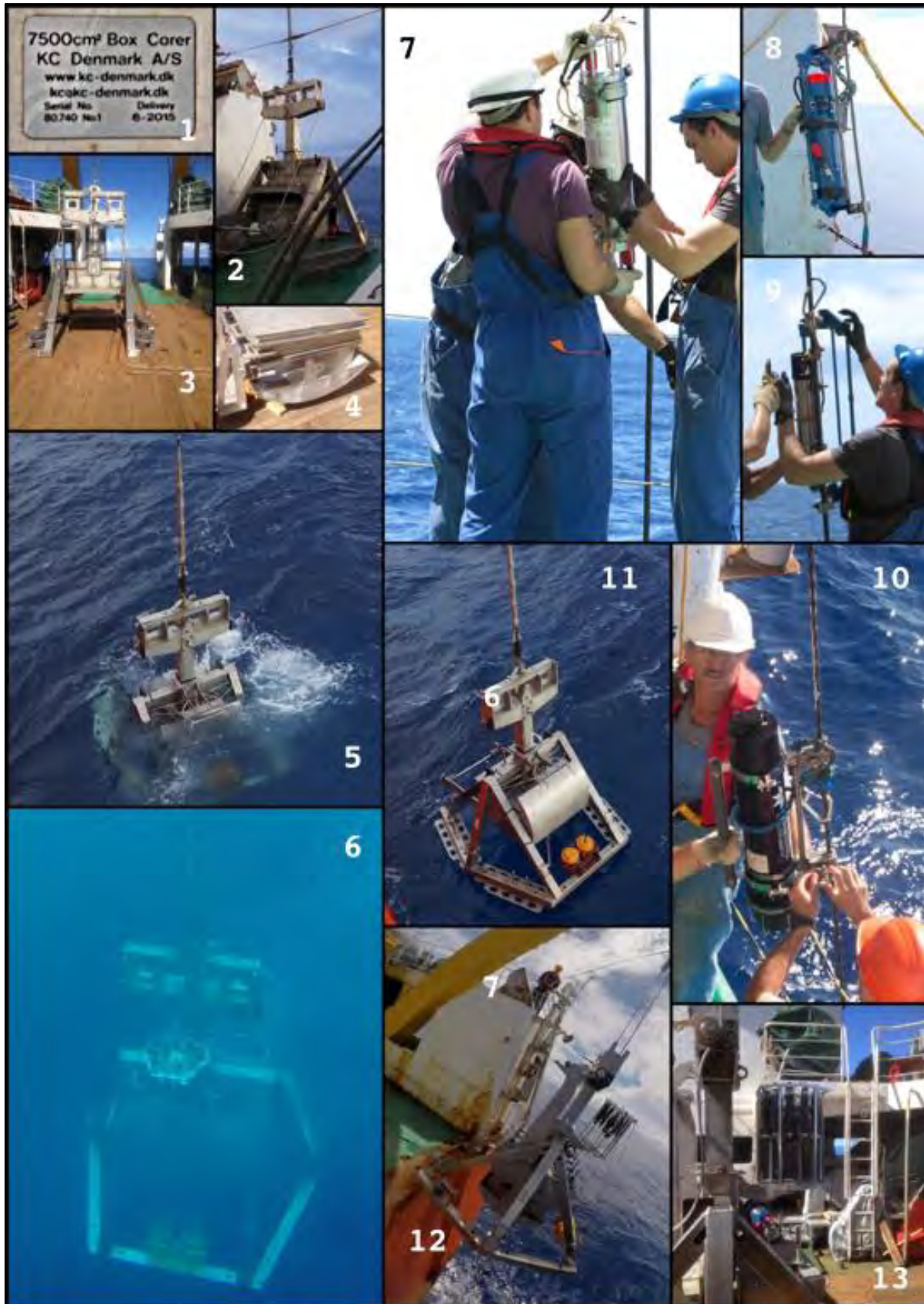


Figure 4-10: Details and operations with the KC box-corer

Photos taken by the author, Rod Conroy, Mele Christina Pomee, Sisilia Kamila Faeamani, Victor Hugo Rocha Lopes.



Figure 4-11: Details and recovery of the YMG box-corer

Photos taken by the author, Mele Christina Pomee, Sisilia Kamila Faeamani, Victor Hugo Rocha Lopes.

Box-coring using mostly a 0.75 m² box-corer (but in places a 0.25 m² unit) was undertaken during the TOML CCZ15 expedition to collect samples for mineral resource estimation, to collect biological samples for environmental base-line measurement and to collect geotechnical data. Box-core operations involved:

- Deployment and recovery off the stern of the vessel using three strand wire and the vessel's starboard hydrographic sample winch (Figure 4-9);
- The vessel maintained minimum forward speed, typically 0.3 to 0.7 knots into result (combination of surface wind and waves);
- The box-core's progress and status (fired or not) was tracked using a signal from a 12 kHz pinger;
- Landing points were within 500 m of the planned grid co-ordinates (as per dive plans) with the following pre-conditions:
 - Landing points avoid steeper areas (>10° slope) based on pre-existing multi-beam bathymetry;
 - The hydrographic surveyors guiding the landing never sight the backscatter product of the existing multi-beam coverage (to eliminate chance of sighting bias);
- USBL navigation provides location to within ±15 m.

As mentioned above, two types of box-corers were used during the TOML CCZ15 cruise:

1. 0.75 m² box-corer manufactured by KC Denmark (80.740 code; Figure 4-11). For part of the cruise, the KC box-corer included a carousel of 12 small volume (300 ml) Niskin bottles for water sampling. Each side of the box has an internal width of just below 87 cm (there are minor variances of 1 - 2 mm with the corner welds), so the true area of 7569 cm² is used for the abundance estimation.
2. 0.25 m² box-corer manufactured by YMG (Figure 4-12), but based on a 1970s USNEL/Scripps design.

The sampling program and processes and logging schema were designed by the author who served as Chief Scientist on the expedition. Logging was completed manually by the Lead Scientist on shift. The manual completed logs were scanned for filing and then key results transposed into MS Excel.

All weights were taken using a Wedderburn Marine motion compensated scale (WM42; Serial number #3380724) that was checked and calibrated in Brisbane, Australia, before shipping to the vessel. The scale has a 40 cm x 40 cm plate with vessel motion recorded and corrected electronically. Scales are claimed to be accurate to 60 kg +/- 50 g, which was as observed during the cruise. The scales were checked using 12 x 1.5 l or 12 x 2 l water bottles and recorded weights were consistent with the mass of water plus packaging.

Upon arrival on deck, the nodules were photographed *in situ*, removed from the box and weighed three times:

- 1st time with mud still attached (preliminary weight) to enable biological analysis of an unwashed sample;
- 2nd time after washing in filtered salt water (washed weight);
- 3rd time several days later and after exposure to 30-90 minutes in ~25° C air conditioning and removal of any ponded or sweated free water (aired weight).

Note that this third aired weight is the official 'wet weight' of the sample. A 'dried weight' would only be possible after drying of the entire sample in a laboratory oven, and this is more easily, and just as accurately, estimated from moisture estimates per the test-work in section 4.7.

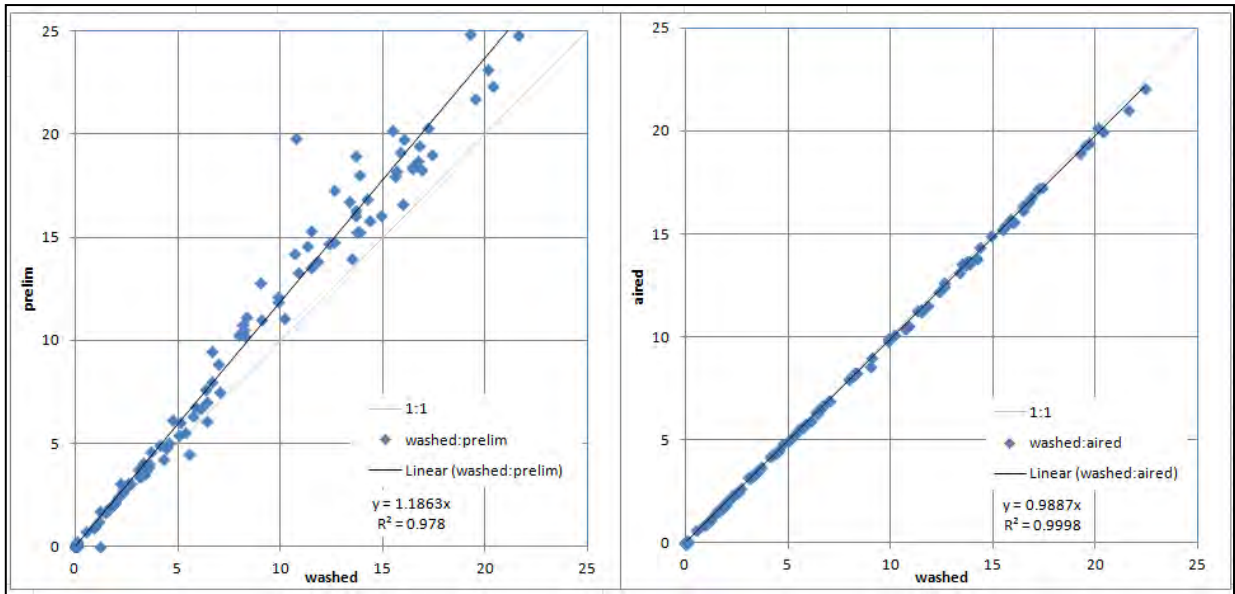


Figure 4-12: Preliminary vs. washed vs. aired box-core nodule sample weights (kg)

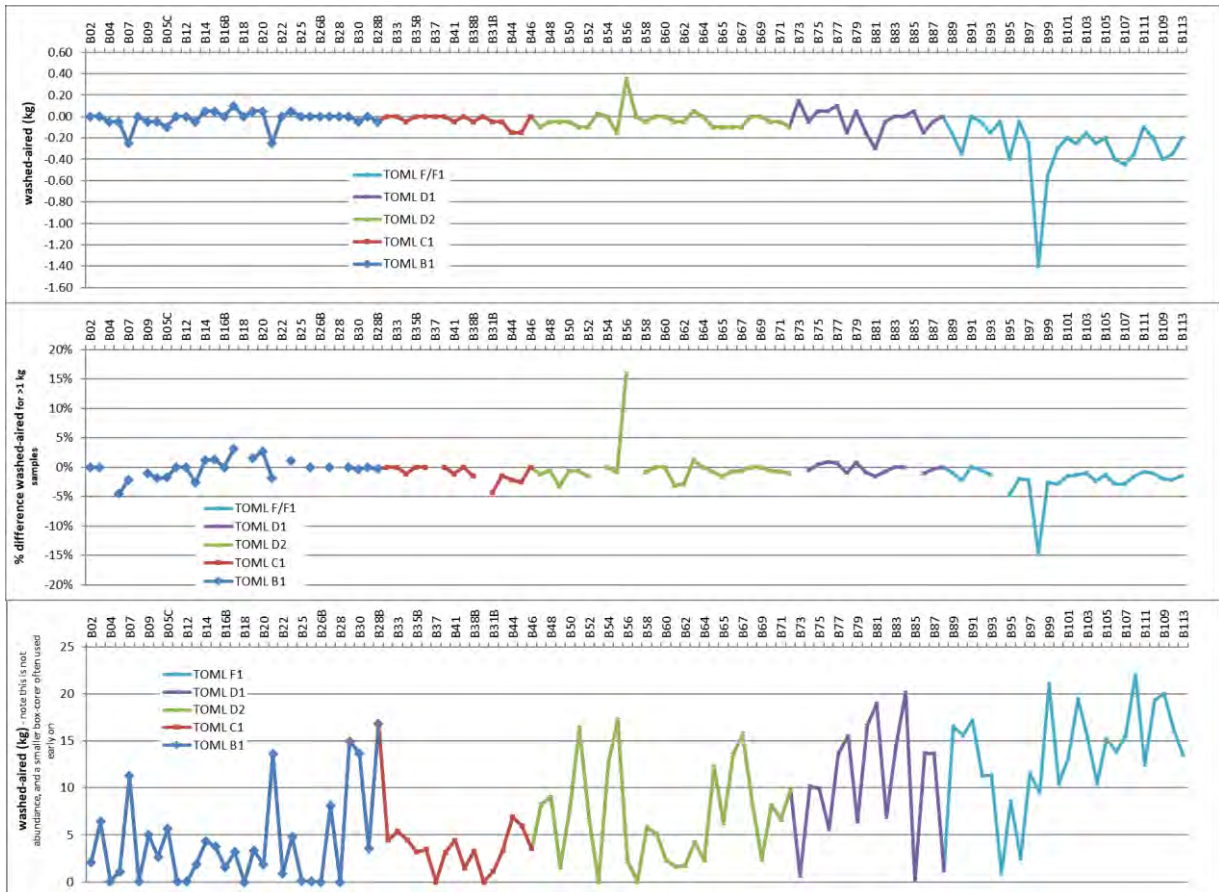


Figure 4-13: Differences in washed vs. aired box-core nodule sample weights by area

Note also that at each stage of handling, despite due care, some attrition of the nodules occurred with loss of a small (generally <1%) of fine material (clay to sand sized). The bulk of this loss occurred at the washing stage, but it was noticeable at the aired stage as well. The rate of attrition varied by nodule type (rough

nodules broke up more) and by sampled sub-area (the nodules in the southern part of Area F were especially soft).

The difference between the washed and other weights is illustrated below in Figure 4-13. There is almost no difference between the washed and aired weights (average for all samples over 1 kg is -0.87%; in Area F it is -1.86%), with the cause of the minor differences debatable, for example:

- moisture i.e. related to sample size versus or storage devices (plastic bags with larger samples are fuller and may lose a little less water prior to air drying step); or
- attrition; softer type 1 smooth nodules only tending to show slightly more erratic results than type 2 rough-smooth nodules).

To ensure transparent chain of custody, during TOML CCZ15 handling of nodules was at all times supervised by the Chief or Lead Scientists, who were also the only people permitted to weigh the nodules, record the weights and seal bags and pails for transport. Nodule sampling was managed as follows (refer Figure 4-14, Plates 1 to 24):

- From the box, nodules were removed to the weighing station (in the geology laboratory or adjacent to the box-core landing spot on the back deck; (Plates 8 &13);
- Here, preliminary weight was taken and recorded, the nodules were washed, firstly the selection with observed fauna, then the rest of the nodules;
- Then the washed weight was taken and recorded (Plate 14);
- Then the nodules were carried to the geology laboratory where they were arranged and photographed by a designated scientist before temporary storage in sealed plastic bags in a designated area;
- Then at the conclusion of sampling of an area (1-7 days after collection), the samples were laid out about 6-20 at a time for airing (Plates 21 & 22);
- After 30 to 90 minutes of airing, reference and duplicate samples were selected, re-packed weighed again, sealed in plastic bags security tagged with tamper-proof tags or tape and then photographed (Plates 19 & 20);
- Then the nodules were packed into specially marked pails with tamper-proof tape (Plate 23);
- Duplicates were collected from roughly one in ten samples. Subsamples were taken using cone and quartering;
- Pails were then transported (escorted by Chief or Lead Scientist) to a refrigerated container (reefer) on deck for transport to Brisbane, Australia, where the main assay laboratory is located (Plate 24);
- Reference samples were placed in specially marked and labelled pails for airfreight to Brisbane, Australia (also for backup in case of loss of the reefer in transit);
- Duplicate samples were placed in specially marked containers and labelled for airfreight to Jacobs University, Bremen, Germany, where the check laboratory is located. These samples and all container pails were sealed with tamper-proof tape.



Figure 4-14: Details and operations regarding sample processing

Photos taken by the author, Mele Christina Pomee, Sisilia Kamila Faeamani, Victor Hugo Rocha Lopes.

4.2.1.4 NORI and Marawa Box-coring

The two box-corers built for the TOML CCZ15 expedition were sold, rented and transferred via creditor seizure to Deep Green Metals in 2018 and 2019. Thus, the process described above also applies in part to the NORI and Marawa samples. There are however differences in operations and handling procedures as described in Lipton, Nimmo and Stevenson (2019, 2021). Key points are:

1. The survey vessel held position on DP (dynamic positioning) until the corer was approximately 30 m above the seafloor and within a 35 m target circle, then the corer was lowered to the seabed;
2. Seabed imagery was via a go-pro video camera, in part with a laser scale;
3. On recovery three processing protocols for environmental, geotechnical, and resource were undertaken in the following sequence (reproduced from Lipton, Nimmo and Stevenson (2021)):
 - a. The top of the sample with the supernatant water still in situ was photographed.
 - b. The water was then carefully siphoned, bailed and/or suctioned off the sample and processed for biological analysis by the biological team onboard.
 - c. The undisturbed surface of the retrieved material (nodule surface) was photographed.
 - d. A 50 cm by 50 cm area of the retrieved material was cordoned for biological study.
 - e. Three sub-samples were obtained from the undisturbed areas outside of the biology exclusion area for geotechnical purposes. All nodules except for possible buried nodules captured in the 2.638-inch push samples followed the Mineral Resource processing path.
 - f. All surface nodules, when extracted from the box, proceeded to the biology wet laboratory where they were washed with cold seawater through a sieve.
 - g. All buried nodules in the 50 x 50 cm area reserved for biologic sampling also proceeded to the biology wet laboratory. After washing, these nodules were returned to the geology wet laboratory.
 - h. All buried nodules outside of the area of biologic investigation were washed of mud on deck and proceeded to the geology wet laboratory for description, measurement, photography, and sequestration in sample bags within gasket sealed pails.



Figure 4-15: Details and operations regarding sample processing

Reproduced from Lipton, Nimmo and Stevenson (2021). 1 = Sample with supernatant water photographed. 2. Water siphoned off for biological processing. 3. Boxcore with water removed showing GoPro camera mount and 50 x 50 cm frame demarcating area for biological study. 4. Example of GoPro top shot showing nodule distribution. 5. Geotechnical samples being taken. 6. Each layer was excavated for nodules, which were placed in collection trays for further biological processing and mineralogical logging.

4.2.2 Available sample datasets

For this thesis, there were ten sample datasets available as follows, with primary sample numbers by area and sub-area per Table 4-2:

1. **Basic geochemical data – section 4.4**
Comprising nickel, copper, cobalt, manganese and in some cases iron and a few other elements, this exists for historical data mostly sourced from the International Seabed Authority and including both confidential and public information. Little is known about analytical methods but review by Nimmo, Morgan and Banning (2013) found good consistency between the different Contractor dataset sources as covered in Chapter 5.
2. **Detailed geochemical data – section 4.4**
Discussed in more detail in section 4.5.1 for the TOML box-core samples. This includes LOI, Al₂O₃, BaO, CaO, Cr₂O₃, CoO, Fe₂O₃, K₂O, CuO, MgO, MnO, Na₂O, P₂O₅, SO₃, SiO₂, NiO, TiO₂, PbO, ZnO by chromite/manganese ore fused disk XRF method (ME-XRF26s at ALS Laboratory Group in Brisbane, Australia) for all samples as well as Ag, Al, As, Ba, Be, Bi, Ca, Cd, Co, Cr, Cu, Fe, Ga, K, La, Mg, Mn, Mo, Na, Ni, P, Pb, S, Sb, Sc, Sr, Th, Ti, Tl, U, V, W, Zn by high grade four acid ICP-AES method (ME-ICP61a at ALS), and Li, Be, Sc, Ti, Rb, Y, Zr, Nb, Mo, Te, Cs, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Ta, W, Pb, Th, U by 0.5M HNO₃ ICP-MS (at the Integrated Environmental Studies Program Group, Earth and Space Sciences Program, at Jacobs University in Bremen, Germany) for selected samples. Broadly similar element suites and elements are available for the NORI (Lipton et al., 2019) and Marawa box-cores.
3. **Variance (aliquant) geochemistry – section 4.4**
Carried out on the TOML dredge samples from CCZ13 and CCZ15 each dredge sample was sub-sampled ~ 30 times to characterize “worst case” variance with regards to mineral processing. Analysis was for LOI, Al₂O₃, BaO, CaO, Cr₂O₃, CoO, Fe₂O₃, K₂O, CuO, MgO, MnO, Na₂O, P₂O₅, SO₃, SiO₂, NiO, TiO₂, PbO, ZnO by chromite/manganese ore fused disk XRF method (ME-XRF26s at ALS).
4. **Sediment Chemistry – section 4.4**
Carried out on many of the NORI D box-core samples and varies by sample but including: chlorophyll and algal counts, wet and dry weights, moisture, as well as Al, Sb, As, Ba, HCO₃, Bi, B, Cd, CaCO₃, Ca, C, TIC, TOC, CO₃, Cr, Co, Cu, OH, Fe, Pb, Mn, Hg, Mo, Ni, NO₃-N, NO₂-N, OM, PO₄-P, TP, Se, Ag, Sr, Te, Tl, TS, U, V, Zn. (at Wetlab Nevada and ALS Washington, USA).
5. **Nodule Density – section 4.6**
Carried out on some of the TOML box-core nodule samples both as single nodules and parcels using an immersion method per the section below.
6. **Sediment Density – section 4.6**
Carried out on some of the TOML box-core sediment samples by box-core level using a sub-core and an immersion per the section below. When combined with vane shear measurements provides an essential summary of possible bearing loads.
7. **Moisture determinations – section 4.7**
Carried out on some of the CCZ13 TOML dredge samples, with a combination of air and oven drying per the section below.
8. **Attrition testing – section 4.8**
Carried out on one of the CCZ13 TOML dredge samples, with a combination of wet and dry tumbling of sub-samples per the section below.
9. **Packing testing – section 4.9**
Carried out on two end-member TOML dredge samples.
10. **Nodule long-axis measurements – Chapter 5**
Carried out on most TOML box-cores with readings from the samples laid out on a sample grid compared to equivalent readings from photos of the box-core sample in-situ on the vessels deck and in some cases the seabed immediately prior to sampling.

Table 4-2: Available dataset: number of samples by area

Area	Basic Chemistry	Detailed Chemistry	Variance Chemistry	Sediment Chemistry	Nodule Density	Sediment Density	Moisture determinations	Attrition testing	Packing testing	LAE (grid)
TOML A	20	2	2				1		1	
TOML B	76	1	1				1			
TOML B1	45	30		5*	4	5				27
TOML C	73	1					2			
TOML C1	27	16	1	5*	2	3		1		14
TOML D	43	10	10				6			
TOML D1	18	15		2*	2	3				15
TOML D2	33	27		3*	2	3				26
TOML E	13									
TOML F	21	19	4	3*	1	6	1	1		15
TOML F1	10	10		1*		3	1			10
NORI A	40									
NORI B	30									
NORI C	137									
NORI D	373	213		200						
NORI DSAO	39	39		30						
Marawa 18	10									
Marawa 19	23	2								
Marawa 20	49	18								
other	2733									
total	3813	403	18	249	11	23	12	1	2	107

Note that one sample may have multiple analytical methods or multiple test scenarios performed on sub-samples. *bioavailable selective leach (not used in this thesis)

4.3 Seabed precipitate types and classification

This section comprises three inter-related subjects. Namely:

1. Classification of nodule forms and facies. This has value in mineral resource assessment (e.g. (Lipton et al., 2019)), biological studies (e.g. (Tilot et al., 2018)) and engineering (e.g. sizing of nodules versus sizing hydraulic transport systems). The TOML areas studied during the CCZ15 expedition provided a wide range of nodule sizes and forms for classification.
2. Nodule forms reflect their growth history. This involves consideration of the mechanisms concerning nodule formation and leads to a conceptual analysis of key drivers behind the main types of nodule facies.
3. Other precipitates. Nodules are not the only precipitate type on the seafloor, massive diagenetic crusts are an obvious endmember of some of the processes that form nodules and other types of precipitates are included for completeness.

4.3.1 Nodule Classification

4.3.1.1 *Prior nodule classification schema and methods to define the TOML system*

It seems to be that there are almost as many nodule classification systems published, as there are exploration Contractors in the CCZ (e.g. Table 4-3). Classification systems include examples with a strong focus on the morphology of the nodules individually e.g. (Halbach and Ozkara, 1979; Yegiazarov and Zyka, 1985) and others that combine areas into type facies (e.g. Ifremer's (Menot et al., 2010), KIOST's (Chang et al., 2005), YMG's (Kruglyakov, 2014)). Application of these classification systems and facies can be quite elaborate.

Ultimately a facies system of some sort seems to be convenient for characterizing some local scale areas, and it has been used by biologists to try and classify associated fauna (Veillette et al., 2007; Menot et al., 2010). However, facies do not seem to be easily applied to other areas, especially over greater distances. (Menot et al., 2010) found that they had to define other variants of the facies previously proposed by Ifremer (e.g. termed BP, C+, C+M, CP, 0, "Western" or mixed) and ultimately these defined a continuum of types mostly between and around their three main facies. TOML experienced similar issues with the application of the Yuzmorgeologiya system during the TOML CCZ15 cruise.

A classification system universal to CCZ is that of International Seabed Authority (2010b), Figure 4-1. This system was originally defined at a 2003 ISA workshop that included most of the exploration Contractors of the time as well as other experts. Through three simple classes, it effectively accommodates a wide range of types of nodules.

Table 4-3: Some other known logging systems

	(Meyer, 1973)					(Piper et al., 1979)			(Sorem, 1977)		(Halbach et al., 1975); (Halbach and Ozkara, 1979);			(Skornyakova, 1984; Yegiazarov and Zyka, 1985)		
TOML equivalent type Table 4-4	RS-bo	S	RS	I-S-lo		I-RS	sm-R	s-S	?S	?RS	S	RS	S	S	RS-rg	R
Morphology	discoid, fungoid	ellipsoidal till spherical	Spherical, ellipsoidal	very spherical	irregular-spherical	discoid, ellipsoidal	Ellipsoidal, spherical	ellipsoidal	spherical	discoid	Spherical, ellipsoidal	discoid, ellipsoidal	spherical	intergrown, spherical	discoid, ellipsoidal	spherical, discoid, ellipsoidal
Surface texture	botryoid, Top – smooth, lower part - rough	smooth	smooth, rough	smooth	Top – smooth, lower part - rough	Top – smooth, lower part - rough	rough	smooth	-	-	thinly porosity, smooth	Top – smooth, lower part - rough	Coarse porosity rough	smooth	Top – smooth, lower part - rough	Large and globular
Concentric (nuclei)	one	-	-	-	palagonite	-	-	one, several (a few)	rock debris	Debris of nodules	rock debris	Debris of nodules, rock debris	Debris of very old nodules	Some concentric	-	one
Texture	non-central concentric	symmetric concentric	concentric symmetric	concentric symmetric	concentric, radial	-	-	-	Fissile (thin-layer)	Coarse layering	-	-	-	Fissile (thin-layer)	Coarse concentric layering	Coarse concentric layering
Mineral composition	-	-	-	-	-	todorokite	-	δ -MnO ₂	-	-	δ -MnO ₂ , poorly crystalline	Top – the sane type B; lower part - the sane type A	δ -MnO ₂ , well crystallized	δ -MnO ₂ with 10 Å todorokite	δ -MnO ₂ with 10 Å todorokite	todorokite, birnessite
Size, cm	3,0 - 15,0	2,0 - 6,0	0,5 - 6,0	5,0 – 8,0	≤ 25,0	5,0 and more	< 5,0	1,5 - 3,0	-	-	0,5 - 8,0	≤ 14,0	1,0 - 3,5	-	-	-
Mn, %	27,90	24,70	21,20-23,50	20,50	15,90	-	-	-	-	-	16,00 - 24,00	22,00 - 30,00	23,00 - 32,00	19,80	-	25,50
Fe, %	5,40	6,70	6,60	11,30	-	-	-	-	-	-	8,00 - 15,00	4,00 - 8,00	< 7,00	11,50	-	6,20
Modulus Mn/Fe	-	-	-	-	-	-	-	-	-	-	< 2,50	2,50 - 5,00	> 4,00	< 2,50	2,50 - 5,00	2,50 - 10,00
Ni, %	1,40	1,29	1,22	0,70	-	rich	rich	-	-	-	-	-	-	0,69	-	1,14
Cu, %	1,22	1,09	1,00	0,50	-	rich	rich	-	-	-	-	-	-	0,46	-	0,98
Co, %	0,19	0,20	0,22	0,25	-	-	-	rich	-	-	0,25 - 0,35	0,15 - 0,25	0,10 - 0,20	0,36	-	0,20
Ni+Cu, %	-	-	-	-	-	-	-	-	-	-	1,10 - 1,90	1,50 - 2,80	2,00 - 3,00	-	-	-
Secondary ore elements	-	-	-	-	-	-	-	-	-	-	TiO ₂ (> 1,2 %)	TiO ₂	Mo, Zn, TiO ₂	Pb (≤ 0,10 %), TiO ₂	-	Zn (≤ 0,16 %)
Genesis	-	-	-	-	-	diagenetic	diagenetic	hydrogenetic	-	intermittence growth	hydrogenetic,	hydrogenetic - diagenetic	early diagenetic	hydrogenetic,	hydrogenetic - diagenetic	diagenetic

Adapted from an original compilation by the TOML CCZ15 science team. Mineral compositions are as stated originally in the sources (refer section 4.4. YMG are Yuzhmoregeologiya their type class (Yegiazarov and Zyka, 1985) relates foremost to the Russian exploration contract area and translate well to TOML B.

The TOML system was developed from the ISA system by the author during the TOML CCZ15 expedition, with assistance by other scientists on board (section 9.2.1). Essentially, a series of mostly optional prefixes and suffixes are added to the three ISA classes. This system was found to be straightforward to apply to the wide range in textures and forms mapped and sampled from the TOML areas (that span a significant proportion of the entire CCZ as mentioned above). Another key benefit of the system is retained simplicity so that the logging is more easily consistent between different geoscientists and can be applied to both high quality seabed photos and physical samples.

This is not to say that more specific local classification systems, or more specifically facies classes, do not have application. As already mentioned in section 3.4.11, a nodule facies scheme with two or three types can be applied to almost all of NORI D and TOML F. This classification system used by NORI is illustrated in Table 4-6.

4.3.1.2 Results of nodule classification

As mentioned above, the nodule classification system used in this study is based on the ISA schema (Figure 4-1). It is presented below in Table 4-4 and involves five criteria:

- criteria **1**: size (from the major horizontal axis) and **2** general texture (i.e. the rough/smooth textures per Figure 4-1) are normally the minimum required to complete the logging;
- optional additions are criteria **3**: nodule aspect (thinness vs width for oblate to slightly prolate forms and major vs minor horizontal axes for the rarer highly prolate forms), **4**: degree of fragmentation (Figure 4-16), and **5**: degree of botryoidal texture (normally seen on the tops of RS type nodules).

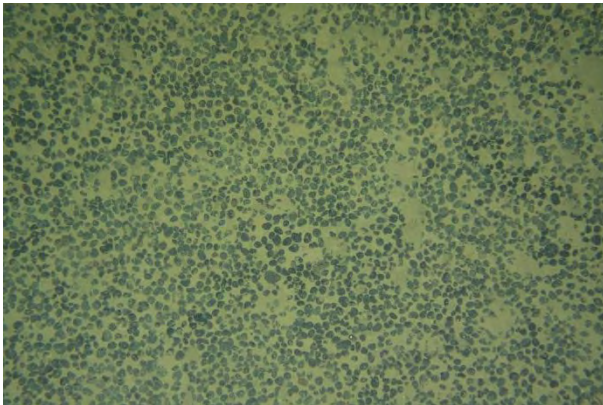
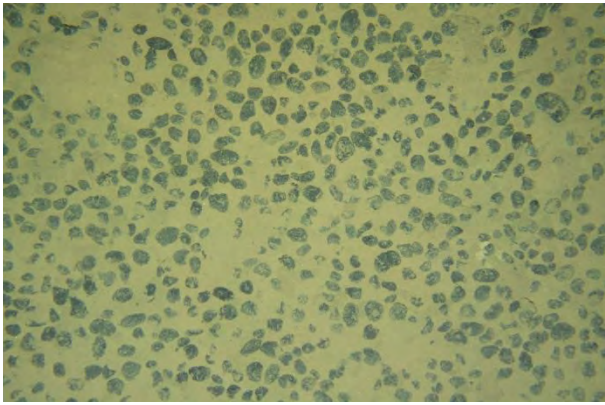
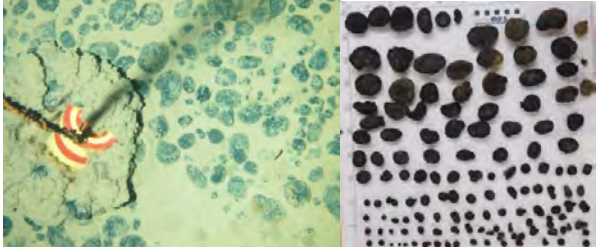
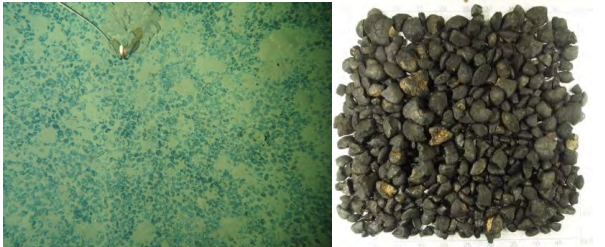
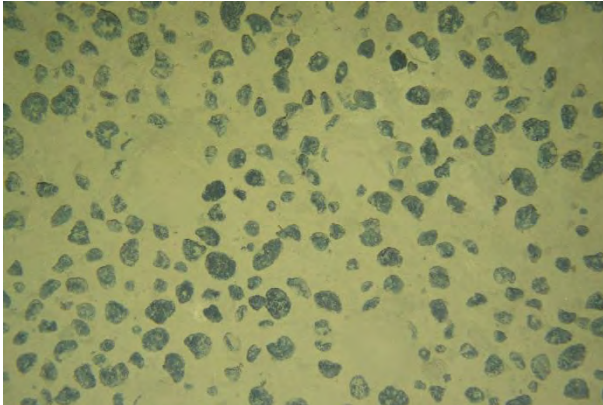
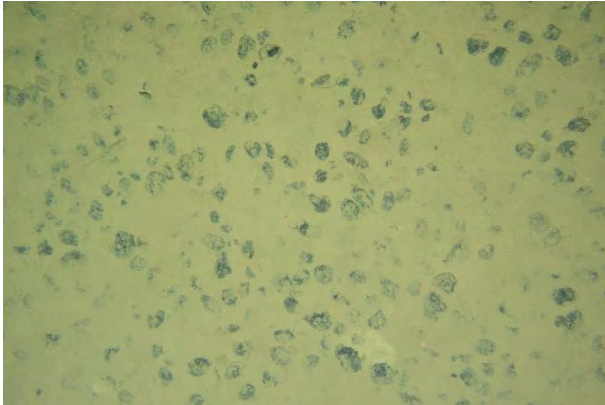
Table 4-4: TOML CCZ15 Nodule classification and proportions seen in logging during CCZ15

		1: size (long or major axis length)					
		=<2 cm		2-5 cm		>5 cm	
		s (small) 8%	sm 11%	m (medium) 20%	ml 24%	l (large) 18%	mx (mixed) 18%
2: type	S (smooth) 10%	s-S 1%	sm-S 2%	m-S 5%	ml-S 1%	l-S 0%	mx-S 1%
	RS (rough-smooth) 84%	s-RS 7%	sm-RS 8%	m-RS 13%	ml-RS 22%	l-RS 18%	mx-RS 17%
	R (rough) 6%	s-R 1%	sm-R 2%	m-R 2%	ml-R 1%	l-R 0%	mx-R 1%
3: aspect (thinness to width aspect for oblate, and prolate across horizontal dimensions)							
high		regular		low		irregular	
-hi 4%		-rg 82%		-lw 3%		-ir 5%	
4: fragmentation level							
rare		moderate			common		
-ra 53%		-md 27%			-cm 20%		
5: botryoidal texture							
well developed		poorly developed			absent		
-bo 54%		-po 13%			-no 34%		

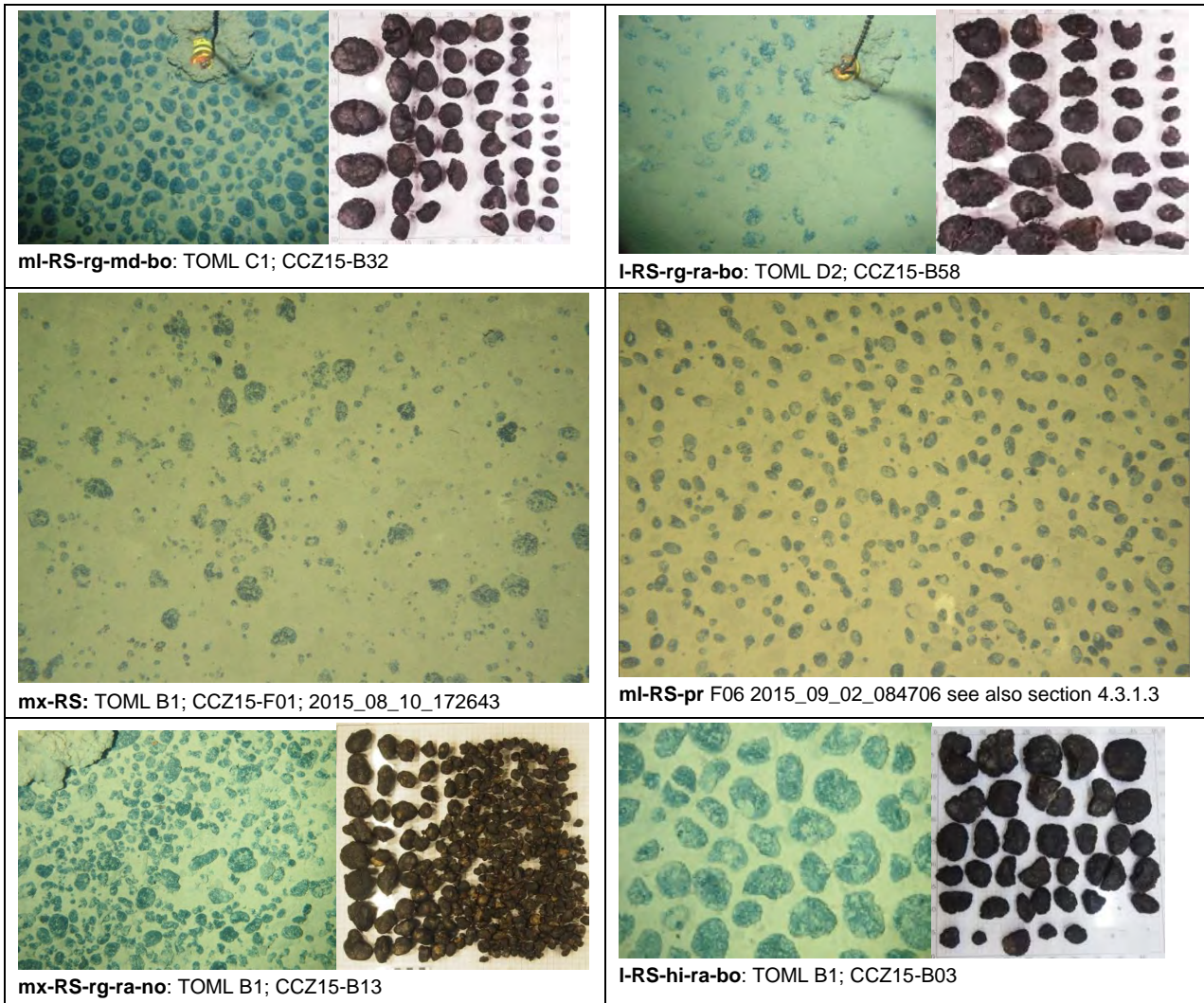
Logging is from box-cores and from towed photo profiles, number of samples = 15,684. In photo-profile images, criteria 3 to 5 are normally difficult to resolve so are often left off the classification. These proportions are from CCZ15 box-core nodule samples (=110).

The classification was tested via all of the logging from the CCZ15 expedition i.e. some 15,684 readings (e.g. per examples in sections 9.15, 9.18). From Table 4-4 it is apparent that in the TOML areas at least: smooth-rough nodules⁵ are the most common, especially in the medium to large size range, and are the only type for large nodules; rough nodules are relatively rare; and medium smooth type nodules are more common than smaller ones.

Table 4-5: Example nodules

	
<p>s-S: TOML B1; CCZ15-F03; 2015_08_22_115003</p>	<p>m-RS: TOML B1; CCZ15-F01; 2015_08_11_121357</p>
	
<p>sm-RS-rg-ra-po: TOML B1; CCZ15-B02</p>	<p>m-S-rg-cm-no: TOML F1; CCZ15-B105</p>
	
<p>I-RS: TOML B1; CCZ15-F01; 2015_08_10_220159</p>	<p>I-RS with cover: TOML D2; CCZ15-F09B; 2015_09_15_110550</p>

⁵ Note that per Lipton, Nimmo and Parianos (2016) the schema classes were originally called smooth-rough type nodules rather than rough-smooth type nodules, but this was changed as the ISA schema uses the term rough-smooth.



More examples of nodules (hand specimens) relating to the classification schema comprise section 9.15.

Full resolution images in Section 9.13

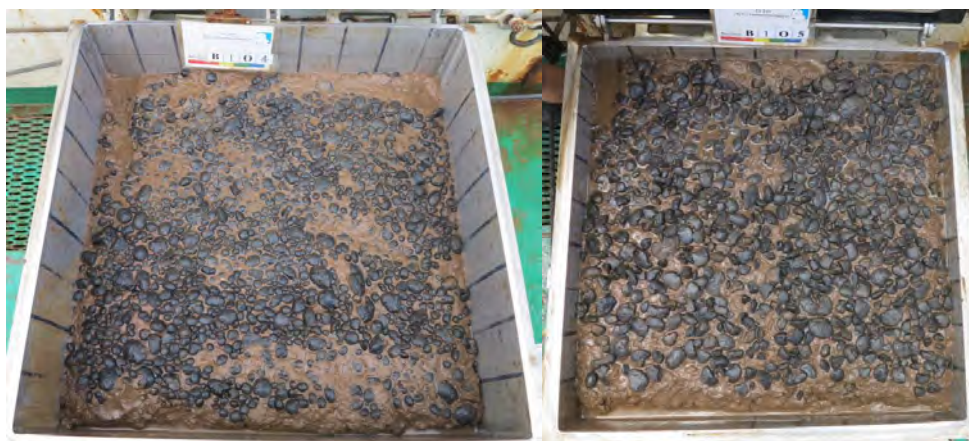
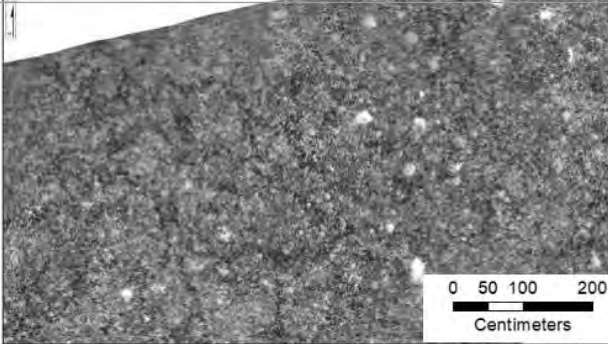
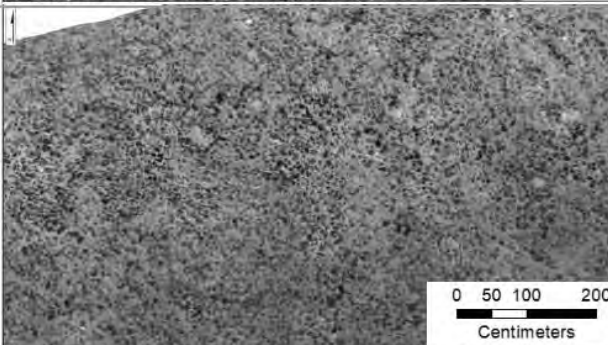
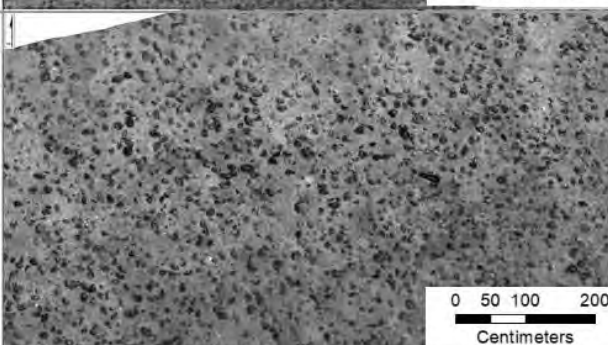


Figure 4-16: Examples of rare and common levels of fragmentation TOML F

Box cores were taken ~20 km apart and both have S-type nodules (type 1 facies of Lipton, Nimmo and Stevenson (2019)) nodules from B104 with rarer fragmentation are smaller 2.2 cm long axis vs 3.5 cm for B105

Table 4-6: NORI D Nodule classification

Nodule Camera Facies Type	Description	Example
Type 1 Densely Packed/Interconnected	>50% nodules ~1-10 cm, uncertain Low to moderate confidence in camera imagery to resolve individual nodules	
Type 2 Mostly Individual/Locally Interconnected	~20-40% Nodules ~5-20 cm Moderate to high confidence in camera imagery to resolve individual nodules	
Type 3 Mostly Individual/Sparse	10-20% nodules ~5-20 cm Moderate to high confidence in camera imagery to resolve individual nodules	

Reproduced from Lipton, Nimmo and Stevenson (2019).

Note Type 1 typically equates to sm-S and type 2/3 to I-RS in the TOML schema.

4.3.1.3 Formation mechanism for strongly prolate nodules

Any nodule that does not have at least 2 identical length axes (oblate) is technically prolate. Most nodules are only slightly prolate (>0.6 minor to major horizontal axes) and thus casually termed oblate. Strongly prolate nodules (~0.5 minor to major horizontal axes; Figure 4-19) are unusual and not known to be specifically documented in the scientific literature. During the TOML CCZ13 and CCZ15 expeditions, prolate nodules were collected occasionally in dredges and during the TOML CCZ15 expedition towed seabed photographic records were collected of prolate nodule occurrences.

Schoening and Gazis (2019) present detailed nodule dimensions from two areas of the CCZ (used for Figure 4-17). While facies are likely mixed in the sample groupings, significant variance is seen between areas, in part due to the relative proportions of prolate nodules.

In seabed photographs, strongly prolate nodules are usually seen in disorganised orientations (Figure 4-18) and less commonly in organised i.e. aligned orientations (Figure 4-19). Analysis of the aligned examples elucidates their origin.

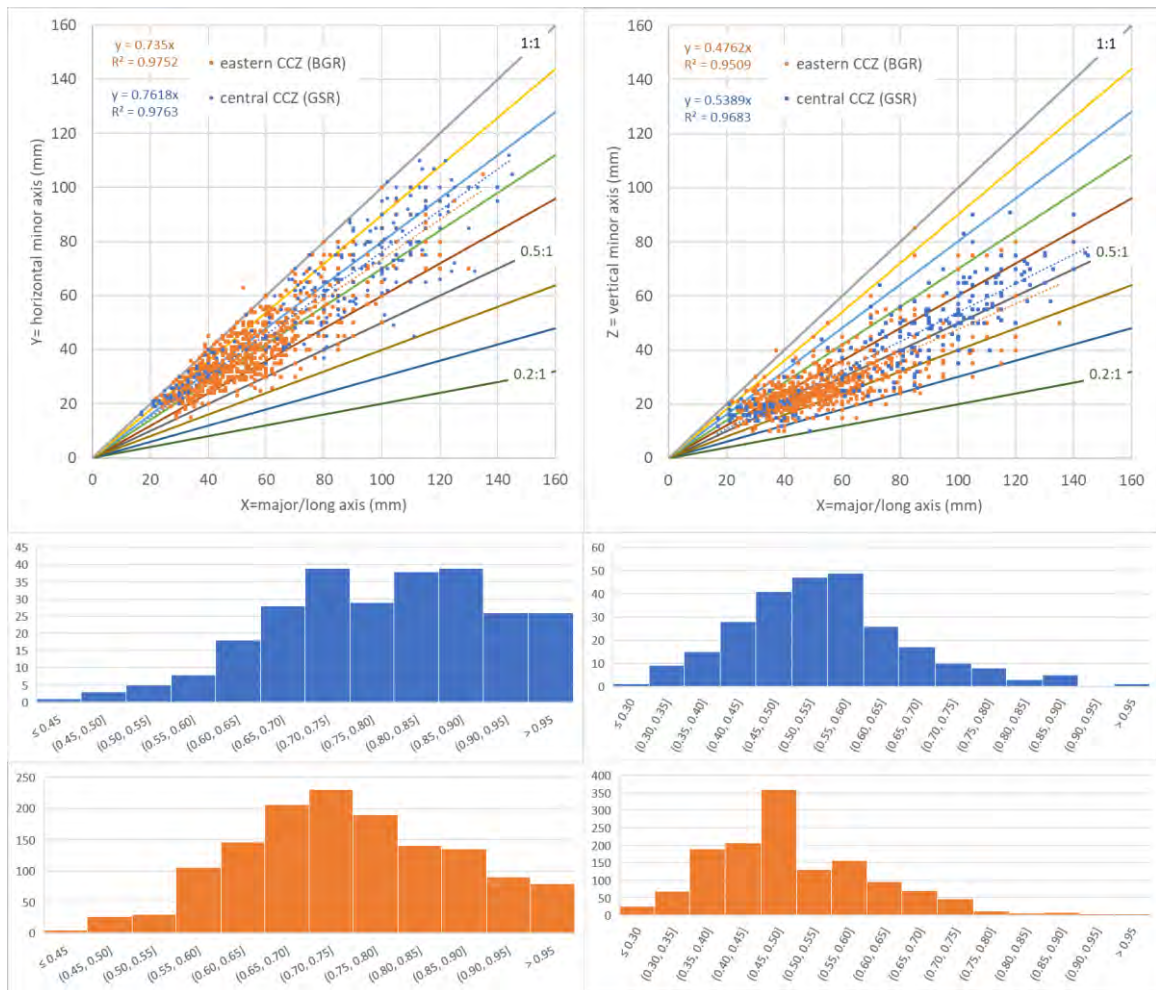


Figure 4-17: Sizes and proportion of example nodules from the BGR and GSR areas

Source: (Schoening and Gazis, 2019). The GSR sample area is located ~100 km WNW from TOML D1,D2 and the BGR sample area ~150 km N of NORI D DSAO

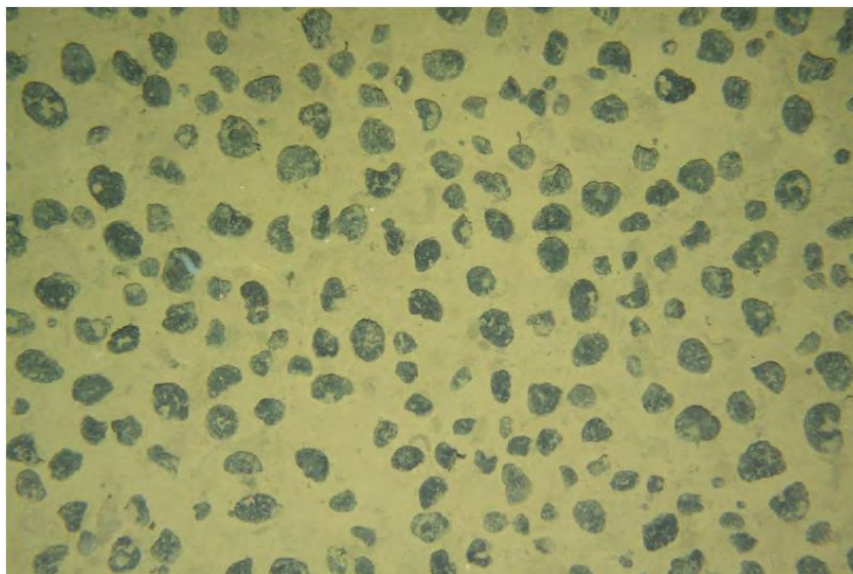


Figure 4-18: Example of disorganised strongly prolate nodules amongst oblate (or slightly prolate nodules).

Image is 2.4 by 1.6 m CCZ15 F01- 2015_08_11_014151

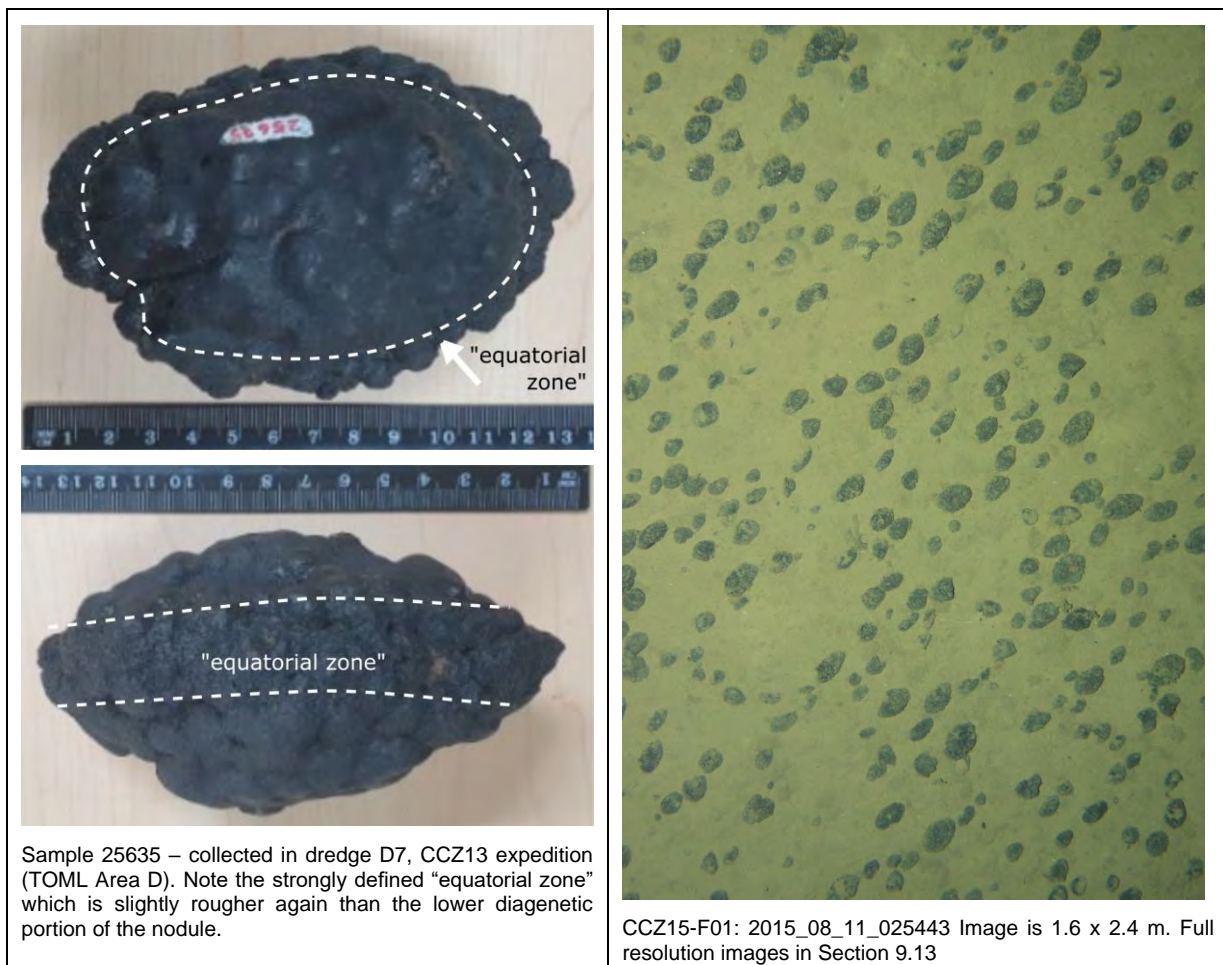


Figure 4-19: Example prolate nodule and aligned nodules example

A ~ 2 km example series is presented in section 9.16 from the CCZ-F01 photo profile line in TOML sub-area B1 (~13 km east of the B5338 sub-area). Key features include:

1. the nodules are generally classed as I-RS-pr-ra-bo with the large major axis between 5 and 10 cm in length and a well defined ‘equatorial zone’ (Figure 4-19);
2. there is often a mix of oblate nodules and strongly prolate nodules with the latter ranging up to 90% of the nodules within a frame;
3. the strongly prolate nodules often have their long axis aligned parallel to the gentle slopes on which they form (see map at base section 9.16, Figure 4-19, Figure 4-20).

Note that MBES bathymetry resolution is poor at this level of analysis. The bathymetry of the start of the photo traverse is a little complicated due it lying at the edge of the MBES nadir and the possibility of complex local stratigraphy related the ridge appearing to be formed in part from chalk dissolution (i.e. east-west embayments into the north-south trending ridge); however the bathymetry in the centre and end of the traverse is much simpler and clearer.

4. A key implication is that at least some of the sediment drifts mapped in Chapter 3 are contourite type deposits *c.f.* (Rebesco et al., 2014).

- the alignment of the nodules swings over the course of several frames as the slope changes direction.

Note that the stability of the towed camera is believed to be normally very high based on towing dynamics and accompanying video viewed by the author.

Thus, it concluded that prolate nodules are formed by consistent seabed currents travelling longitudinally along certain abyssal hills. The geochemically active layer may, in effect, be likely better preserved in the lee of the nodule. This is supported in some images by the apparent slope (Figure 4-19) and by the presence of the large sediment drift at the start of the photo series and mapped from the MBES along the abyssal valley and slope to the south. Some currents may move to and fro because of tides.

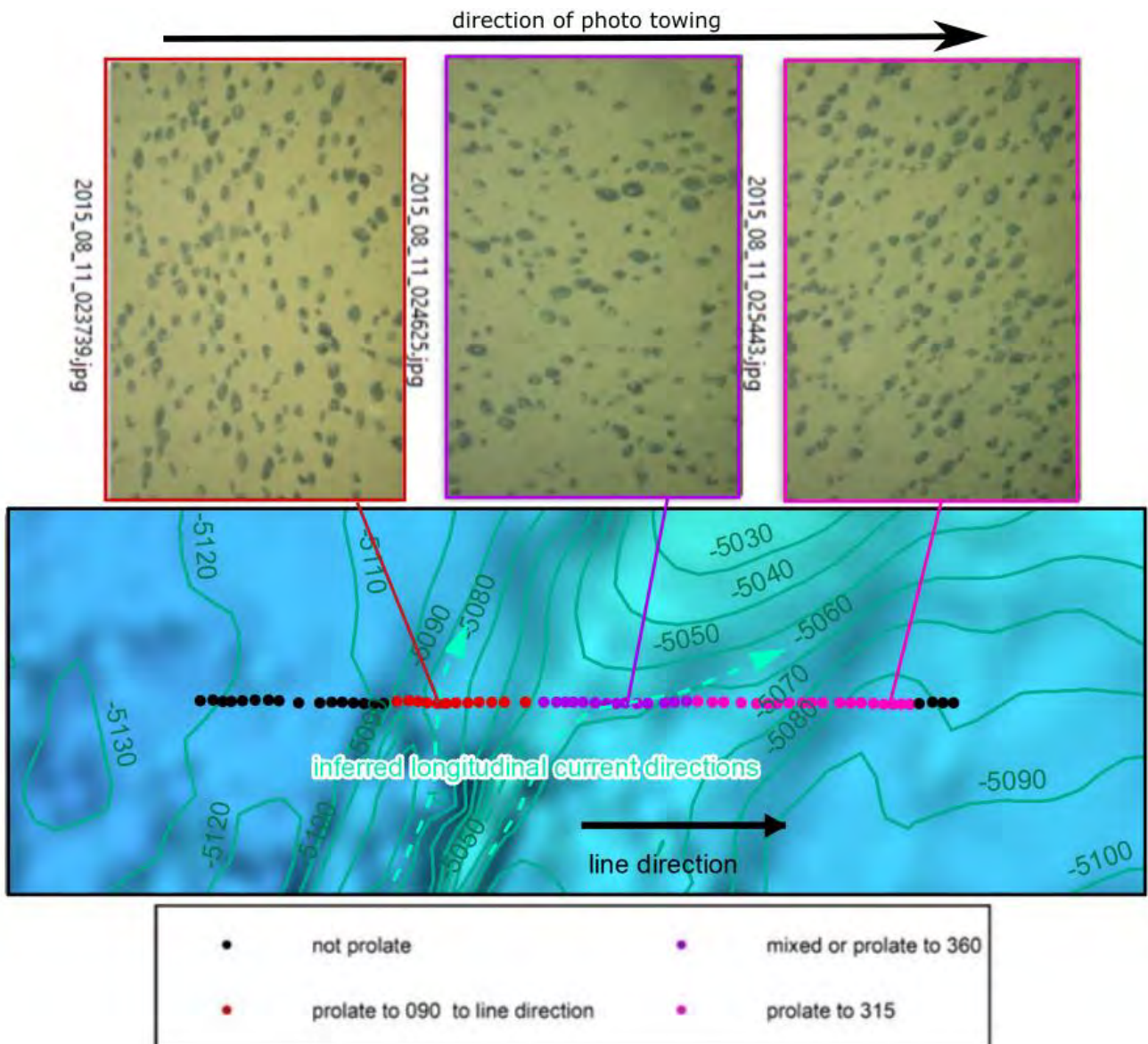


Figure 4-20: Alignment of prolate nodules in eastern TOML B1
 Photos taken left to right. All images from photo-profile CCZ15-F01; full sequence in section 9.16.

4.3.2 A conceptual analysis of nodule types and their possible growth conditions

4.3.2.1 Role of Geochemically Active Layer (GAL) in nodule growth

A fundamental starting point is the interpretation that very slow rates of growth mean that nodule forms (e.g. Table 4-3, Table 4-4, Table 4-6) reflect their growth history. Nodule forms are frequently mapped as facies, with a scale of the order of 10s of metres to kilometres of range for a given facies (usually defined from towed or AUV based photos; Chapter 3, (Kuhn et al., 2011; Tilot et al., 2018; Lipton et al., 2019)). A key implication is that as nodules grow in a GAL, the form of the nodules reflects the nature and history of the GAL itself, at the facies scale. Based on measured growth rates, that the time period under consideration for seabed nodule growth of between 1 and 15 cm diameter is of the order of 0.5 Ma (Chibanian) to 5 Ma (early Pliocene). This may extend to as far back as 10 Ma (early late Miocene) in what might be exceptional circumstances (per growth rates in Figure 4-2, Figure 4-3 and nodule major axis lengths discussed further below).

For this discussion a (the) GAL is taken to be a <10 cm thick chemically enhanced seabed layer that includes an upper epibenthic water column component and a lower sedimentary component (clay-ooze). In some cases, the sedimentary component is all but absent (hydrogenetic per Figure 4-1) and in other cases the epibenthic water column component is very limited (e.g. nodules with typically high cover in TOML Area D1, D2; Figure 3.36), or not involved (diagenetic per Figure 4-1). The sedimentary component is often very soft (Lipton et al., 2016) and the epibenthic water column component presumably distinct (but usually not involving a nepheloid layer; seabed images in Appendix 3E). Also, the GAL certainly varies in thickness based on the rates of input and output of chemical constituents, and changes in immediate seabed morphology. Thus:

- Chemically the GAL includes:
 - o Decaying organic matter (currently 0.4-0.6% in the BGR eastern area (BGR, 2018)) under currently oxic or sub-oxic conditions (Dymond et al., 1984; Wegorzewski et al., 2014), which is deposited in a series of episodic fluxes as listed in the footnote² below;
 - o Intense carbonate dissolution (at CCD of ± 4500 metres and below the lysocline positioned several hundred metres above) as well as significant organic silicate dissolution (section 4.1.2);
 - o Other contributions from biological activity starting with microbial activity and including bioturbation (section 4.1.2; (UK Seabed Resources, 2014)).
- The GAL appears to be influenced physically at the facies scale by:
 - o local clay-ooze textures such as mega-ripples or hummocks, e.g. section 3.3.3 or per Type 2 nodule distribution in Lipton, Nimmo and Stevenson (2019)
 - o currents e.g. associated with clay-ooze drifts (e.g. prolate nodules in section 4.3.1.3);
 - o sub-stratum e.g. escarpments and volcanic edifices (e.g. small nodules on hard substrate in Table 3-6).

Note that the base of the GAL is distinct from a redox boundary or interface which is normally located further below in clay-ooze (Figure 4-1). The clay-ooze below the GAL but above the redox boundary is both metal rich and bio-active if somewhat oligotrophic, especially with increasing depth (BGR, 2018; Global Sea

Mineral Resources, 2018). The question of contribution to nodules of this oxidative layer is modelled and discussed by Dymond *et al.*, (1984), who consider it not important.

In some cases then, certain nodule forms likely reflect changes to the GAL. i.e. processes that change a GAL at the facies scale⁶, over time periods significant enough to affect nodule growth. These are:

- changes in sedimentation type, likely via long term changes in current patterns – based on the mapping in Chapter 3 (Figure 3-33; >80% by area); and
- changes in nature of sub-stratum (e.g. tectonic readjustment of escarpments, pothole formation in chalk, ‘recent’ volcanic activity (section 3.3.4) – based on the mapping in Chapter 3 (Figure 3-33; <20%).

Note that microanalysis suggests that nodules only start to grow under prolonged sub-oxic conditions (section 4.4.3.2). Also that benthic storms or similar (section 1.1.1.1.2) and changes in rate of bioturbation with changes in local fauna (A. Flynn *pers comm* 15th February 2020) are expected to be too temporary, i.e. they would not affect a GAL over time periods significant enough to affect nodule growth.

4.3.2.2 Relative growth of nodules

A “facies of nodules”, is invariably a group of nodule forms and sizes. Even within a single sample (e.g. seabed photograph of several dozens to hundreds of nodules), this can be:

- more commonly, a narrow to wide range of nodule sizes in a predictable distribution (i.e. two parameter generalized Rayleigh distribution (GRD; (Abd-Elfattah, 2011) per Yu and Parianos (2021) Figure 4-29, Figure 4-22);
- less commonly, a mix of nodule sizes either in a bimodal or irregular distribution (Figure 4-29, Figure 4-22).

In considering the relative growth of nodules within a given facies:

⁶ Because this discussion considers the regional to local scale (per definitions in section 4.1.1) over the growth history of nodule, other things that would change a GAL more broadly and/or over a short term are not included in this discussion but for completeness include:

- gradual changes associated with plate drift (500 km, or roughly ½ the width of the CCZ, over the last 5 Ma per Section 2.1)
- Longer term events such as climate change via:
 - o surface blooms of microorganisms related to glacial and interglacial periods and transitions (Bradtmiller *et al.*, 2010);
 - o changes in ocean currents (Hein and Petersen, 2013);
- tectonic readjustment of the seafloor;
- Inter-decadal events such as El Nino and La Nina (Mercator Ocean International, 2020);
- volcanic events (expected to be temporary at regional scale);
- annual variation in primary productivity (Mercator Ocean International, 2020).

- it is unlikely that growth is ever restricted by a shortage of “seeds”, and most of the nodules in Figure 4-36, Figure 4-37 (section 4.4.3.2) have type 2 busserite rich material as a nucleus, rather than exotic material;
- growth rates are not equal in all directions as most nodules (RS-type) in the CCZ are in effect slightly prolate and typically very irregular spheroids ((Yu and Parianos, 2021); Figure 4-23), with a distinct “keel” and flattened top. This indicates transitions to lower rates of growth towards the top (hydrogenetic) and base (diagenetic) of the GAL. In some cases this may develop to the point of a so-called ‘equatorial zone’ (Figure 4-19).
- in areas of high nodule abundance, there is simply not enough room between any two nodules for another nodule of similar size. Growth is presumably limited by these adjacent nodules, with movement (via bioturbation; Figure 4-24) of the nodules the reason that they do not normally cement into a massive crust (section 4.3.3). This implies that flux attempting to attach to the sides of nodules are detached or abraded off during their movement.
- Nodules in effect compete for any available flux (growth material) as supplied by the GAL. But constraints on how their size might benefit or penalize them are equivocal as follows:
 - o Larger nodules have an advantage in that for a given number of nodule particles, the surface area of a few larger nodules would provide a much greater area for absorption for available material flux than a few smaller nodules (Figure 4-25). So, the probability of flux material landing and sticking to a larger nodule is higher. This may be critical if flux is limited or reducing in rate.
 - o Smaller nodules have an advantage in that they require less volume of material to grow faster (Figure 4-25 implies this may be significant for small to medium sized nodules). In due course (when the larger nodules start to need much larger volumes and if flux is limited), this should allow newly formed smaller nodules to ‘catch up’ with larger nodules, narrowing the distribution. But periods of very high flux could allow all surfaces (large and small) to grow equally quickly.
 - o For a given volume however, smaller (or broken pieces of) nodules would have a higher surface area than a few large nodules. Incidental breakage may thus help increase overall abundance if flux rates are episodic.
- The rate of GAL change is also difficult to constrain:
 - o At a local scale, GAL change could be to all intents permanent, if say it was subject mainly to tectonic or structural re-adjustment of the substrate (edge of abyssal hills);
 - o At a regional scale rate of change for the GAL could be similar to rates of change of the lysocline (Figure 4-24).

Thus, the range of nodule sizes seen in most facies (Figure 4-29, Figure 4-22) is interpreted to result from one, or more probably a combination, of the mechanisms in Table 4-7.

Table 4-7: Mechanisms behind nodule forms at the facies scale

Mechanism	Comment
Relative changes in growth rates, for example due to micro-currents and eddies redirecting limited material flux to favour some nodules over others. This being self-reinforcing for larger nodules with greater surface areas.	<p>Seabed currents (h) in Figure 4-24 are constant and most dynamic forces constantly acting on nodules. Their speeds are sufficient to move clay-ooze (section 1.1.1.1.2). They change direction with the tides and they have likely topographic influences that could conceivably manifest at the facies scale (based on distribution of clay-ooze drifts from multibeam echosounder and sidescan sonar clay-ooze textures per sections 3.2.5, 3.3.3).</p> <p>This is supported in part by prolate nodule forms relating to current section 4.3.1.3; including apparently random orientations in medium abundance nodule facies.</p> <p>Note that nodule growth to a two parameter GRD may be a consequence of two interacting long lived effects. If so, the inherent growth of nodules is one effect, and the influence of currents is taken to be the most likely second effect for the abovementioned reasons.</p>
Change in GAL thickness	<p>A reduction in GAL thickness is interpreted to be a special case related to the bimodal and other irregular distributions (Figure 4-29, Figure 4-22), where it would favour smaller nodules over the larger ones which at best could develop more pronounced equatorial zones (Figure 4-19).</p> <p>An increase in GAL thickness would conversely presumably benefit all nodules.</p>
Bioturbation	Some kind of bias in bioturbation ((e), (d) in Figure 4-24) cannot be ruled out as there can be a relationship between nodule facies and species distribution (Tilot et al., 2018), albeit with causality not being clear.
Periods of very high flux of material.	<p>Periods of very high flux (e.g. seasonally; (Garcia et al., 2019)) are expected to be more of a regional effect and not manifest at the facies scale. The exception may be in areas where the GAL 'ponds' after such events.</p> <p>The Type 1 nodules from TOML F and NORI D may be part of this regional trend – very high primary productivity leads to a shallow oxidative layer in the clay-ooze.</p> <p>This may explain nodules with well formed botryoidal tops in large to very large nodules in flatter areas (e.g. NORI A in Chapter 3) via periodic saturation and creation of sub-oxic conditions even at the surface.</p>

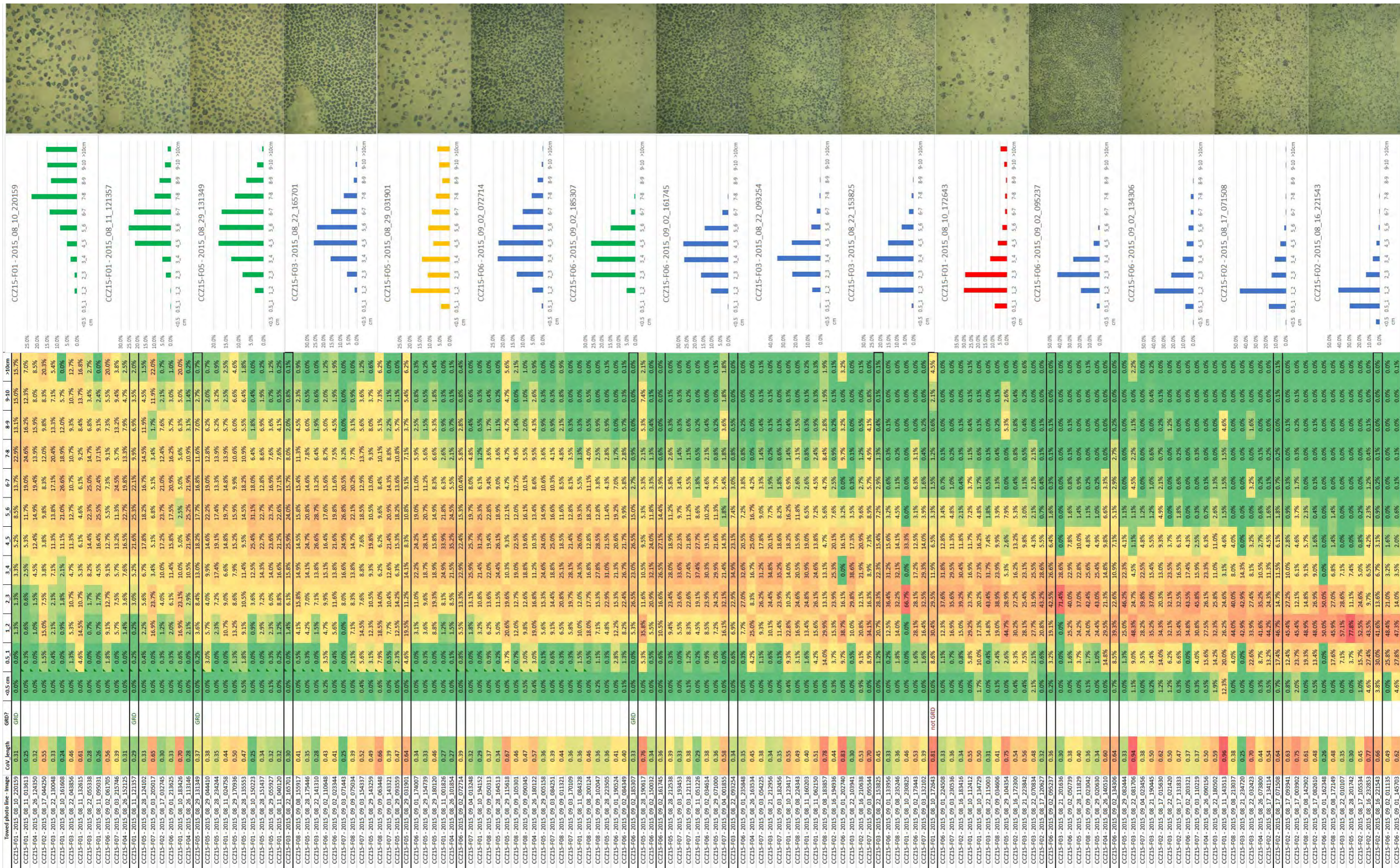


Figure 4-21: Nodule size distributions from towed photographs in TOML B and C.

Photos were collected using the Neptune towed camera system on the lines per section 3.2.6. Photos were georeferenced (using an average distance from towed photos as some photos after image processing; prior to manual long axis measurements by the TOML science team on the CCZ15 expedition (section 9.1). Green histograms are for those samples passing goodness of fit for GRD (see also Chapter 6), red for those that failed. Blue are untested but look likely to pass, yellow are uncertain. Standardised histogram bins are a compromise to suit the bulk of the samples and are non-deal for very large nodules. Full resolution images in Section 9.13

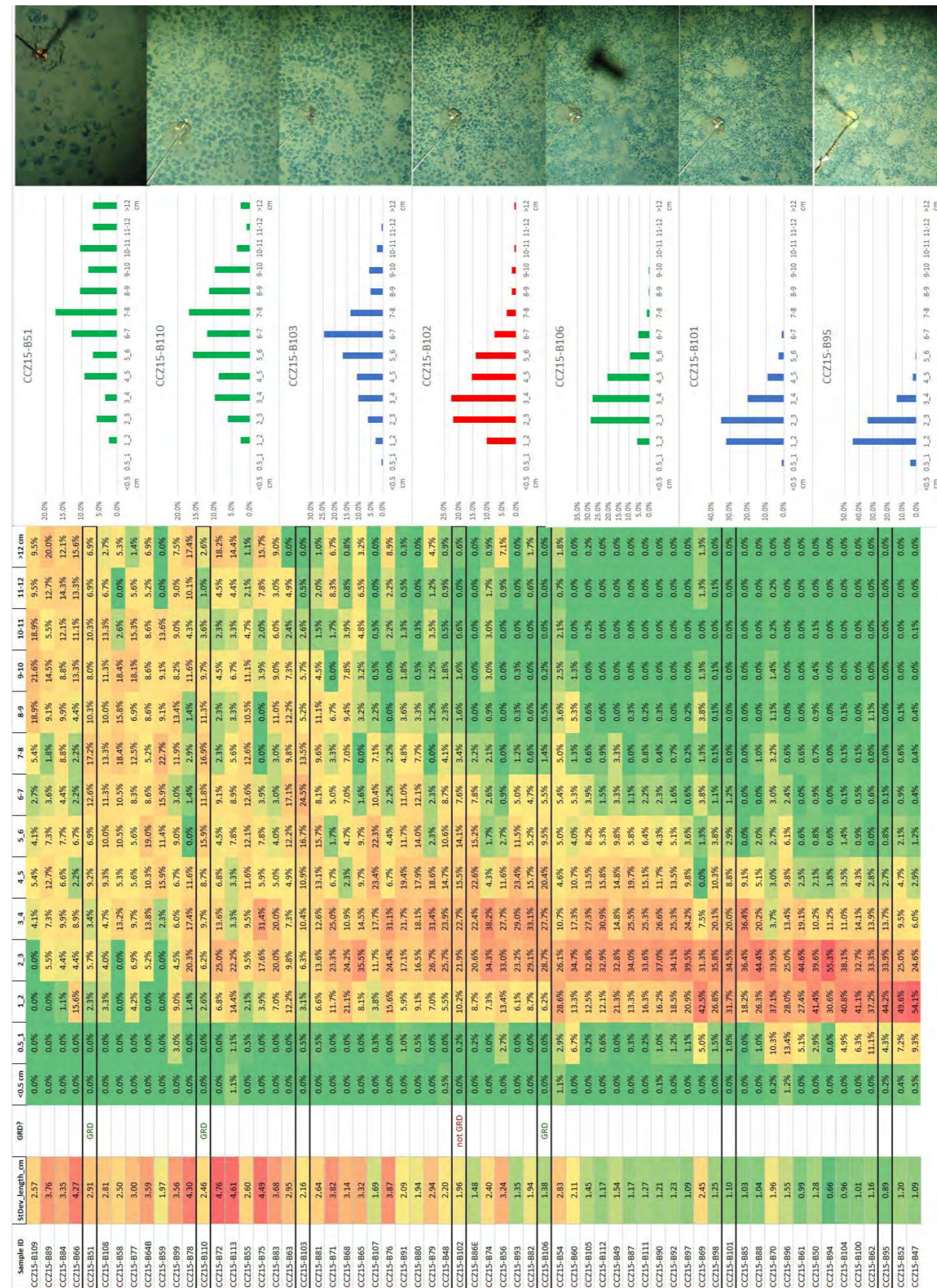


Figure 4-22: Nodule size distributions from box-cores in TOML D and F

Note that the long axis data used is from the box-core samples (per sections 4.2.1.3) after washing and weighing and laying out on a grid. This is required for TOML D as the powder cover is high and in TOML F as there are not towed photos available. Seabed photos are shown in the examples for comparative purposes with Figure 4-29. In some cases, the process of washing and weighing the nodules increases the rate of breakage and can impart a small bias (higher count lower lengths) to the measurements. All samples used passed a visual QA/QC process to ensuring the sample nodules were not too broken. Green histograms are for those samples passing goodness of fit for GRD, red for those that failed. Blue are untested but look likely to pass. Standardised histogram bins are a compromise to suit the bulk of the samples and are non-deal for very large nodules.

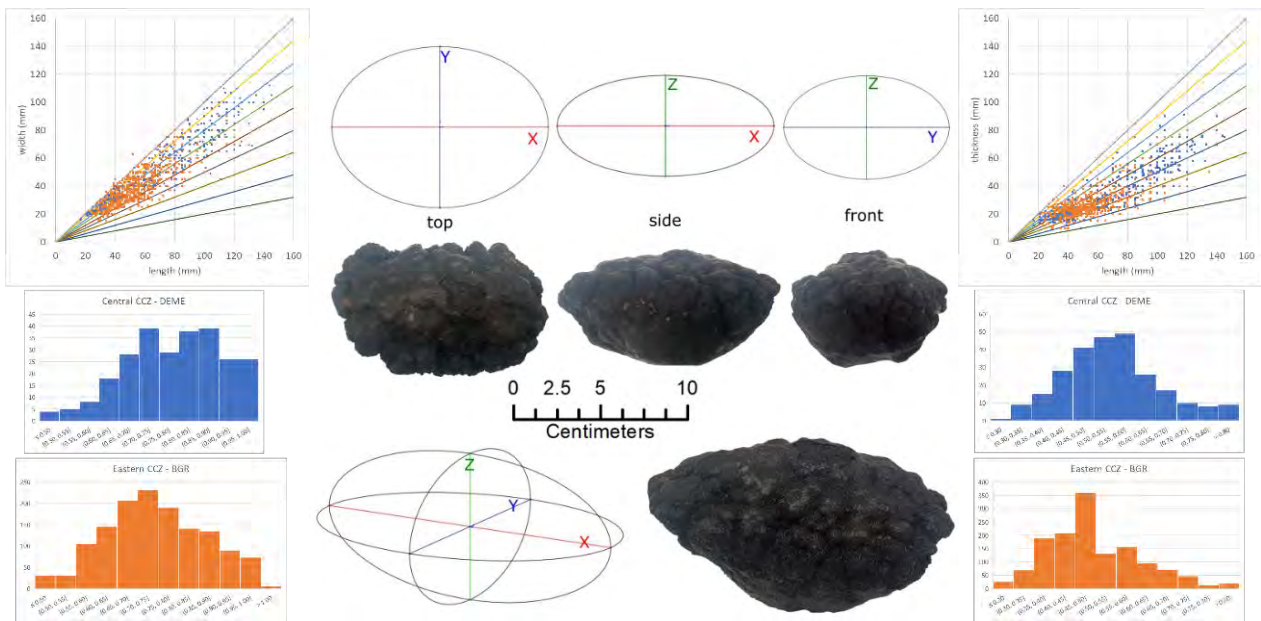
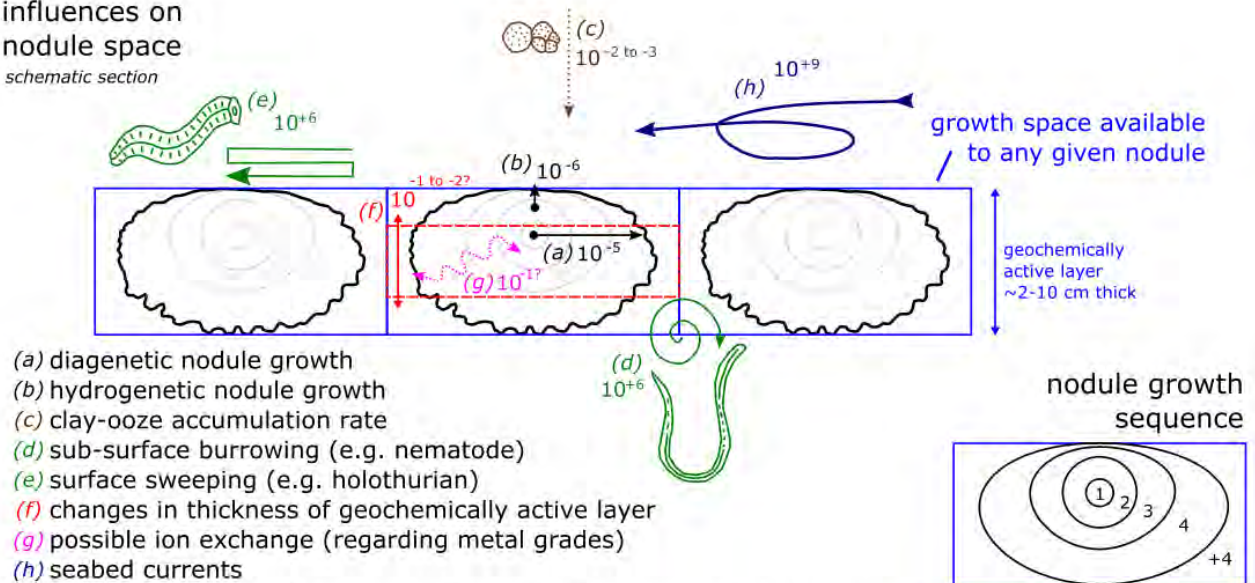


Figure 4-23: Dimensions of an example nodule near the average measurements of Schoening and Gaziz (2019)

Ratio of X:Y:Z is 1:0.75:0.5. Although the ratios do vary considerably per the associated charts.

influences on nodule space
schematic section



- 1 - manganese minerals accumulate into a micronodule or coat an existing one
- 2 - steady diagenetic growth in all directions
- 3- slower hydrogenetic to the top, faster elsewhere
- 4 - slower growth to the base of the geochemically active layer, faster to the sides
- post 4 - growth only as space and flux allow

Figure 4-24: Space constraints on nodule growth

Speeds are in m/ka for (a) and (b) (Piper and Fowler, 1980; Chang et al., 2005); (c) (Kim et al., 2011); (d) and (e) (Gray and Lissmann, 1964); (f); (Sigman et al., 1998) assuming this would be similar to lysocline changes; (g) (Novikov and Bogdanova, 2007) based on doping of powders in a laboratory; (h) (Hayes, 1979)

4.3.2.3 Other points

Note that the mechanisms for forming the nodules may be different to the mechanisms for keeping them at the seabed surface. The fundamental question about why nodules stay at the surface arises from the sedimentation rate being two to four orders of magnitude higher than the nodule growth rate (as illustrated in Figure 4-24; and originally raised by Piper and Fowler (1980)).

As reviewed by Dutkiewicz, Judge and Müller (2020), currents and bioturbation are two leading hypotheses for why nodules remain at the seabed. As also shown in Figure 4-24, compared to sedimentation rate, bioturbation is 8-9 orders of magnitude faster (assumed \cong dynamic) and currents are 11-14 orders of magnitude faster. Currents, per section 1.1.1.1.2, and Figure 4-24, are significantly faster than interpreted or assumed by Dutkiewicz, Judge and Müller (2020), and clearly capable of moving surficial clay-ooze (note also ripples in Figure 4-26). Bioturbation is of course limited in extent compared to currents (especially given low megafauna biomass in the CCZ including the TOML areas; e.g. (Simon-Lledó et al., 2020)).

More significantly, additional consideration is needed as to why currents or bioturbation would not bury the nodules rather than expose them. Currents are interpreted to eddy around nodules per the example of prolate nodules, but in TOML D (section 3.4.6) are conversely associated with generally higher degrees of nodule cover. Burrowing fauna are known to make mounds that occasionally bury nodules but probably more significantly, filter feeding holothurians are seen to sweep clay-ooze off the tops of nodules (Figure 4-26) and filter feeding nematodes would be expected to constantly repack clay-ooze around nodules (Figure 4-24, (Lipton et al., 2016)).

Another question is where do the old (>5 Ma nodules go). Regarding this question it is noted that:

- a) Buried nodules are noted by Cronan (1973), Kotlinski and Stoyanova (2006), Lipton, Nimmo and Parianos (2016), and Wegorzewski *et al.*, (2020), with some areas hosting ~25% buried nodules by mass between 10-40 cm below the surface. Unfortunately, comprehensive dating of these nodules has not yet been reported;
- b) If nodules were buried at a slow enough rate (say due to rare undermining events from bioturbation), then they could be sustainably replaced in the newly available space in the GAL with new nodules despite their slow growth rate (note size distributions in Figure 4-21, Figure 4-22). This especially if there was some reason why older larger nodules were slightly more prone to burial than smaller younger ones...

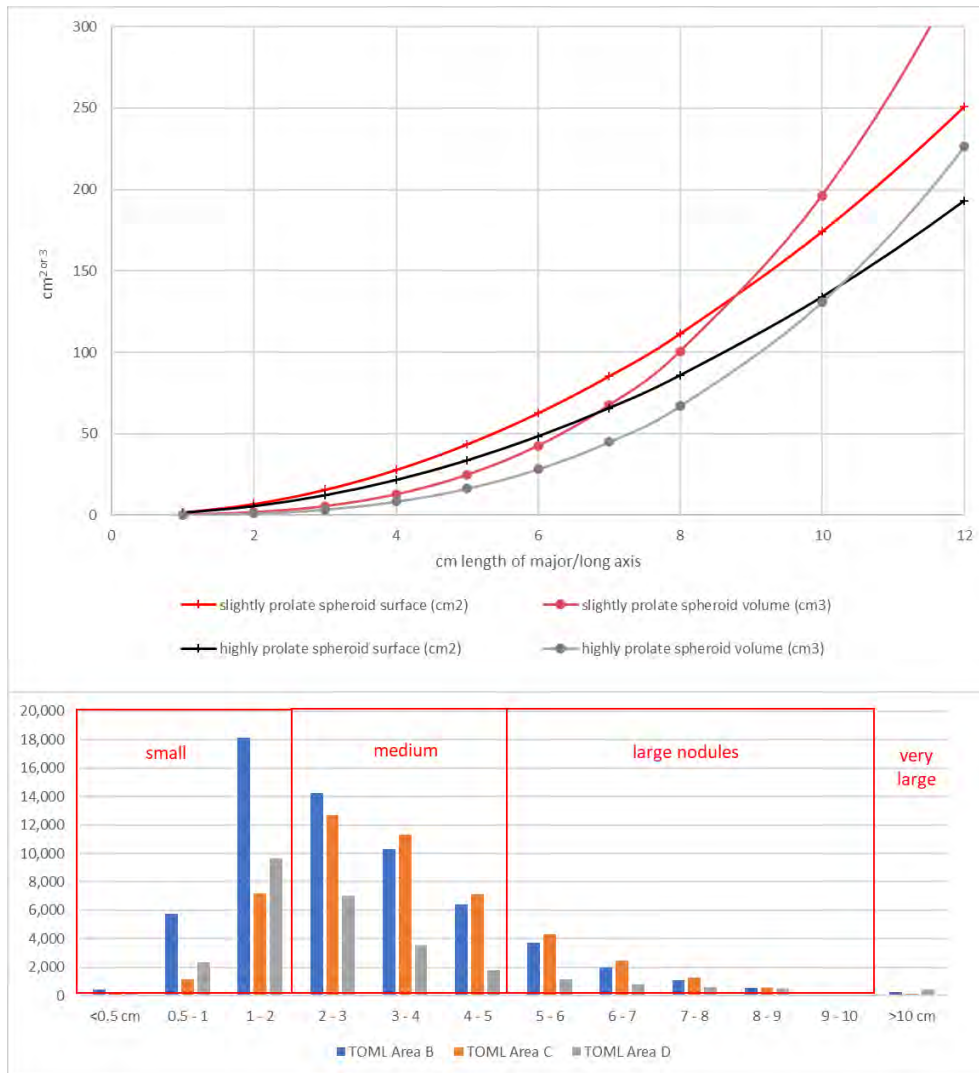


Figure 4-25: Surface areas and volumes of different sized prolate spheroids against field data

Nodule size data from towed photo-profiles in the TOML areas. Nodules vary in form but are generally closest to the slightly prolate form (X:Y;Z is 1:0.75:0.5 per Figure 4-23), nodules actually described as “prolate” in Table 4-4 are closer to the highly prolate form (X:Y;Z is 1:0.5:0.5). Note lengths for TOML D are likely underestimated due to a high degree of clay-ooze “powder” cover in that area.

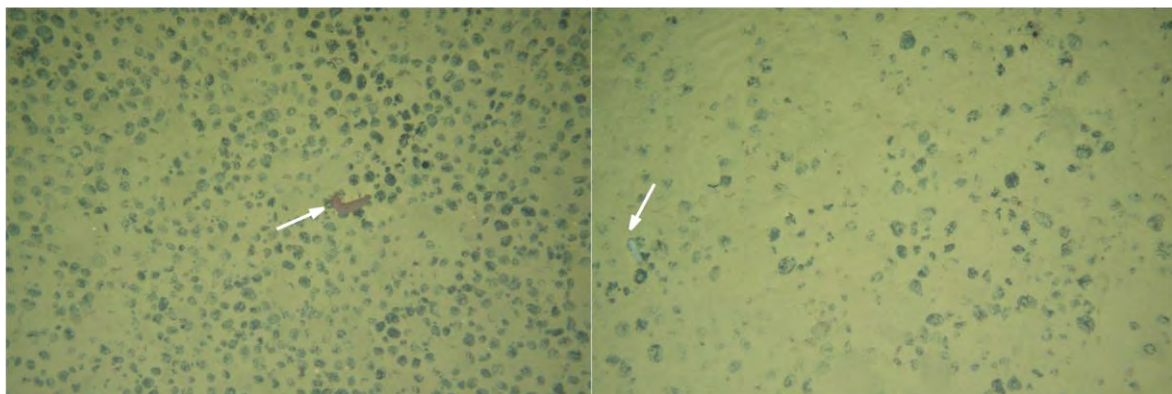


Figure 4-26: Examples of sweeping off of clay-ooze from nodules by holothurians

Left is TOML B1 (CCZ15-F01 2015_08_10_123744) right is TOML D (CCZ15-F09B 2015_09_14_171835), an area with consistently higher clay-ooze powder cover. Both images 2.4 x 1.6 m in view. Note clay-ooze ripples in the top-left corner of the image from TOML D. Full resolution images in Section 9.13

4.3.2.4 Main forms of nodules and interpreted role of GAL and future work

Based on the above discussion, Table 4-8 summarizes how nodule facies and GAL could interrelate. Fundamentally, within the CCZ, flux rates are assumed to be more or less equal. Large thick nodules would need a thick GAL, high abundances of nodules would require a stable GAL, currents would be the main driver behind less stable GALs, and bimodal or chaotic distributions of nodules would result from a thickness reduction of the GAL.

Table 4-8: Nodule forms with respect to Geochemically Active Layer

Geochemically active layer	Very thick (>10 cm)	Thick (5-10 cm)	Med (2-5 cm)	Thin to None (<2 cm)
Stable	Abundant mostly very large RS type nodules. Example is NORI A (Figure 3-60)	Abundant mostly large to medium RS type nodules More common in TOML D, F than B, C (Figure 4-29, Figure 4-22; Type 2 in Table 4-6)	Abundant mostly medium to small SR type nodules (e.g. CCZ15-B105 in Figure 4-22; Nodule size distributions from box-cores in TOML D and F; Type 1 in Table 4-6)	Abundant small S type nodules (e.g. CCZ15-F03; 2015_08_22_115003 in Figure 4-21; Nodule size distributions from towed photographs in TOML B and C. CCZ15-F02; 2015_08_17_091200 in Table 3-12; Selected seabed photos WSW to ENE across Knoll B4046)
Unstable	Few very large to large RS type nodules Example setting is at the edge of clay-ooze sediment drifts. But this can occur on any clay-ooze surface. (e.g. CCZ15-F01; 2015_08_10_220159 in Figure 4-21; Type 3 in Table 4-6) Prolate nodules are one example of nodules forming in a less stable GAL. (e.g. CCZ15-F06; 2015_09_02_084706 in Figure 4-21)		Few very medium to small RS and S type nodules Example settings are at the edge of clay-ooze cover at escarpments, potholes and volcanics. But this can occur on any clay-ooze surface. (e.g. CCZ15-F10 2015_09_16_185038 in Table 3-6; CCZ15-F02; 2015_08_17_015247 in Table 3-8; CCZ15-F05B; 2015_08_28_201742 in Figure 3-35)	
Changed (thick to thin)	Bimodal or other disparate sizes of RS nodules. This can occur on any clay-ooze surface. If the thin GAL is stable abundances can be quite high. (e.g. CCZ15-F01; 2015_08_10_172643 in Figure 4-21)			
Absent (very dynamic conditions)	Nodules do not form Examples are in clay-ooze sediment drifts or in some narrow zones on hard substrates at escarpment edges (e.g. CCZ15-F01; 2015_08_10_222844 in Figure 3-42)			

A clear issue associated with the necessarily holistic scope of the work in this section is the numerous gaps in supporting evidence. While ongoing empirical study will likely assist with some of these gaps, key restrictions apply in terms of the very long-time frames involved in many of the influences and mechanisms invoked above.

Thus, per section 4.10, it is suggested that future work consider a self-consistent growth rate model. This could include mass-balance computations (e.g. building on those described in Dymond *et al.*, (1984) and Wegorzewski and Kuhn (2014)) and geometric computations. In addition to the above-mentioned features, such a model may need to consider conditions and nodule facies from locations outside the CCZ (per bounding conditions) and of course the question of where do the old (>5 Ma) nodules go.

4.3.3 Diagenetic Crusts and other deposits

These include ferro-manganese crusts, opal and zeolite. The minor amounts of ferro-manganese crust found in the CCZ are not the same as hydrogenetic cobalt-rich crusts typically found on the top of seamounts e.g. in the Pacific Prime Zone in the north-west Pacific Ocean, e.g.(Hein and Koschinsky, 2014). Two types have been logged, both by TOML and by Ifremer (Menot *et al.*, 2010):

- Massive crust is five to ten centimetres thick and is typically found in blocks several decimetres a side (e.g. Figure 4-27, Figure 4-29), but occasionally as pavement (e.g. Figure 4-28, Figure 4-29); and

- Crust-fragments are small to medium sized (<20 cm) discrete fragments of ferro-manganese (e.g. Figure 4-28, Figure 4-30). These are found on hard irregular and typically light brown to cream substrate believed to be opal-CT (section 4.4.2).

The first drill-hole at DSDP site 156, terminated just below the sediment surface (0.49 m) in a black ferromanganese oxide crust. The site report describes something effectively identical to the massive crust type described above i.e. “consist of fragments of crust 1 to 2 cm thick which show internal laminations of yellow brown material separated by massive black manganese and iron oxide phases. The upper surface of the crust is slightly botryoidal, and the internal laminations tend to follow the undulations of the botryoids.”(Cronan, 1973).

Crusts have been collected by TOML in dredges and identified in towed photo-profiles. Neither crust type was collected in box-cores during the TOML CCZ15 cruise, and their extent is deemed insignificant in terms of the mineral resource estimation in Chapter 5. One issue is discriminating diagenetic crusts from ferro-manganese coated chalk fragments, which are thought from towed photos to be more common in some of the TOML sub-areas (chalk fragments were also never encountered in box-core nor dredge, except perhaps as a minority component within the nodules in CCZ15-B08 which have 15% CaO, versus a more normal 2-3%).

The massive crust clearly forms some distance into the clay-ooze as it occasionally contains preserved casts of worm burrows. It is also possible that they form in horizons below the surface as fragments are sometimes seen in lines in seabed photos (Figure 4-29), and as suggested by an unusual sub-surface reflector seen during a dredge landing in TOML A that captured some massive crust (Figure 4-27).

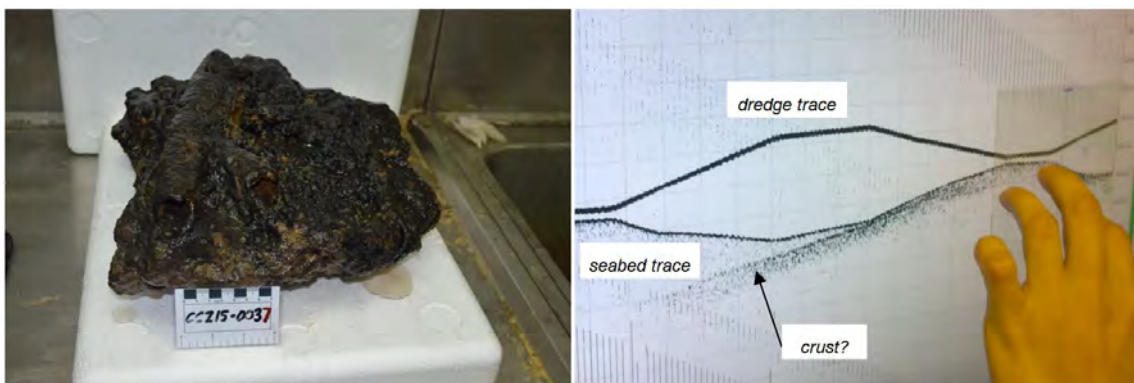


Figure 4-27: Crust and possible related acoustic signal

Worm tube cast in large crust fragment dredged from TOML Area A (sample CCZ15-D01) and acoustic pinger trace from that dredge. Note that dredge sample CCZ15-D02, taken 40 km away from D01 did not contain any crust fragments.

The massive crusts are likely to form much like nodules do and they can grade into nodules, both physically and chemically (Figure 4-29). The crustal fragments may form in areas with lots of “seeds” (e.g. from deposited volcanic ash) or more probably from pieces of reprecipitated opal as interpreted during the TOML CCZ13 cruise (Figure 4-30).

A third, rarer crust-like material are zeolites. These form from halmyrolysis (subsea diagenetic alteration) of both volcanic material (probably ash within the CCZ) and likely from opal rich sedimentary material (Venkatarathnam and Biscaye, 1973). Thin sheets of zeolite crust were identified in the photo-profiling in just a few locations in Area B (e.g. Figure 4-31), and in one location in Area D.



Figure 4-28: Graded crust, photos of both crust types from submersible Nautilie, and brown veins in soft crust
Graded fragment from CCZ13 dredge D04 in Area D, with dark nodules at top (upper part of photo) and more brown mud rich lower section with worm burrows (benthic mud washed out); Nautilie pictures of crusts from (Menot et al., 2010); Brown veins not analysed but may be barite in manganese-oxide indurated clay-ooze (incipient diagenetic crust); dredge sample CCZ13, D06

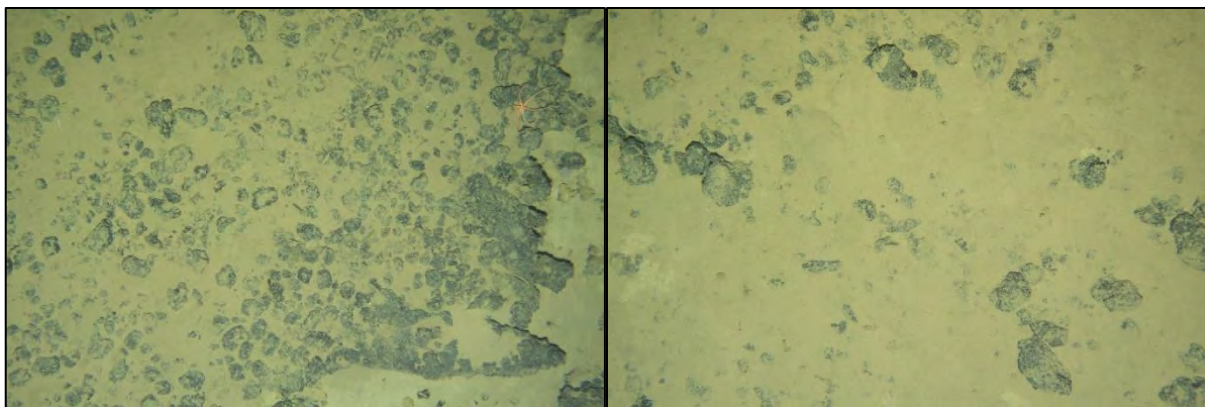


Figure 4-29: Examples of massive crust and fragments TOML Area D

Photos: 2.4 x 1.6 m; L->R: CCZ15-F10 (TOML D2); 2015_09_16_025313;; CCZ15- F09B (TOML D2); 2015_09_15_111256. Full resolution images in Section 9.13

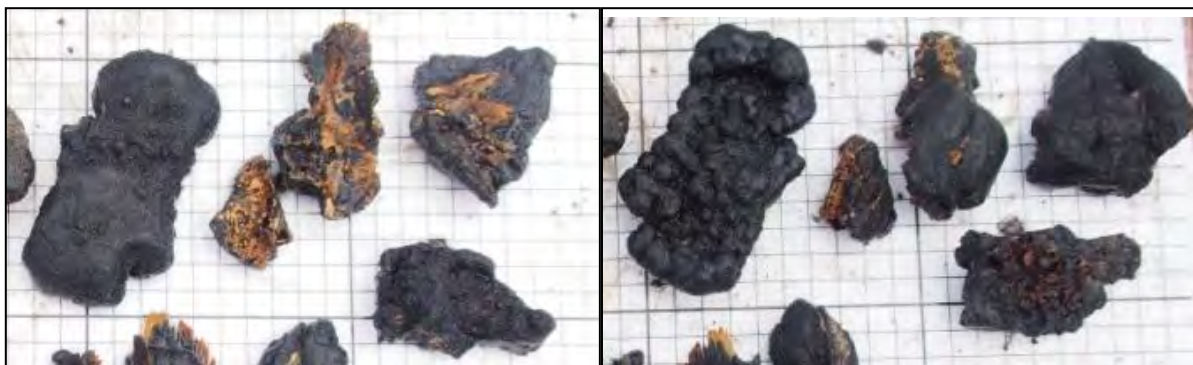


Figure 4-30: Ferromanganese coated crust fragments interpreted to be opaline

Collected in dredge CCZ13 D08 in Area D; photos are of each side; large squares are 10 cm

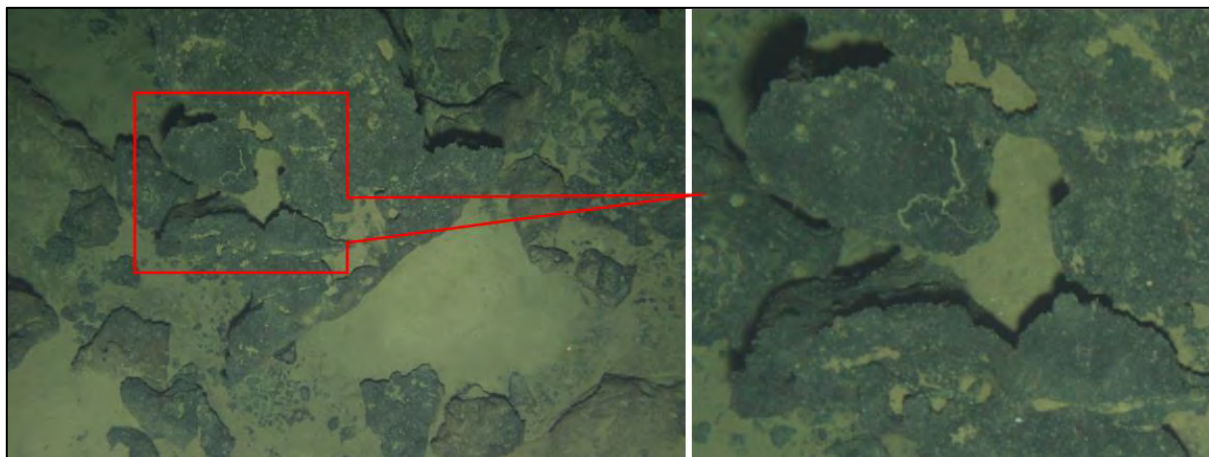


Figure 4-31: Zeolite crust on carbonate, Area B

Photo at left: 2.4 x 1.6 m; CCZ15- F02 - 2015_08_17_054645 Full resolution image in Section 9.13

4.4 Nodule mineralogy

CCZ nodule mineralogy is not a subject specifically studied for this thesis. However, a review helps contextualise some of the other studied subjects, e.g. nodule chemistry and also helps for completeness. The results of two microanalysis projects completed with/for the author are also included for similar reasons and these include some new information and contributions.

4.4.1 Fe-Mn phases

On review, CCZ Nodules are understood to be mostly comprised of seven essential manganese and iron oxides, as well as minor accessory biogenic and rock-forming minerals.

Mineralogical descriptions are often confusing to the casual reader. This is due to inconsistencies in published identification of mineral components as a result of:

- The very fine grained to amorphous nature of the nodules;
- Some critical changes that can occur in mineral structure with heating and/or depressurization; and
- A related lack of consistency in naming of the manganese minerals amongst mineralogists, which in turn relates to differing opinions on the role of formalised names versus informal or working names (see below).

Accordingly, essential manganese and iron minerals are summarised per the author's interpretation as follows, with reference to (Burns and Brown, 1972; Haynes et al., 1985; Ford and Bertsch, 1999; Post, 1999; Choi et al., 2004; Johnson and Post, 2006; Novikov and Bogdanova, 2007; Frey et al., 2014; Wegorzewski and Kuhn, 2014).

Buserite is a 10 Å layered manganese mineral (phylломanganate) that is likely the most important metal bearing phase in nodules. Buserite is not yet a formal mineral name so is not used by some mineralogists, however an application for recognition as a new mineral (mineral name) would “most probably be successful” (mindat.org, 2005). An issue with identifying buserite is that synthesised versions convert to birnessite at anywhere between room temperature and 200°C depending in part on cation composition (cations such as Ni²⁺, Mg²⁺, Ca²⁺, and Co²⁺ tend to stabilize buserite). However, the peak transform temperature of ferromanganese nodule bearing buserite has been determined by differential thermal

analysis to be at 120 to 130°C (Figure 4-32). Buserite can be referred to as “unstable” by mineralogists as it is distinguished from todorokite in XRD by a heating and reanalysis step.

Birnessite is a 7 Å layered manganese mineral that is often studied with buserite for use in fuel cells and prion and contaminated land remediation, due to ease in cation doping and mineral transformation. Unlike buserite it has one layer of interlayer crystalline water molecules (buserite has two) and is stable to about 200°C. Its abundance in nodules may have been overestimated in early (1970s) mineralogical work.

Vernadite is a name frequently used for “turbostratic” layered manganese minerals i.e., minerals such as buserite and birnessite are disordered along the basal plane with “big” molecular sheets turned into platelets that are barely discernible by electron microscopy. Asbolane is another term sometimes used for disordered manganese minerals. Vernadite is often used to describe iron rich portions of nodules, due to iron minerals intimately associated with the platelets.

Todorokite is a 10 Å tunnel structured manganese mineral (tectomanganate) that is stable to about 600°C. Due to the similar spacing distance, some earlier researchers may have confused buserite for todorokite and todorokite is likely relatively rare in nodules. It is mentioned as a minor phase in surface nodules by Wegorzewski and Kuhn (2014) and more significantly in buried nodules by Wegorzewski *et al.*, (2020).

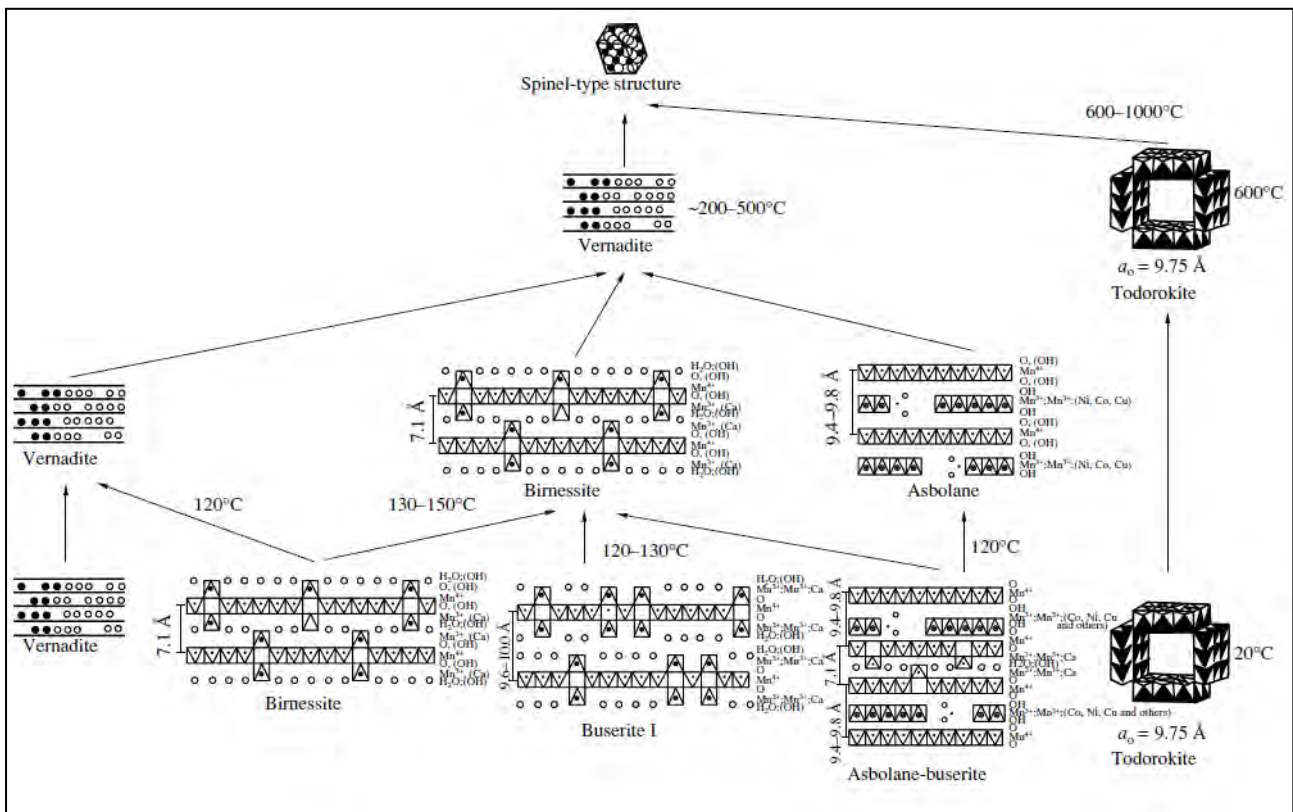


Figure 4-32: Generic model for transformations of manganese minerals during heating
Based on samples from oceanic ferro-manganese rocks Source: (Novikov and Bogdanova, 2007)

Goethite is a very common iron oxide on the earth’s surface. While pure crystalline goethite is stable to about 270°C (except for minor dehydration or dehydroxylation of surface iron (oxo) hydroxo functional groups at 200-250°C) it can be found gradational with/into poorly crystalline and less stable “gels” that are also difficult to identify and measure in methods such as x-ray diffraction.

Feroxyhyte is an unstable high pressure form of goethite (i.e. it starts to breakdown once a nodule is lifted to surface). This may be the most important iron-mineral component of nodules and is epitaxially intergrown with vernadite in the type 1 layers. Its density is thought to be near-identical to goethite.

Lepidocrocite is a highly stable iron mineral also found in nodules. It transforms to maghemite at 250-300°C. It is more dense than goethite.

Detailed studies and classification of the internal micro-textures of nodules include Choi *et al.*, (2002) and Wegorzewski and Kuhn (2014). As mentioned above, they later classify two main layer types from an electron microscope study on nodules from the BGR area in the eastern CCZ:

- Layer type 1: dense layer with average Mn/Fe ratios of 1.80, average Ni + Cu of 0.81 wt.%, Co contents of 0.30 wt.% (interpreted as hydrogenetic metal precipitation from oxic waters). These layers consist of Fe-vernadite (δ -MnO₂) epitaxially intergrown with feroxyhyte (δ -FeOOH).
- Layer type 2: growth structures (dendritic growth structures and dense layers) with average Mn/Fe ratios of 96, Ni + Cu of 3.9 wt.%, Co contents of 0.08 wt.%, and a distinct Ni + Cu maximum of 6.51 wt.% at a Mn/Fe ratio of 56 (interpreted as suboxic-diagenetic, metal precipitation from suboxic pore waters). Type 2 layers mainly consist of turbostratic phylломanganates such as 10 Å vernadite (buserite), 7 Å vernadite (birnessite) and todorokite are minor compounds.
- Also mixed layer type 3: These layers can occur in the transition from layer type 1 to 2 or build-up of inhomogeneous growth structures. The Mn/Fe ratios of this material range between 3 and 11, Ni + Cu of 1 – 4.6 wt.%, and Co contents are between 0.02 and 0.77 wt%. In most cases these growth structures represent a mixture of type 1 and 2 layers.

A feature studied by (Novikov and Bogdanova, 2007) is that of modification of nodule chemistry. Specifically the mineral buserite is favoured by mineralogists for cation exchange experiments (e.g. for use as toxic metal accumulators) because the mineral is easy to dope with alternate cations. In laboratory experiments, a dust of buserite changes chemical composition within a few hours of being subjected to a solution of a particular cation (e.g. Na, Ca, or Ni). (Novikov and Bogdanova, 2007) also managed to increase nickel grades in samples up to 8% and copper up to 11%. While not specifically discussed by (Novikov and Bogdanova, 2007), it seems possible that nodule grades internally might change over time e.g. isotopic signatures reset e.g. (Ku *et al.*, 1979), and grades might change if the nodule moves past the CCD or enters a diagenetically active environment (Figure 4-24).

4.4.2 Other mineral phases

Compared to the relatively small list of essential nodule forming minerals, McKelvey *et al.*, (1983) describe a very wide range of accessory minerals from Pacific nodules, which they classify into:

1. Sheet silicates and zeolite minerals.
2. Clastic silicate and volcanic (volcanogenic) minerals.
3. Biogenic minerals.

These minerals are often not detected by typical X-ray diffraction methods on bulk samples because most exist as fine-grained crystallites similar to the manganese- and iron-phase minerals. McKelvey *et al.*, (1983) only found some of these minerals in concentrates after acid leaching although some minerals were identified by selective area electron diffraction.

These fine-grained hydrous aluminium silicates may have formed by submarine alteration (halmyrolysis) of the primary minerals in basalts or ash transported from distant eruptions. These include chlorite, illite, kaolinite, montmorillonite, nontronite, pyrophyllite, and talc. The most common clay present is generally montmorillonite. These minerals were probably incorporated from sediments during nodule growth.

The zeolites are authigenic and are found in cracks and cavities in the interior of nodules as well as sometime intergrown with the manganese oxides. Zeolites are hydrous silicates with a very open framework and large interconnecting spaces or channels that are filled with sodium, calcium, and variable amounts of water (Bischoff et al., 1981). They are mostly the species phillipsite with rarer analcite, clinoptilolite, epistilbite, erionite, and mordenite. Zeolites are also found in separate precipitates to nodules and their formation has been linked as a possible driver for the release of Mn^{2+} for nodule formation (Bischoff et al., 1981).

Clastic silicate and volcanogenic minerals occur as individual grains that may form the core or become incorporated into the nodule during growth. The more common clastic silicate minerals are quartz and various feldspars but there is a large number or trace and rare minerals, presumably all originally windborne before settling to the seabed and incorporation. The minerals assigned to a volcanic origin are magnetite, anatase, ilmenite, and sphene.

Note that McKelvey *et al.*, (1983) also include barite in the volcanogenic component and while barite is a common hydrothermal phase it is not a major component in other volcanic rocks. Biogenic barite on the other hand is widespread in marine sediments (McMurtry, 2001).

Biogenic minerals include bones and teeth of fish, sharks, and whales (apatite, aragonite and calcite), and siliceous opaline skeletal remains (frustules) of some types of plankton. The debris, such as bones and teeth are generally within the cores of nodules whereas the plankton remains are observed throughout the nodules and were probably incorporated during growth. The opaline debris in the interior of the nodule may undergo dissolution and be associated with the formation of phillipsite and secondary opal.

Opaline frustules are remains of plankton and are a major part of the host clay-ooze sediments for CCZ nodules. Such plankton include phytoplankton (mostly diatoms and silicoflagellates), and zooplankton (mostly radiolarians) and the frustules are composed of hydrated silica ($SiO_2 \cdot nH_2O$; also called bSi or opal-A). The opaline silica is relatively disordered or amorphous (DeMaster, 2003), and it can dissolve in seawater/porewater and then reprecipitate as secondary opal-cristobalite/tridymite (also known as opal-CT or porcellanite). Opal-CT can then transform to microquartz chert (DeMaster, 2003; Yanchilina et al., 2020).

Opal CT formation occurs if for example there is saturation in terms of silica content in water and the accumulating ooze itself. Within the tropical north Pacific, there are high levels of silicic acid in the mid-water, relative to other oceans at this latitude (section 4.5.2.2). This is likely related to circum-ocean currents from the far north Pacific. Estimates of the amount of biogenic SiO_2 within nodules using the a normative formula of (Leinen, 1977) suggests minimal amounts are present, and this is supported by scanning electron microscopy (Figure 4-33, Figure 4-34, section 4.4.3).

Both opal-CT and microquartz chert have been thought to normally only form at temperatures higher than typically found at the sea-floor ($>50^\circ C$). This may be the case for significant amounts of microquartz chert (Yanchilina et al., 2020), but Botz and Bohrmann (1991) use oxygen isotopes to confirm that opal-CT can occur at shallow burial depths and at temperatures of between 0 and $4^\circ C$ (the CCZ seafloor is at a temperature of about $1.5^\circ C$).

Of interest as a stratigraphic marker amongst the biogenous oozes are *Ethmodiscus* silty clays, typically tens to hundreds of cm below the surface in the IOM area (Kotlinski, 2003). This ooze is primarily composed of *Ethmodiscus rex* (*E. rex*), which is often referred to as a 'giant' diatom simply because of its unusually large size which can reach up to 1.8 mm in diameter. High concentrations of *E. rex* have been associated with seabed sedimentation during the Last Glacial Maximum period in seas of Asia e.g. (Xiong et al., 2015). A common strategy of *E. rex* is to migrate down from the photic zone into the water column for up to two weeks at a time in search of 'dark nitrate' (Villareal and Carpenter, 1994).

Of note are salts that are the result of precipitation from contained seawater, namely are sylvite, halite, and other common evaporites. These residues are also the primary source of the anions-borate, bromide, chloride, fluoride, and iodide in manganese nodules.

McKelvey *et al.*, (1983) mention that several elements are associated almost entirely with the accessory minerals of the nodule discussed above. These are Al, Cr, K, P, and Si. High Al contents in three of the nodule samples from TOML B1 (CCZ15-B12, B13, B17) are interpreted to be associated with volcanoclastic components. Other elements associated with the accessory minerals and possibly with the Fe-Mn phases by McKelvey *et al.*, (1983) are Ba, Mg, Na, and Zr.

4.4.3 Microanalysis

Microanalysis on example TOML nodules was conducted for or with the author by two parties:

- 1) Daniel Franks, assisted by G. Luthje and D. McAuley at Queensland University of Technology Central Analytical Research Facility conducted quantitative microprobe scans on two TOML D nodules collected during the CCZ13 expedition (Table 4-9) as part of a student vacation program;
- 2) Anglo American Technical Solutions staff (P.V. Hey, S. Naik, S. Dhlamini, Y. Scharneck) conducted QEMSCAN bulk mineralogical analysis (BMA) on 17 nodules from 9 sites in TOML B1, C1, D1, D2 and F1 collected during the CCZ15 expedition (Table 4-9) as part of project evaluation program.

Table 4-9: Nodule samples for microanalysis

TOML sub-area	Dredge/box-core ID	Latitude	Longitude	Depth (m)	Nodule description
D	CCZ13-D4 (25685)	13.723	-123.966	4,700	m-S
D	CCZ13-D7 (25695)	13.883	-124.326	4,400	l-RS
B1	CCZ15-B07	13.81157	-132.48083	4,959	ml-RS-rg-ra
B1	CCZ15-B21B	13.67548	-132.63251	4,862	l-RS-rg-md-bo
C1	CCZ15-B33	15.25177	-129.57667	4,900	ml-RS-rg-md-bo
C1	CCZ15-B45	15.11178	-129.72761	4,890	m-S-rg-md
D2	CCZ15-B51	13.97681	-124.32412	4,532	l-RS-rg-md-bo
D1	CCZ15-B77	13.55251	-125.16491	4,487	l-RS-rg-md-bo
D1	CCZ15-B86E	13.54223	-125.02078	4,480	m-RS-rg-ra-bo
F1	CCZ15-B104	10.73547	-117.93057	4,420	m-S-rg-co
F1	CCZ15-B111	10.59633	-118.07833	4,389	m-S-rg-co

4.4.3.1 Microanalysis Methods

Per Queensland University of Technology Center for Analytical Research Facility (2021), the JEOL JXA 8530F Hyperprobe is a field emission electron microprobe for high-precision, standards-based quantitative elemental analysis (Be to U) and x-ray mapping using Probe for EPMA and Probe Image software. It boasts an electron gun operating up to 30 kV and several mA beam current, with detection limits routinely ≤ 100 ppm and reaching < 10 ppm. There are twelve analyzing crystals are distributed among five wavelength dispersive spectrometers (WDS) including a large crystal "L" type and two high count rate "H" types. The Hyperprobe's detector array features two sealed Xe and three gas-flow proportional counters. Additional capabilities for imaging and qualitative analysis include a Thermo Noran System 7 EDS system, JEOL panchromatic cathodoluminescence (CL) detector, and both standard and high-resolution xCLent spectroscopic CL detectors.

The two samples analysed using this microprobe were vacuum impregnated with resin before cutting, mounting onto a thin-section and polishing to an exposed surface. The sections were then analysed in the microprobe. As specific calibration standards were not available, and as the concentrations in (Figure 4-33, Figure 4-34) are lower than expected, the results should be taken as qualitative.

Quantitative Evaluation of Materials by Scanning Electron Microscopy (QEMSCAN) raster scans mineral samples with an electron beam and use energy dispersive x-ray response to quantitatively estimate chemical composition and, via spectral libraries, mineralogy (Gottlieb et al., 2000). The method is popular in mineral processing applications where numerous quantitative estimates of ore characteristics are often needed.

For each of the nine sample sets there were a number of nodules included. Where possible, two nodules from each sample were taken and cut using a diamond saw so as to assess the variations in the samples. The cut portions of the nodules were then placed into a mould and impregnated with resin under vacuum. The resulting slabs were then polished and analysed with the QEMSCAN.

The precision of the QEMSCAN chemical analysis is uncertain, given that reference standards are not available, however the chemical analysis levels in section 9.17 Appendix 4C: Anglo American Technical Solutions QEMSCAN report appear to be reasonable and the key distinction between the Mn rich and Fe rich phases in Figure 4-35, Figure 4-36, and Figure 4-37 was taken at 45% Mn and 5% Fe.

4.4.3.2 Microanalysis Results

The microprobe analysis of the two dredge samples from TOML D both show typical iron rich (type 1) and manganese rich (type 2) layers. Higher zoom images of the type 2 layers show that they are made up of what appear to be concentrically grown botryoidal 'micronodules'. There are alumino-silica mineral phases around the micronodules and in larger cracks/voids within and cross-cutting the type 2 and type 1 layers. The QEMSCAN results below suggest this is smectite. The micronodules also contained an interlayered magnesium-calcium rich phase that is interpreted to be zeolite (i.e. phillipsite etc per Bischoff *et al.*, (1981), section 4.4.2).

Other features include an alumino-silica layer associated with higher cobalt that might indicate a sub-oxic growth phase involving abundant diatoms (Figure 4-33; section 4.5.2.3) and an unusually Co depleted Mn-Ni phase at the base of an otherwise normal type 2 layer which might indicate the converse. The higher zoom images also show very fine ($< 10 \mu\text{m}$) silicic and calcic particles included within the micronodules.

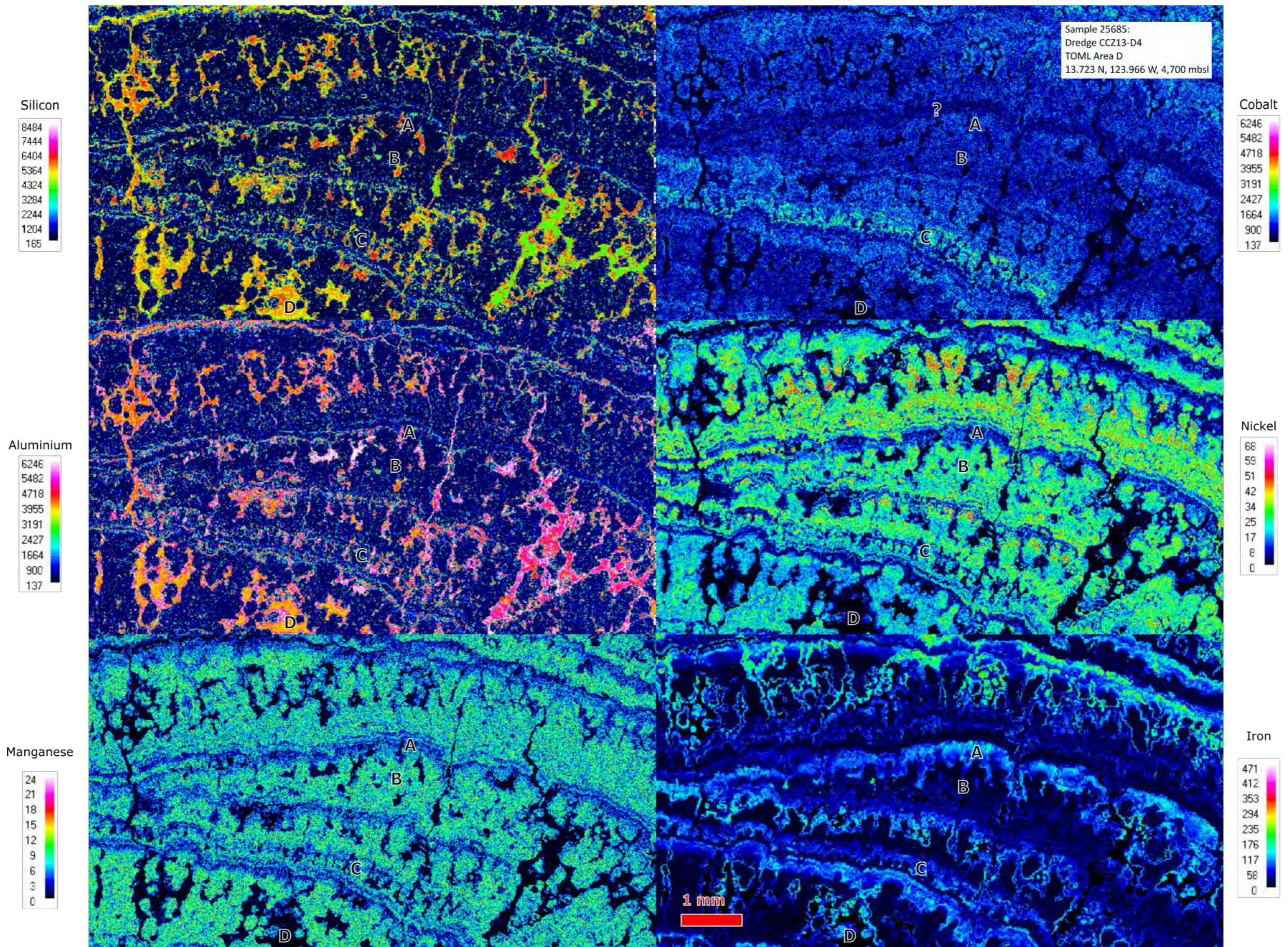
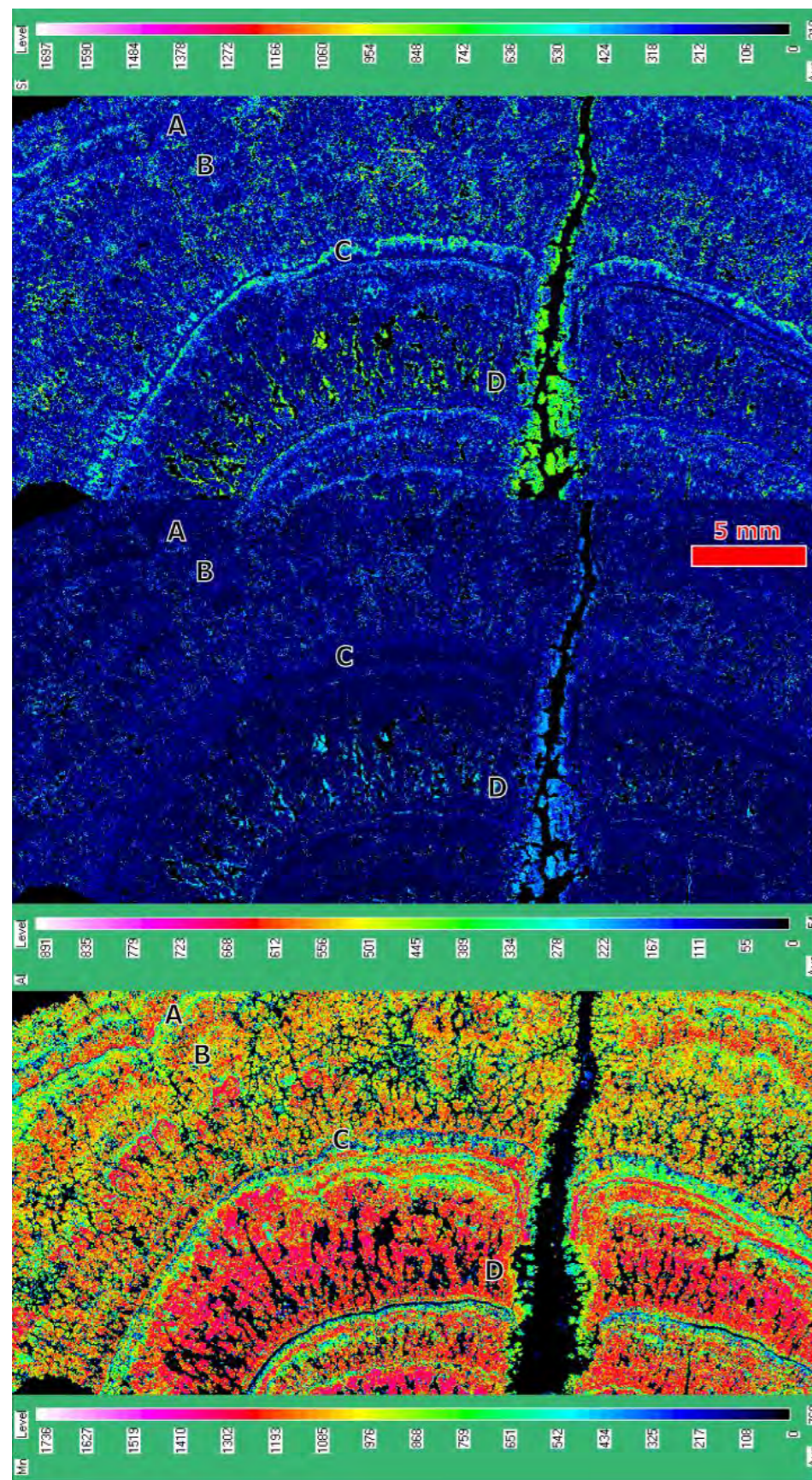


Figure 4-33: Microprobe analysis of part of a nodule from TOML D

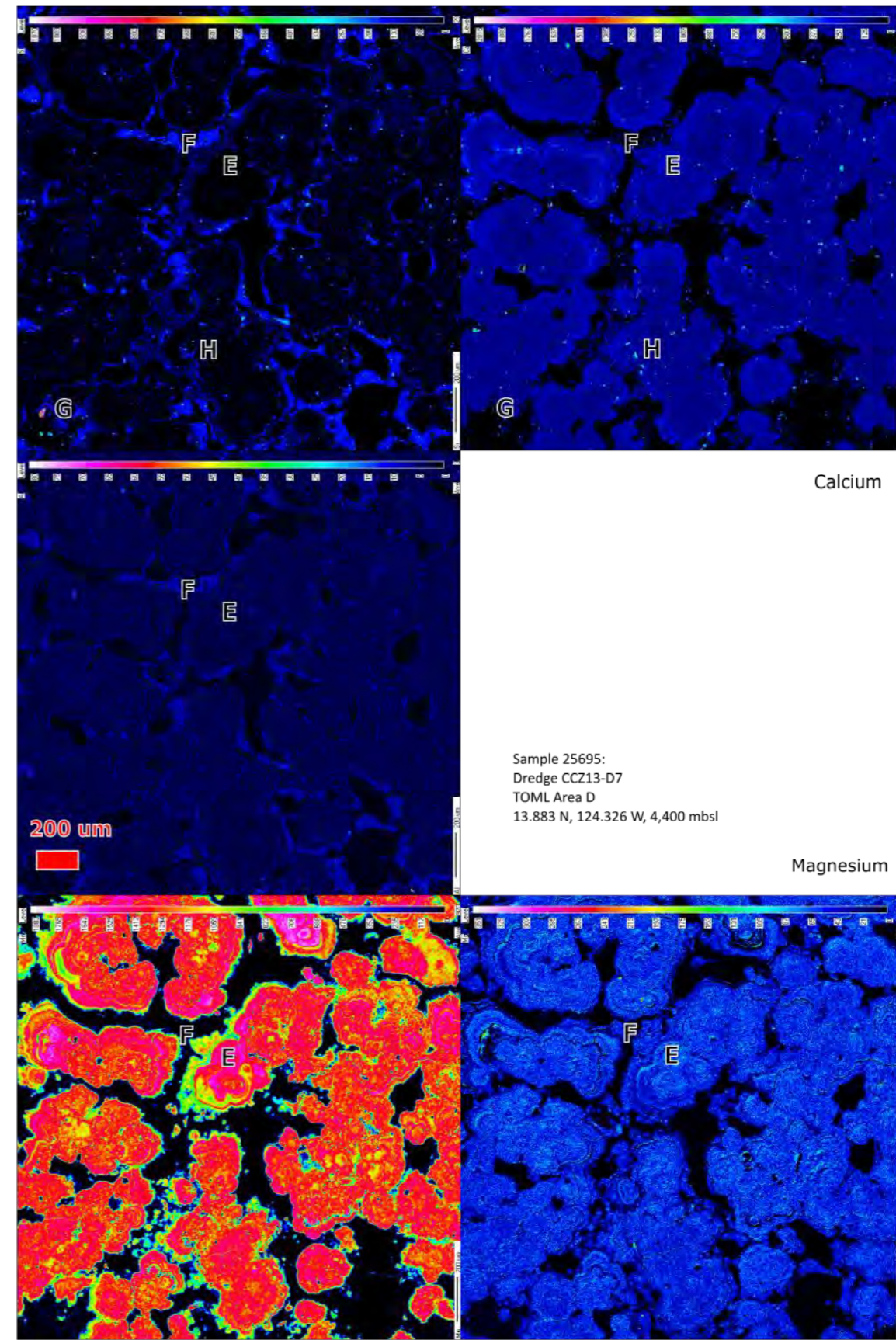
Images collected by D. Franks, G. Luthje and D. McAuley – Queensland University of Technology, 2015 and supplied to the author. Compilation and annotation/interpretation by the author. A: iron rich (type 1) layer, B: manganese rich (type 2) layer, C: alumino-silica layer associated with cobalt, D alumino-silica void/fracture fill (refer to mineral phase 3 (likely smectite) in QEMSCAN results further below), ?: refers to an unusually Co depleted Mn-Ni phase at the base of a type 2 layer.



Silicon

Aluminium

Manganese



Sample 25695:
Dredge CCZ13-D7
TOML Area D
13.883 N, 124.326 W, 4,400 mbsl

Figure 4-34: Microprobe analysis of parts of another nodule from TOML D

Images collected by D. Franks, G. Luthje and D. McAuley – Queensland University of Technology, 2015 and supplied to the author. Compilation and annotation/interpretation by the author. A: iron rich (type 1) layer, B: manganese rich (type 2) layer, C : silica layer, D alumino-silica void/fracture fill, E: manganese micronodule with minor interlayered magnesium and calcium (iron analysis not available but iron is expected to increase with the decrease in manganese towards the edge), F: alumino-silica void fill discrete from micronodules, G: disseminated and included silicic particles, H disseminated and included calcic particles.

For the QEMSCAN results, chemical based mineral phases rather than mineral species are used in Figure 4-35, Figure 4-36 and Figure 4-37. This is due to the fine grained, intergrown and variable composition of the oxide phases, and as the spectral libraries for nodules are (were) not available at the time of analysis. There are seven phases as follows:

- 1) Mn rich phase: interpreted to be predominantly buserite per the discussion above;
- 2) Fe rich phase: interpreted to be predominantly vernadite per the discussion above;
- 3) FeAlKCaMg-Si phase: likely to be a smectite such as Fe- montmorillonite e.g. (Charpentier et al., 2011), and potentially intergrown with opal CT;
- 4) KNaAlFe-Si phase: likely to be a zeolite such as phillipsite (Bischoff et al., 1981) or maybe clinoptilolite e.g. (Hay, 1986);
- 5) CaP phase: likely to be bio-apatite;
- 6) Fe-Si phase discriminated from 4. by minor Mg, Al and K: may be chlorite;
- 7) Mixed Ca, ?Ba S phase: likely to be remnant calcite ooze mixed with barite (barium was not measured but the presence of S is indicative as CaSO_4 is not thought to be stable in this environment).

For accuracy, in the referred figures the mineral phases are referred to by the above names/numbering, but for convenience in the discussion they are referred to by interpreted mineral name.

Some key features from Figure 4-36 and Figure 4-37 are:

- Vernadite – buserite ratios do not vary between areas, and types of nodules (Figure 4-35). Some nodules have cores only of buserite, others of intergrown buserite and vernadite (ie no vernadite dominant cores and no nodules with fine layering to a central point). This indicates most nodules start forming under prolonged sub-oxic (?diagenetic) conditions.
- All areas have simple concentrically grown nodules and nodules composed of older fragments with more recent coatings although in the case of samples from TOML F, such more recent coatings are very thin.
- In most nodules from TOML B, C and D, smectite (FeAlKCaMg-Si mineral phase 3) is more common in voids or coating buserite micronodules (see also Figure 4-34). It seems much rarer in nodules from TOML F.
- Zeolite (KNaAlFe-Si mineral phase 4) are also found in voids and are less common than smectites (and unlike smectites not also found in cracks). They are more common in the older fragment cores of two samples from TOML C, as well as from a simple nodule from TOML F that appears to have an ex-pumice pseudomorph smectite or amphibole seed.
- The ?chlorite phase (Fe-Si phase 6) is usually rare and in small grains except for one nodule from TOML F which has a rim around and through a vernadite ?mini-nodule included at one end of the oval shaped nodule.
- While a barite chemical signature is found in nodules through the TOML/NORI/Marawa areas, and small calcic flecks are noted in Figure 4-34, the calcite-?barite mix (mineral phase 7) is rare to absent

in the scanned nodules with the exception of a simple nodule from TOML F which has a distinctive layer of this material.

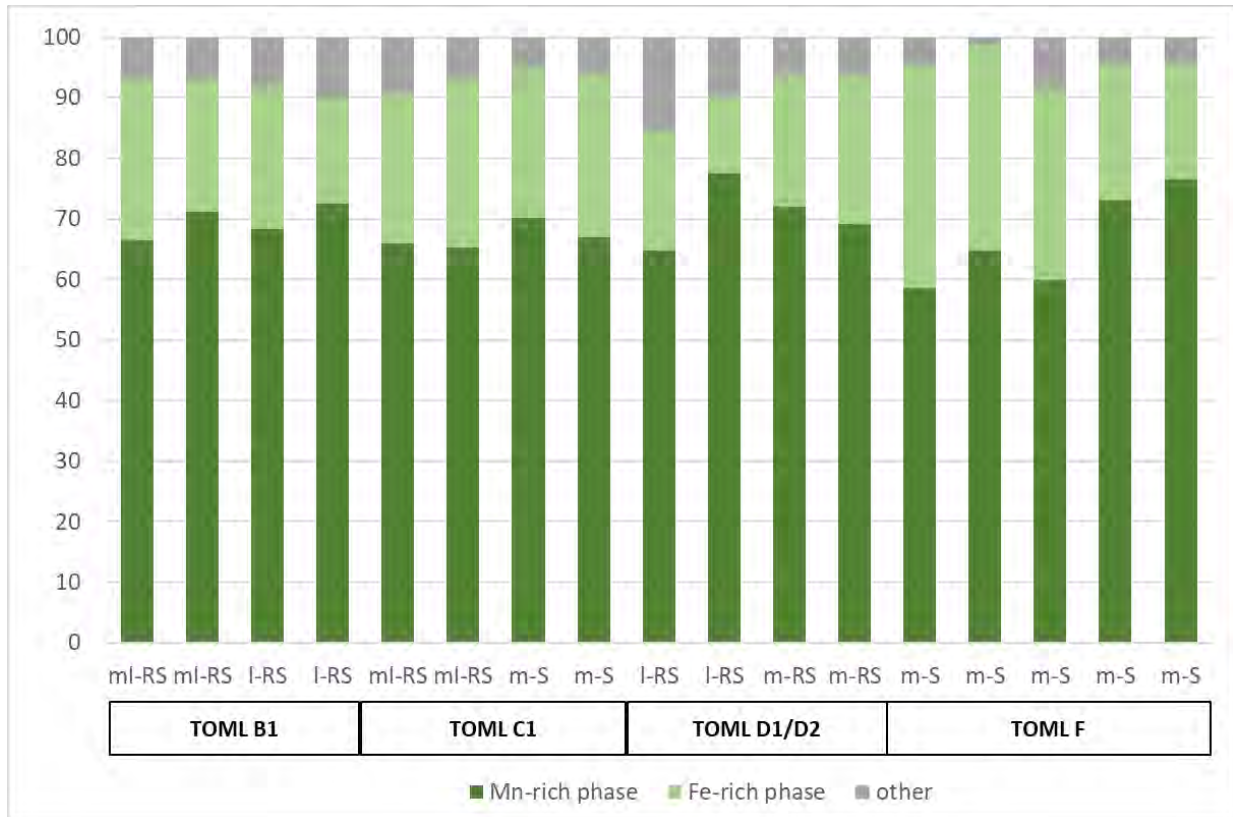


Figure 4-35: QEMSCAM mineral phases for the nodules in Figure 4-36 and Figure 4-37

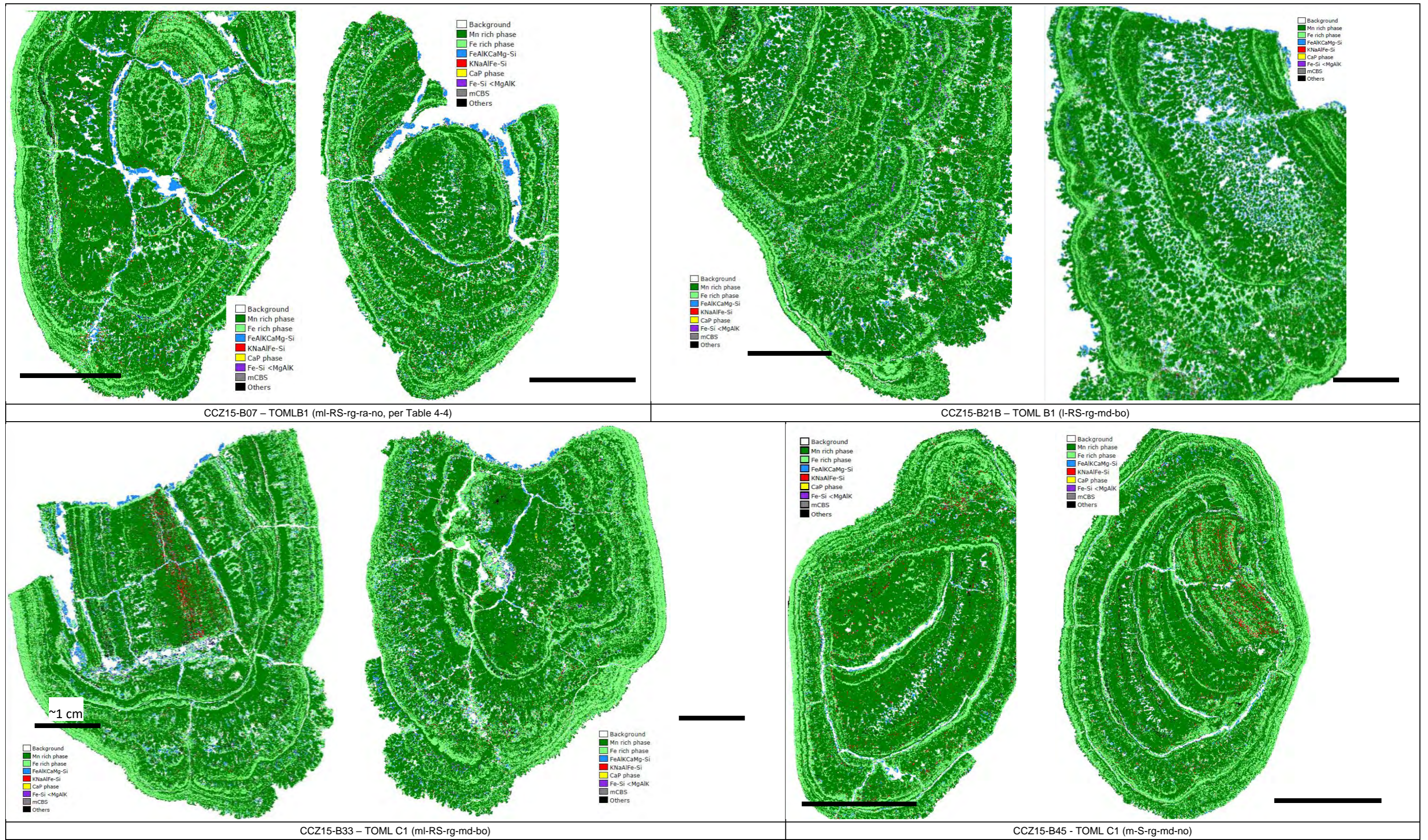


Figure 4-36: QEMSCAM mineral phases for TOML B1 and TOML C1 example nodules

Images collected and processed by P.V. Hey, S. Naik, S. Dhlamini, Y. Scharneck – Anglo American Technical Solutions, 2017 and supplied to the author. Compilation, logging and reinterpretation by the author (refer to section 9.17).

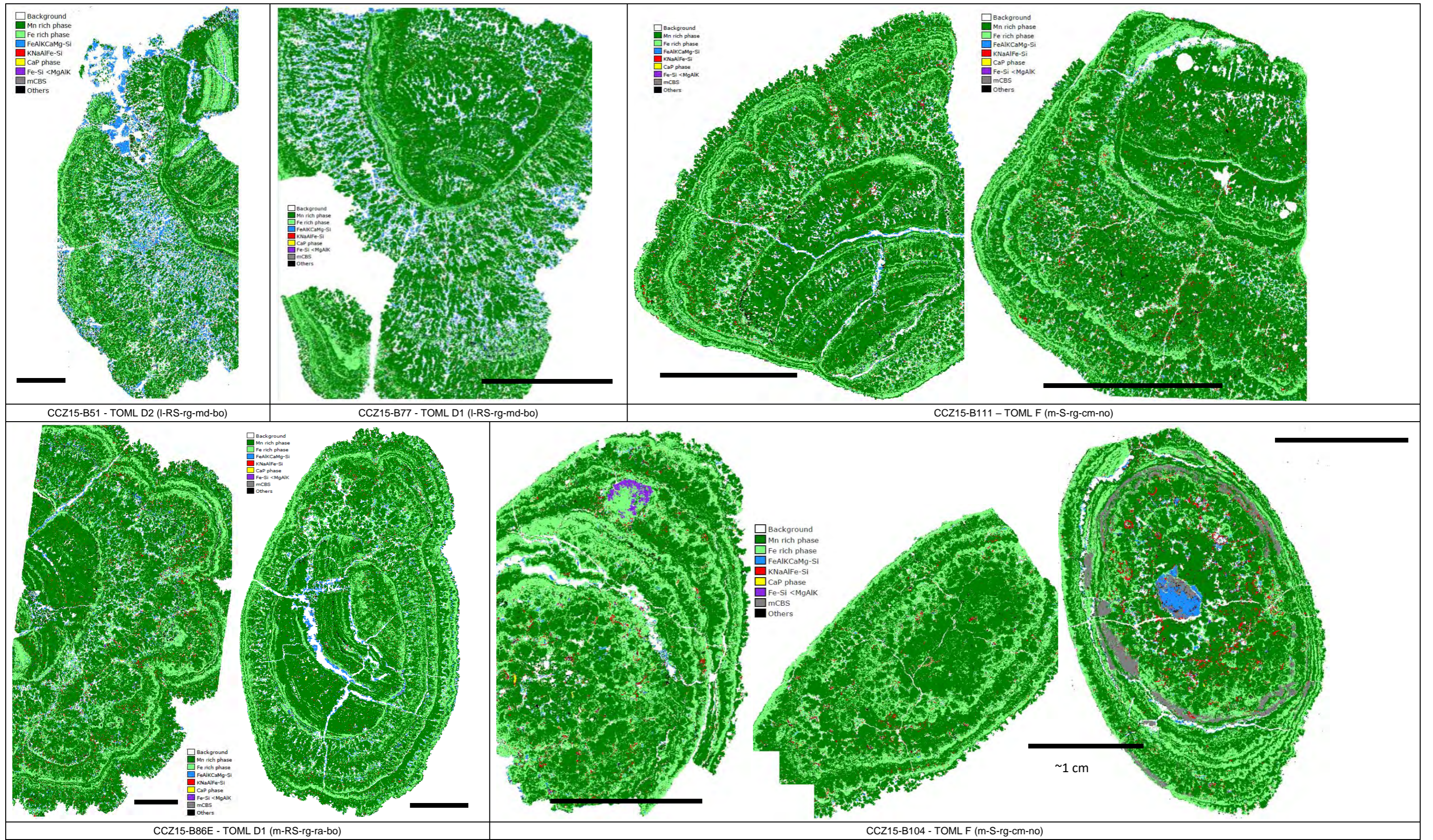


Figure 4-37: QEMSCAM mineral phases for TOML D1, D2 and TOML F example nodules

Images collected and processed by P.V. Hey, S. Naik, S. Dhlamini, Y. Scharneck – Anglo American Technical Solutions, 2017 and supplied to the author. Compilation, logging and reinterpretation by the author (refer to section 9.17).

4.5 Nodule Chemistry

As listed in Table 4-2 there are several datasets available to the author regarding nodule (and crust and sediment) geochemistry. In this study, the focus is on the comprehensive multi-element dataset of nodules sampled by box-cores and dredges from the TOML, NORI and Marawa areas. Reference is often made to other dataset including historical and other published datasets, as well as crust and sediment analyses in certain cases. After some general contextual comments, this section highlights (often subtle) regional and local scale differences in nodule chemistry and discusses possible causes.

To some extent, and unlike the sediment in which they reside, the composition of nodules represent:

1. a record of chemical change during the period of their growth;
2. a normalized or 'buffered' chemical signature, in that distribution coefficients for elements into the ferro-manganese phases are likely to be quantitatively important.

4.5.1 Chemical analysis methods

In this section, unless specified otherwise, elemental compositions are whole rock (nodule) measurements in either dry weight percent or dry parts per million. Sample drying being to 105° C per section 4.7.2.7.

4.5.1.1 Historical Data

Very little is known about the methods behind chemical analysis of the historical data. By comparing the data between the groups that collected it (via box-plots, log-probability plots and summary statistics) and with the data collected by TOML (Lipton et al., 2016), it is clear that:

- the analyses are of completely fused or dissolved nodules dried to comparable temperature (typically 105° C per section 4.7.2.7) prior to aliquot weighing;
- there are no serious issues of bias in any of the historical data sets;
- regional trends discussed further below are seen in historical data as well as the more recent data collected on the TOML/NORI/MARA contract areas.

The TOML tenement area was a Reserved Area and as such was sampled by Pioneer Investor or developed nation sponsored contractors (Chapter 2). These sample data provide the basis of a database held and maintained by the ISA. These data were used initially to define the areas of the TOML application, and subsequently to estimate an inferred mineral resource for the part of the TOML tenement area that they covered (Nimmo et al., 2013).

The most detail regarding collection is for the samples collected by contractor Yuzhmorgeologiya from the Russian returned areas (NORI A and B and TOML B (Lipton et al., 2016)):

1. Extraction of all nodules from the grab sampler;
2. Crushing of all nodules to a maximum particle size of up to 10 mm;
3. Drying (approximately 24 hours) of all samples at 105° C until constant weight was achieved;
4. Crushing of all samples to 1 to 2 mm particle size and splitting of 400 to 500 g using a splitting device;
5. Pulverizing of the split sample (not less than 400 g) was carried out in the vibrating grinder up 100 mesh particle size (0.074 mm);
6. Formation of analytical sample (200 g) and a duplicate (200 g).

Chemical analyses were carried out on sub-samples with an approximate weight of 0.5 g, selected from the analytical sample. Determination of Ni, Cu, Co and Fe content was carried out by AAS and the content of Mn by a method of photometric (electrometric) titration. Note that the Russian Fe grades were not supplied to TOML by the ISA.

4.5.1.2 Box-core and TOML dredge data

All the TOML, NORI and Marawa box-core data and the TOML dredge data was analysed at ALS Laboratory in Brisbane, Australia.

ALS Laboratory Group in Brisbane, Australia has extensive experience in the analysis of high manganese materials by the XRF method. ALS operates quality systems based on international standards ISO/IEC17025:1999 "General requirements for competence of calibration and testing laboratories" and ISO9001:2000 "Quality Management Systems -- Requirements".

ALS-Brisbane preparation processes is:

1. Samples are sorted into sequential order;
2. Samples are then transferred to barcode labelled aluminium trays and loaded onto trolleys which are placed in a large natural gas fired oven for drying;
3. Oven temperature is a maximum of 105°C;
4. After drying, samples are jaw crushed in a Jacques jaw crusher to bring particle size to less than 10mm;
5. Assuming samples weigh less than 3 kg, the crushed samples are then pulverised in an LM5 mill to a powder with typical particle size >85% passing 75 µm. Very small samples are pulverised in a smaller bowl using an LM2 mill.

Prepared samples were then analysed in one or two ways:

1. All samples were analysed for major elements using chromite/manganese ore fused sample disks and X-ray fluorescence (XRF; method ME-XRF26s) for all samples. Specifically returning LOI, Al₂O₃, BaO, CaO, Cr₂O₃, CoO, Fe₂O₃, K₂O, CuO, MgO, MnO, Na₂O, P₂O₅, SO₃, SiO₂, NiO, TiO₂, PbO, ZnO. Note for elemental concentrations the oxides were converted using a factor derived from the atomic masses;
2. Box-core samples were also analysed for minor elements and rare earth elements (REE) using high grade four acid dissolved sample and inductively coupled plasma atomic emission spectrometry (ICP-AES; method ME-ICP61a). Specifically returning Ag, Al, As, Ba, Be, Bi, Ca, Cd, Co, Cr, Cu, Fe, Ga, K, La, Mg, Mn, Mo, Na, Ni, P, Pb, S, Sb, Sc, Sr, Th, Ti, Tl, U, V, W, Zn. Note that some elements were at levels below the detection limit of ME-ICP61a.

For the fusion / XRF method, it is standard practice for ALS to:

1. Place an approximate 0.33 g aliquot into a glass vial, which is then placed in an oven at 105 degrees for a minimum of 1 hour (usually more);
2. The sample is then removed from the oven and immediately weighed in the vial (still warm);
3. The dried sample is then transferred to the tared platinum crucible for fusion.

Note that the ALS XRF26s procedure is specifically designed for difficult to fuse chromite and manganese ores, hence the small aliquot.

For the ICP-AES method, ALS specifically worked to minimize hydroscopic absorption (section 4.7.2.5) by:

1. placing the boxes of pulverised samples in paper bags in an oven for 6 hours at 105° C;
2. removing each box from the oven prior to weighing the sample aliquots and one by one each sample was weighed. This ensured that the last few samples in the box were out of the oven for at most an hour prior to being weighed.

For elements in common, this process resulted in ICPAES results being close to those reported by XRF.

4.5.1.3 Quality assurance and quality control

Check samples for the TOML box-core samples were submitted to a laboratory “Jacobs” operated by the Integrated Environmental Studies Program Group, Earth and Space Sciences Program, at Jacobs University in Bremen, Germany. Outside of quality assurance, these results are not specifically used in this study but details on the laboratory and its methods are included in Lipton *et al.*, (2016).

Quality assurance and quality control (QA/QC) procedures for the TOML box-core samples was stringent as this data was the basis for the contemporary mineral resource estimate discussed in Chapter 5. For the 104 box-core Submitted Portion samples submitted to ALS, 34 were duplicated (32.6%) with 25 Submitted Duplicates to ALS (24.0%); and 15 Field Duplicates to Jacobs (14.4%).

Six submitted portion samples were duplicated both as Submitted Duplicates and Field Duplicates (5.7%). The results of the checks was very good as detailed in Lipton *et al.*, (2016).

The QA/QC process also necessarily included a range of blanks and laboratory nodule standards for both box-core and dredge samples with minimal issues per Lipton *et al.*, (2016) for TOML and Lipton *et al.*, (2021) for NORI. The QA/QC process for the Marawa samples is not documented but understood to be identical to that for the NORI samples.

4.5.2 Chemical analysis results

The chemical analytical results were compiled into MS Excel spreadsheets for the analysis presented here. Due to the confidential nature of much of this data only major element data for box-core and TOML dredge samples is included in 9.18 Appendix 4D: Box-core and dredge major element chemical analysis, but written requests to view other data will be passed to the data owners (International Seabed Authority and Deep Green Metals Inc) for consideration.

4.5.2.1 General Attributes

The TOML, NORI and Marawa nodules analysed here are very typical of CCZ nodules using the Mn:Fe and Ni+Cu discrimination diagrams of Bonatti *et al.*, (1972) and Halbach *et al.*, (1981) as shown in Figure 4-38, Figure 4-39. On the REY based discrimination diagrams of Bau *et al.*, (2014) they are intermediate between the “hydrogenetic” and “diagenetic” type nodules. Per section 4.1.2, the Mn/Fe ratio in both diagrams indicates a mixed oxic/sub-oxic origin and the elevated Ni and Cu indicates proximity below the calcite lysocline. Nodules from the Peru Basin and Indian Ocean Nodule Field show a much greater range of values relating to more dominantly sub-oxic conditions in the former (in the past often ascribed to ‘diagenetic’ conditions) and often more oxic conditions (ascribed to hydrogenetic or hydrogenous conditions) in the later.

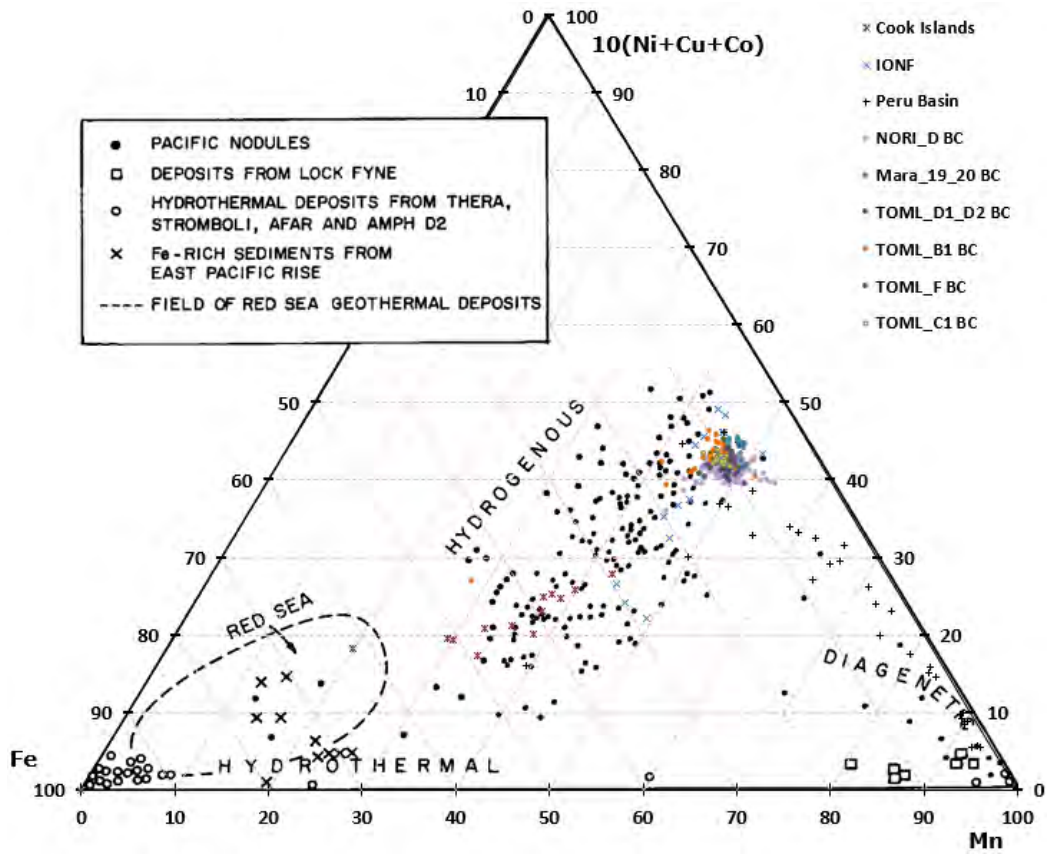


Figure 4-38: Fe-Mn signature of box-core nodule samples and other province datasets

Chart after Bonatti *et al.*, (1972); other chemistry from the Indian Ocean (Pattan and Parthiban, 2011); Peru Basin (Von Stackelberg, 1997); Cook Islands (Glasby *et al.*, 1983).

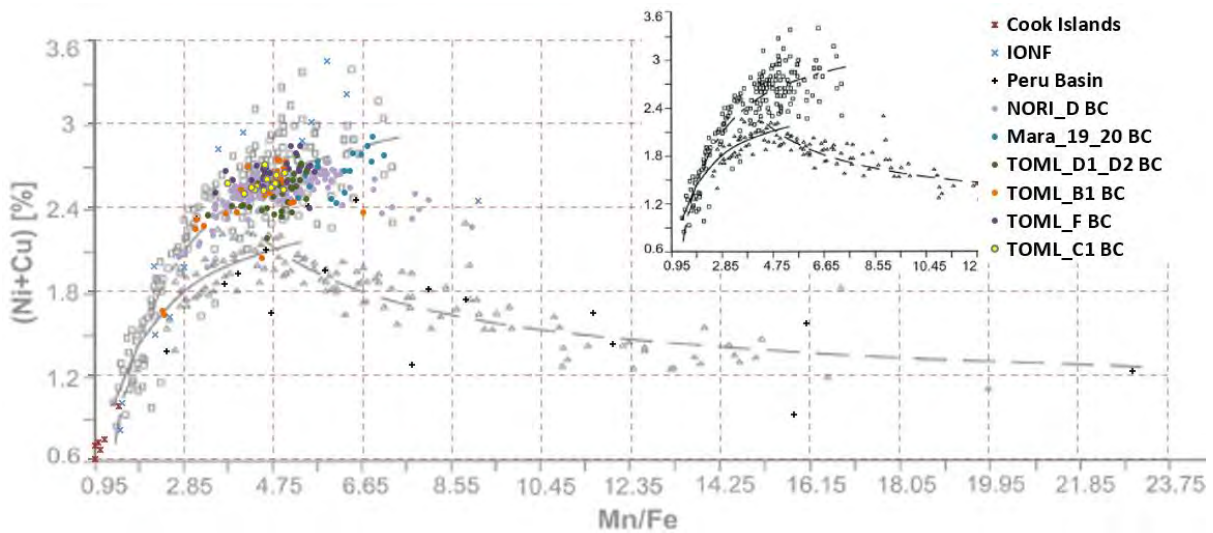


Figure 4-39: Fe-Mn ratio signature of box-core nodule samples and other province datasets

Chart after Halbach *et al.*, (1981). Hollow squares from the CCZ and triangles from the Peru Basin.

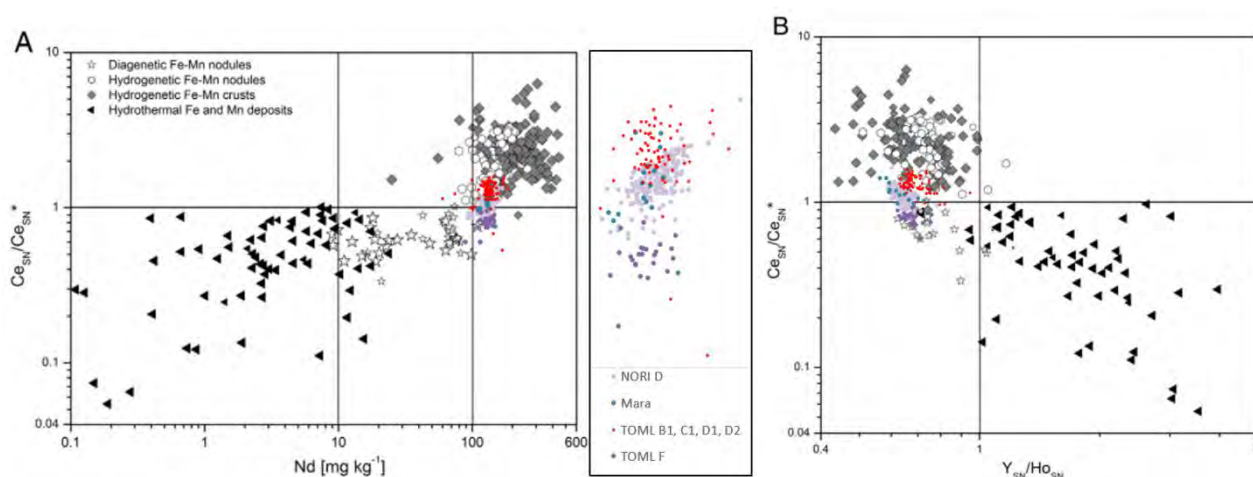


Figure 4-40: Ce-Nd signature of box-core nodule samples against other province datasets

Charts and interpreted genetic type samples after Bau *et al.*, (2014). Inset is for Ce_{SN}/Ce_{SN}^* vs Nd per chart at left. Trend in Ce_{SN}/Ce_{SN}^* for TOML F/NORI D reflects the S->N Ce grade trend evident in Figure 4-48. $_{SN}$ means normalised to the Post Archean Australian Shales (PAAS) of Taylor and McLennan (1985), Ce_{SN}^* means the average of La_{SN} and Pr_{SN} .

Even without any geological domaining, grade variation between nodule box-core samples is very low, with coefficients of variation (CV) typically around of 0.05 to 0.2 (Table 4-10, Figure 4-41). Even extensive sub-sampling (dredge “variance” samples) did not expose any significant variance in grades (CV \leq 0.06 in Table 4-10). Nodule abundance variance is much higher, typically around 0.5 to 0.7 (Table 4-10).

The dredge “variance” samples were groups of up to 30 sub-samples (typically \pm 20 g ea) collected from each dredge in order to study the grade variance or nugget of a sample point. As the dredges were often landed several times in a deployment, a larger range was covered than would be expected in a single box-core.

Table 4-10: Undomained coefficients of variation for historical and TOML nodule samples

Number of samples		Area/sample type	Coefficient of variation				
primary	sub		Mn	Ni	Cu	Co	Abundance
2	60	Area A TOML Dredge Variance	0.09	0.18	0.34	0.22	n/a
18	0	Area A Historical	0.10	0.21	0.35	0.18	0.50
27	0	Area B1 TOML BC	0.20	0.21	0.21	0.18	0.90
1	20	Area B1 TOML Dredge Variance	0.02	0.03	0.04	0.09	n/a
89	0	Area B Historical	0.17	0.20	0.27	0.22	0.67
14	0	Area C1 TOML BC	0.02	0.03	0.03	0.07	0.73
1	30	Area C1 TOML Dredge Variance	0.03	0.03	0.04	0.11	n/a
87	0	Area C Historical	0.08	0.08	0.13	0.13	0.44
38	0	Area D1 and D2 TOML BC	0.03	0.07	0.05	0.09	0.61
10	187	Area D TOML Dredge Variance	0.06	0.10	0.10	0.12	n/a
42	0	Area D Historical	0.05	0.06	0.08	0.10	0.53
12	0	Area E Historical	0.10	0.15	0.17	0.18	0.56
25	0	Area F and F1 TOML BC	0.03	0.06	0.06	0.13	0.23
4	82	Area F TOML Dredge Variance	0.03	0.05	0.08	0.10	n/a
2	0	Area F Historical	0.00	0.03	0.01	0.04	0.27
40	0	NORI A Historical	0.10	0.09	0.12	0.11	0.66
29	0	NORI B Historical	0.11	0.10	0.11	0.10	0.51
137	0	NORI C Historical	0.12	0.12	0.21	0.17	0.59

Number of samples		Area/sample type	Coefficient of variation				
primary	sub		Mn	Ni	Cu	Co	Abundance
252	0	NORI D BC	0.14	0.14	0.15	0.27	0.31
156	0	NORI D Historical	0.10	0.09	0.12	0.26	0.58
16	0	Marawa 1920 BC	0.05	0.05	0.09	0.08	0.93
51	0	Marawa 1920 Historical	0.07	0.10	0.10	0.11	0.73
10	0	Marawa 18 Historical	0.04	0.05	0.05	0.09	0.81

Samples with no or minimal nodule abundances not analysed so not included in chemistry CVs but included in abundance CV.

Figure 4-41 compares the CVs of the historical data and dredge and box-core samples. The size of the circle is proportional to the CV (or spread) of the grades of the samples. One conclusion from the CV values is that abundance is the key problem in mineral resource estimation rather than grade (Chapter 5).

Analysis of correlation coefficients between a range of major and minor elements comprises Table 4-11, and defines a number of fundamental groups:

Group 1 elements are manganese (the single largest components of nodules on a dry basis; section 4.7), and other metals that presumably preferentially adsorb into the key phyllosilicate minerals (section 4.4), i.e. copper, nickel, zinc, tungsten and molybdenum.

Group 2 elements are a combination of continental-crust rock-forming elements such as silicon, aluminium, potassium and magnesium, as well as iron (a key component of nodules under oxic conditions). Much of the silicon and aluminium is likely to be from variably dissolved and diatoms/radiolaria and reprecipitated opal-CT (section 4.4.2), but titanium has been used as indicator of mineral components in deep sea sediments (Dymond *et al.*, 1997). Group 2 elements are significantly inversely correlated to Group 1 elements, likely a simple consequence of mass balance as the two groups together often total around 70% of total oxide weights. Iron's stronger association with Group 2 than with say Group 5 (Co etc.) is somewhat of a surprise, but likely due to relative concentration.

Group 3 elements are barium, sulphur (probably as sulphate) and strontium. Barite (BaSO_4) is used as a key indicator of primary productivity, as Ba preferentially captures S released from decaying organic material in the sediment below the calcite compensation depth, e.g. (Schulz and Zabel, 2006). Sr/Ba ratios are used as an indicator of barite preservation in marine sediments by van Beek *et al.*, (2003). Group 3 is more closely affiliated with Group 1 than Group 2, indicating a link between primary productivity and nodule formation.

Group 4 elements are calcium and phosphorous. They are weakly inversely correlated with Group 1 (but not Group 3). This group is related with marginal calcite/apatite preservation (and incorporation into nodules) at the CCZ seabed.

Group 5 are cobalt and lead, cesium and tantalum. They have a weak correlation with group 2 metals, but surprisingly not with iron. Cobalt also has strong correlations with cerium and uranium in groups 6 and 6b.

Group 6 is the rare-earth elements (and yttrium) and that show strong internal correlation and weaker correlation with Group 1 and Co as well as Group 6b. Group 6b includes some other transition elements, uranium and lead and has broadly similar relationships as the REE albeit with generally weaker correlations, except for Group 2. Cerium the most abundant member of Group 6, is in some ways more like Group 6b, and Yttrium has strong correlations with Group 4.

Group 9 elements are those which generally show no strong correlations. One of these is vanadium whose isotopes have been used as a geochemical tracer for ocean evolution by Wu *et al.*, (2019).

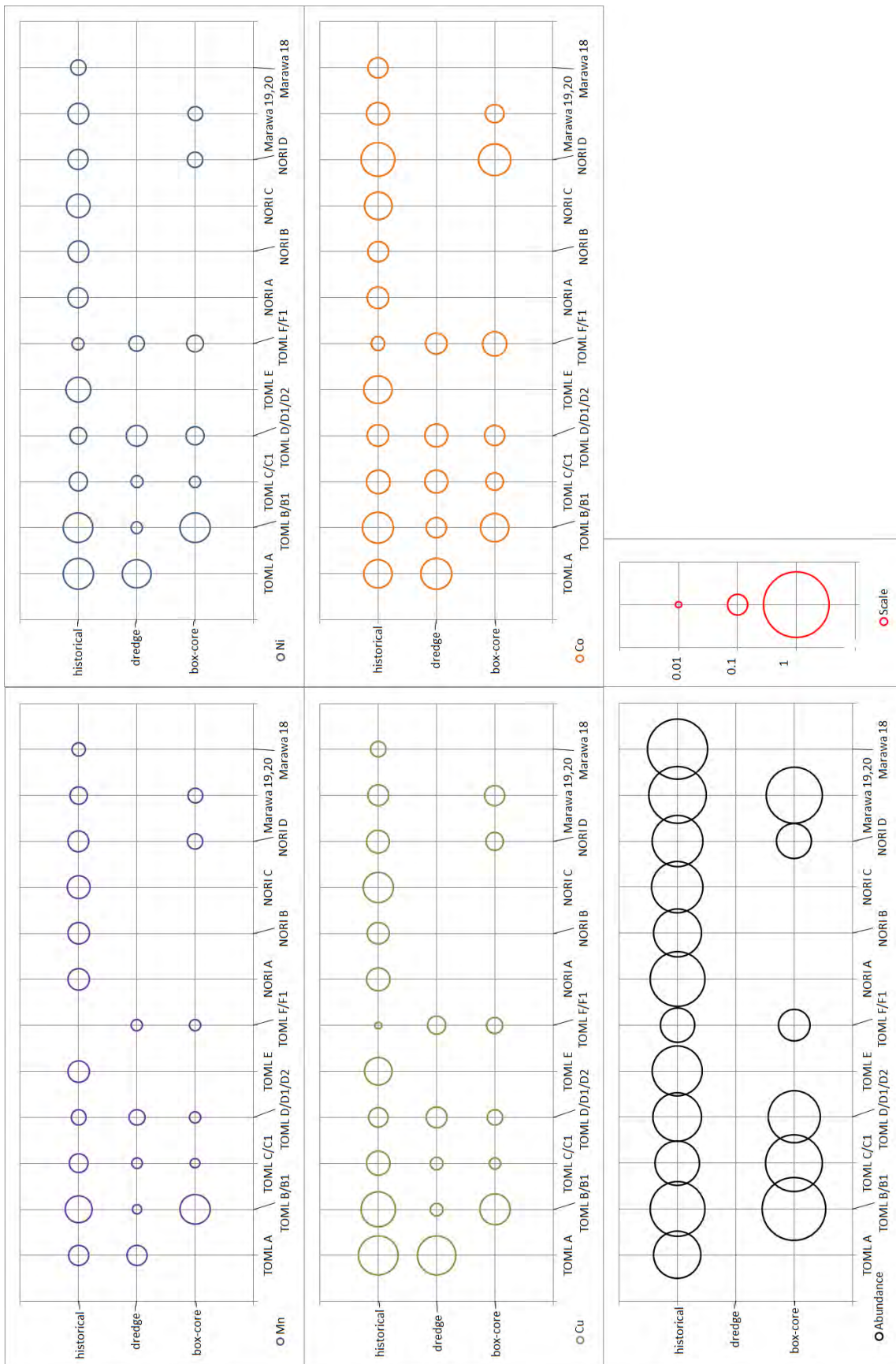


Figure 4-41: Comparison of coefficients of variation for historical and TOML nodule samples
Values from Table 4-10

Table 4-11: Correlation coefficients and basic statistics for TOML and Marawa box-core data

	Group 1					Group 2					Group 3				Group 4			Group 5					Group 6										Group 6b					Group 9									
	Mn_pct	Cu_pct	Ni_pct	ZnO_pct	W_ppm	Mo_ppm	SiO2_pct	Al_pct	Fe_pct	K2O_pct	MgO_pct	Ti_pct	Ba_pct	SO3_pct	Sr_ppm	Ca_pct	P_pct	Co_pct	Rb_ppm	Cs_ppm	Ta_ppm	Y_ppm	La_ppm	Ce_ppm	Pr_ppm	Nd_ppm	Sm_ppm	Eu_ppm	Gd_ppm	Tb_ppm	Dy_ppm	Ho_ppm	Er_ppm	Tm_ppm	Yb_ppm	Lu_ppm	Hf_ppm	Nb_ppm	Th_ppm	U_ppm	Zr_ppm	PbO_pct	Na2O_pct	Ga_ppm	V_ppm		
Group 1	Mn_pct	0.754	0.779	0.765	0.517	0.726	-0.899	-0.885	-0.426	-0.315	-0.203	-0.725	0.432	0.158	0.496	-0.540	-0.303	-0.052	-0.470	-0.217	-0.434	-0.262	0.146	0.040	0.241	0.230	0.310	0.216	0.225	0.141	0.209	0.112	0.166	0.063	0.125	0.116	-0.394	-0.209	-0.031	0.101	-0.068	-0.171	0.023	-0.090	0.306	Mn_pct	
	Cu_pct	0.754		0.525	0.698	0.140	0.783	-0.626	-0.690	-0.715	-0.352	-0.502	-0.813	0.496	0.388	0.339	-0.244	-0.038	-0.057	-0.262	-0.059	-0.281	-0.201	-0.190	-0.250	-0.065	-0.073	-0.027	-0.130	-0.081	-0.078	-0.109	-0.110	-0.055	-0.161	-0.087	-0.042	-0.669	-0.404	-0.196	0.036	-0.356	-0.010	0.038	-0.251	0.121	Cu_pct
	Ni_pct	0.779	0.525		0.609	0.372	0.516	-0.782	-0.701	-0.168	-0.286	-0.029	-0.499	0.159	0.024	0.487	-0.442	-0.235	-0.026	-0.414	-0.220	-0.337	-0.049	0.384	0.132	0.441	0.430	0.477	0.396	0.416	0.322	0.430	0.320	0.333	0.291	0.314	0.297	-0.072	0.057	0.072	0.201	0.202	-0.125	-0.033	0.157	0.121	Ni_pct
	ZnO_pct	0.765	0.698	0.609		0.048	0.669	-0.712	-0.723	-0.381	-0.511	-0.290	-0.673	0.472	0.402	0.513	-0.286	-0.162	-0.387	-0.599	-0.412	-0.426	-0.211	-0.007	-0.260	0.064	0.131	0.039	0.068	-0.046	0.074	0.013	0.069	-0.021	0.001	0.052	-0.435	-0.404	-0.316	0.014	-0.193	-0.296	-0.253	0.206	-0.253	0.121	ZnO_pct
	W_ppm	0.517	0.140	0.372	0.048		0.263	-0.507	-0.474	0.068	-0.022	0.091	-0.202	0.072	-0.276	0.383	-0.398	-0.246	0.273	-0.252	-0.177	-0.224	-0.133	0.346	0.329	0.353	0.343	0.370	0.303	0.292	0.233	0.308	0.198	0.212	0.152	0.168	0.144	0.215	0.315	0.138	0.198	0.383	0.031	-0.245	0.129	0.483	W_ppm
	Mo_ppm	0.726	0.783	0.516	0.669	0.263		-0.616	-0.662	-0.506	-0.355	-0.525	-0.585	0.340	0.217	0.448	-0.322	-0.161	0.086	-0.295	-0.104	-0.368	-0.131	0.045	0.074	0.268	0.244	0.335	0.223	0.239	0.263	0.197	0.202	0.276	0.125	0.241	0.250	-0.376	-0.144	0.098	0.173	-0.001	0.192	0.109	-0.367	0.368	Mo_ppm
Group 2	SiO2_pct	-0.899	-0.626	-0.782	-0.712	-0.507	-0.616		0.961	0.295	0.497	0.205	0.669	-0.313	-0.227	-0.630	0.239	-0.016	0.075	0.630	0.358	0.444	-0.073	-0.433	-0.074	-0.449	-0.468	-0.505	-0.395	-0.445	-0.327	-0.455	-0.367	-0.417	-0.337	-0.348	-0.380	0.285	0.125	0.051	-0.412	-0.045	0.185	-0.003	0.036	-0.247	SiO2_pct
	Al_pct	-0.885	-0.690	-0.701	-0.723	-0.474	-0.662	0.961		0.405	0.468	0.392	0.778	-0.391	-0.306	-0.621	0.203	-0.077	0.070	0.560	0.326	0.425	-0.064	-0.344	0.025	-0.370	-0.396	-0.434	-0.323	-0.379	-0.263	-0.355	-0.301	-0.359	-0.254	-0.283	-0.317	0.381	0.204	0.105	-0.390	0.052	0.183	-0.093	0.125	-0.210	Al_pct
	Fe_pct	-0.426	-0.715	-0.168	-0.381	0.068	-0.506	0.295	0.405		0.075	0.564	0.632	-0.482	-0.362	0.028	-0.034	-0.202	0.012	-0.117	-0.246	0.156	0.111	0.380	0.250	0.179	0.182	0.113	0.173	0.132	0.055	0.261	0.138	0.099	0.206	0.074	0.087	0.775	0.495	0.009	0.121	0.589	-0.023	-0.141	0.305	0.135	Fe_pct
	K2O_pct	-0.315	-0.352	-0.286	-0.511	-0.022	-0.355	0.497	0.468	0.075		0.054	0.195	-0.219	-0.258	-0.541	-0.320	-0.272	0.461	0.814	0.640	0.375	-0.141	-0.115	0.324	-0.067	-0.132	-0.148	-0.035	-0.148	-0.037	-0.164	-0.158	-0.244	-0.120	-0.114	-0.220	0.209	0.315	0.420	-0.252	0.009	0.174	0.061	0.296	-0.127	K2O_pct
	MgO_pct	-0.203	-0.502	-0.029	-0.290	0.091	-0.525	0.205	0.392	0.564	0.054		0.595	-0.368	-0.520	-0.273	-0.120	-0.308	-0.037	-0.048	-0.022	0.113	-0.101	0.082	0.172	-0.050	-0.065	-0.096	-0.024	-0.069	-0.089	0.046	-0.067	-0.133	0.010	-0.099	-0.110	0.370	0.199	0.027	-0.241	0.205	-0.119	-0.287	0.493	0.167	MgO_pct
	Ti_pct	-0.725	-0.813	-0.499	-0.673	-0.202	-0.585	0.669	0.778	0.632	0.195	0.595		-0.537	-0.428	-0.439	0.200	-0.087	0.225	0.274	0.176	0.291	0.125	0.073	0.371	0.048	0.028	-0.023	0.077	0.028	0.120	0.068	0.096	0.022	0.142	0.086	0.049	0.611	0.458	0.326	-0.087	0.355	0.307	-0.110	0.247	0.066	Ti_pct
Group 3	Ba_pct	0.432	0.496	0.159	0.472	0.072	0.340	-0.313	-0.391	-0.482	-0.219	-0.368	-0.537		0.648	0.486	-0.168	-0.127	-0.526	-0.350	-0.399	-0.494	-0.377	-0.387	-0.520	-0.310	-0.280	-0.197	-0.293	-0.215	-0.341	-0.321	-0.341	-0.246	-0.409	-0.323	-0.304	-0.481	-0.522	-0.459	-0.297	-0.330	-0.311	0.202	-0.414	-0.086	Ba_pct
	SO3_pct	0.158	0.388	0.024	0.402	-0.276	0.217	-0.227	-0.306	-0.362	-0.258	-0.520	-0.428	0.648		0.434	0.225	0.301	-0.382	-0.244	-0.284	-0.204	0.106	-0.110	-0.414	-0.100	-0.048	-0.060	-0.148	-0.026	-0.097	-0.094	-0.032	-0.003	-0.064	-0.064	0.001	-0.358	-0.321	-0.366	0.148	-0.270	-0.161	0.240	-0.266	-0.312	SO3_pct
	Sr_ppm	0.496	0.339	0.487	0.513	0.383	0.448	-0.630	-0.621	0.028	-0.541	-0.273	-0.439	0.486	0.434		-0.052	0.057	-0.378	-0.714	-0.760	-0.455	0.112	0.359	-0.199	0.341	0.406	0.416	0.226	0.376	0.221	0.390	0.320	0.401	0.233	0.235	0.298	0.120	0.061	-0.346	0.388	0.414	-0.113	-0.038	-0.196	0.102	Sr_ppm
Group 4	Ca_pct	-0.540	-0.244	-0.442	-0.286	-0.398	-0.322	0.239	0.203	-0.034	-0.320	-0.120	0.200	-0.168	0.225	-0.052		0.922	-0.155	-0.075	-0.131	0.100	0.682	0.108	-0.274	-0.013	0.060	-0.034	0.060	0.077	0.067	0.217	0.217	0.234	0.166	0.279	-0.082	-0.133	-0.226	0.387	-0.171	0.100	-0.116	-0.070	-0.247	Ca_pct	
	P_pct	-0.303	-0.038	-0.235	-0.162	-0.246	-0.161	-0.016	-0.077	-0.202	-0.272	-0.308	-0.087	-0.127	0.301	0.057	0.922		-0.022	-0.061	-0.061	0.103	0.766	0.265	-0.180	0.155	0.225	0.129	0.100	0.207	0.223	0.205	0.353	0.350	0.364	0.304	0.408	-0.167	-0.088	-0.132	0.575	-0.176	0.122	-0.113	-0.027	-0.261	P_pct
Group 5	Co_pct	-0.052	-0.057	-0.026	-0.387	0.273	0.086	0.075	0.070	0.012	0.461	-0.037	0.225	-0.526	-0.382	-0.378	-0.155	-0.022		0.551	0.655	0.406	0.241	0.351	0.781	0.448	0.376	0.309	0.392	0.296	0.500	0.297	0.366	0.262	0.389	0.400	0.325	0.260	0.638	0.770	0.343	0.265	0.678	-0.143	0.317	0.256	Co_pct
	Rb_ppm	-0.470	-0.262	-0.414	-0.599	-0.252	-0.295	0.630	0.560	-0.117	0.814	-0.048	0.274	-0.350	-0.244	-0.714	-0.075	-0.061	0.551		0.862	0.499	-0.002	-0.231	0.297	-0.147	-0.199	-0.206	-0.069	-0.160	0.016	-0.258	-0.141	-0.220	-0.105	-0.050	-0.199	0.031	0.218	0.531	-0.214	-0.175	0.289	0.099	0.253	-0.270	Rb_ppm
	Cs_ppm	-0.217	-0.059	-0.220	-0.412	-0.177	-0.104	0.358	0.326	-0.246	0.640	-0.022	0.176	-0.399	-0.284	-0.760	-0.131	-0.061	0.655	0.862		0.425	0.002	-0.103	0.482	0.008	-0.069	-0.060	0.075	-0.058	0.135	-0.099	-0.024	-0.115	0.031	0.075	-0.034	-0.130	0.139	0.657	-0.115	-0.247	0.306	0.092	0.185	-0.047	Cs_ppm
	Ta_ppm	-0.434	-0.281	-0.337	-0.426	-0.224	-0.368	0.444	0.425	0.156	0.375	0.113	0.291	-0.494	-0.204	-0.455	0.100	0.103	0.406	0.499	0.425		0.184	-0.020	0.219	-0.078	-0.090	-0.235	-0.177	-0.176	0.013	-0.068	-0.025	-0.142	0.024	-0.060	-0.054	0.294	0.416	0.197	0.079	0.098	0.277	-0.112	0.404	-0.115	Ta_ppm
Group 6	Y_ppm	-0.262	-0.201	-0.049	-0.211	-0.133	-0.131	-0.073	-0.064	0.111	-0.141	-0.101	0.125	-0.377	0.106	0.112	0.682	0.766	0.241	-0.002	0.002	0.184		0.687	0.196	0.585	0.634	0.505	0.510	0.608	0.634	0.638	0.755	0.704	0.784	0.711	0.757	0.179	0.305	0.184	0.781	0.188	0.270	-0.137	0.261	-0.094	Y_ppm
	La_ppm	0.146	-0.190	0.384	-0.007	0.346	0.045	-0.433	-0.344	0.380	-0.115	0.082	0.073	-0.387	-0.110	0.359	0.108	0.265	0.351	-0.231	-0.103	-0.020	0.687		0.592	0.903	0.908	0.843																			

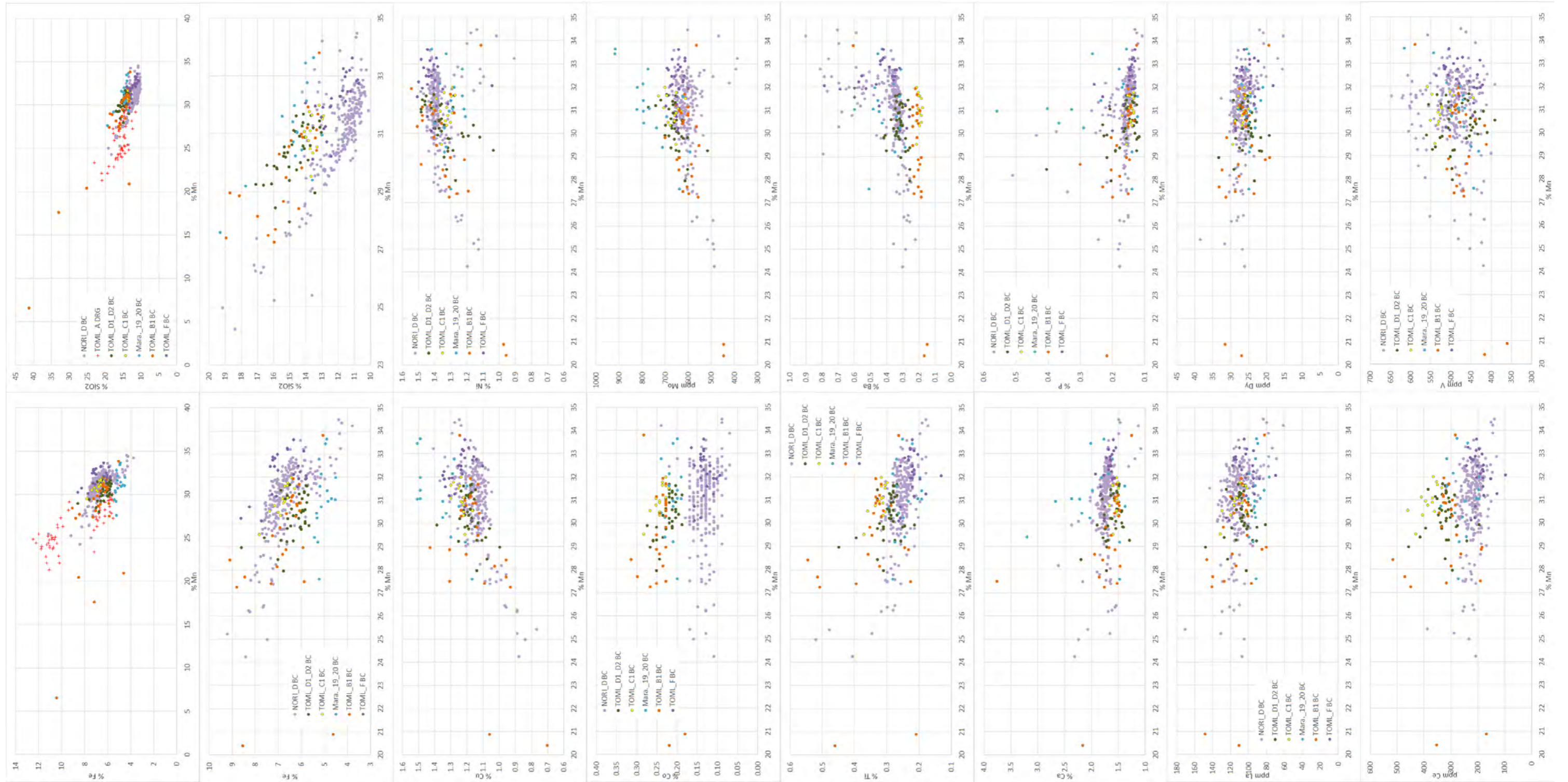


Figure 4-42: Mn-Harker diagrams for polymetallic nodules

4.5.2.2 Regional chemical trends and differences

Data coverage is patchy, but CCZ wide changes in chemistry have been well documented (de L'Etoile, 2003; Morgan, 2003; International Seabed Authority, 2010a) and are in part reproduced in Figure 2-28 and section 9.4. These include generally cross-CCZ (roughly north-south) changes in Mn, Cu, Ni and Co, with the Co change antithetic to the others. This review included almost all contractor datasets, the ISA reserved area datasets and data from some of the commercial consortia of the 1970s/80s (most of which is proprietary). A key gap in the above referenced ISA review is data from the eastern end of the CCZ. The wide geographic range and multi-element nature of the box-core (\pm dredge data) available to the author thus allows for some additional contributions as presented here.

As nodules are dominated by manganese (versus iron and silicates), and with some reference to Table 4-11 above, selected elements by sub-area are shown against manganese in Figure 4-42. These provide a basis to the relationships discussed further below.

Some key points from Figure 4-42 are:

- Even within areas there are distinctly negative trends for iron (presumably reflecting relative dominance of oxic conditions and silica (?incorporation of opaline material and relative dilution of manganese). The two low manganese nodules from TOML B are thought to have a volcanoclastic component (e.g. pumice) included with the nodules. TOML sample CCZ15-B17, which has only 6.4% manganese, is known to include basalt fragments. The two sets of variance dredge samples from TOML A form two discrete populations (e.g. Figure 4-42).
- For a given manganese content, the Marawa nodules have lower 1-2 % lower iron and slightly higher silica contents compared to the central CCZ sub-areas (TOML B, C, D), while TOML F and NORI D in the far east have \sim 3 % lower silica and \sim 1% higher iron.
- Both copper and nickel show solid positive correlations with manganese, but some samples have more erratic higher copper values for a given manganese value and others show more erratic lower nickel values for a given manganese value. For nickel this is especially true for higher manganese contents and interestingly reflects the trend seen for Peru Basin nodules in Figure 4-38 and Figure 4-39. The Peru Basin is understood to have higher sedimentation rates, and a more established sub-oxic environment than the CCZ. While the erratic higher copper and lower nickel values are seen in a range of areas, they seem more common in the Marawa and NORI D areas, which both have higher present day sea-surface primary productivity (Figure 4-48). The erratically lower nickel samples may correspond with higher barium and, in NORI D, lower molybdenum.

Cobalt values trend apparently independently of manganese, (and Table 4-11, also Fe), but there is a distinctly lower level of cobalt in TOML F/NORI Ds nodules. There are similar offsets seen for some other elements and this is discussed further in section 4.5.2.3.

- The Marawa samples also return distinctly higher molybdenum. Review of QA/QC from the lab results was inconclusive regarding the molybdenum, due to low molybdenum in all of the nodule standards used.
- Lower titanium and cerium, but higher barium, calcium and to a lesser extent phosphorous are seen in TOML F/NORI D compared to the other TOML sub-areas. These are all taken to relate to higher primary productivity in the area over the growth-life of the nodules concerned. In the case of barium and titanium this signature extends to the Marawa area, but for calcium, phosphorous and to a

lesser extent cerium the Marawa area shows a broad spread of values (note that the Marawa samples also spans almost 2° of latitude, more than for any other area).

The REE show very close internal correlations in Table 4-11, and both lighter lanthanum and heavier dysprosium show weak negative correlations with manganese. The Marawa samples are again distinctive with slightly lower lanthanum.

- While vanadium isotopes might provide a useful geochemical tracer for the evolution of the oceans e.g. (Wu et al., 2019), vanadium element values, much like the rest of group 9, show no clear trends.

4.5.2.3 The Cobalt Question

A key regional variance amongst the TOML-NORI-Marawa areas is for cobalt grades (Figure 4-43). While nickel, manganese and to some extent copper are more constant, there are generally higher cobalt grades to the north-west and lower grades to the south-east. The reasons for this change are explored in this section.

This is not a new question. Cobalt trends are discussed at some length in (Office of Resources and Environmental Monitoring, 2003). This includes attempts to correlate with the Mahi Mahi Fracture Zone (e.g. Figure 2-2), and with other deposits in the SW Pacific (i.e. with consideration of the oxygen minimum zone and perhaps more significantly, the Antarctic Bottom Water Current, that is believed to play a key role in the formation of the Aitutaki passage (Cook Islands EEZ high cobalt grade nodules). With an implied very low ocean residence time, Glasby (2006) classifies Co as a scavenged-type element (along with Mn) as opposed to Ni (nutrient-type) and Cu (intermediate). Review by Bruland and Lohan (2003) interprets that while in the ocean, >90% of Co is bound in organic ligands.

The recent box-core data set from TOML/NORI D/Marawa provide comprehensive and relatively proximal multi-element chemistry, all collected by the same laboratory, for a more detailed comparison across the CCZ than has been previously possible.

Per Table 4-11 and Figure 4-46, Co grades do not correlate well with Fe, Mn or a combination of these two elements at the regional scale, however there is often positive correlation between Co and Fe at the local scale, and apparent correlation at the inter-province level. At the regional scale, there are closer correlations in elements such as Ce, Si, Ti, Al, Cs, Th, Pb (positive) and Ba, Sr, and Ca (negative), although local correlations may be more significant (Figure 4-46). Normalizing some of these elements by Fe (e.g., Ti, Th, Sr in Figure 4-47) often smooths the correlation regionally and flattens (destroys) the correlation locally. Significantly, for other elements (e.g., Ce, Al, Ba, Ca, Pb, Cs in Figure 4-47) this is not the case. This all indicates that hydrogenetic vs diagenetic growth likely influences cobalt grades locally but not regionally (i.e., at the scale of the CCZ). It is also worth noting here that the busenite : vernadite ratios in nodules analysed by QEMSCAN do not vary significantly across the region (Figure 4-35, Figure 4-36, Figure 4-37).

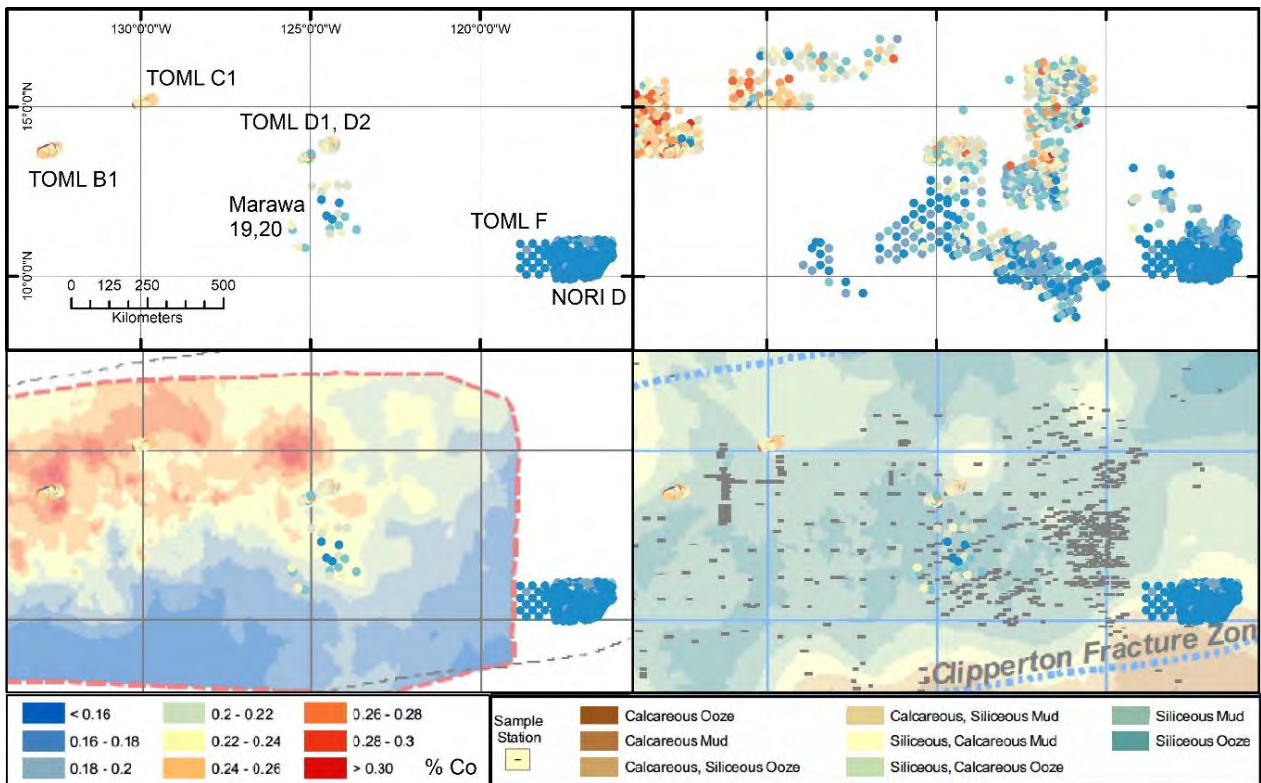


Figure 4-43: Cobalt grade changes central to eastern CCZ

Sources: backdrop maps from International Seabed Authority (2010a); top-right includes reserved area data. Note data gaps in the ISA models may explain some of the variance against the TOML/NORI/Marawa data.

Inter-province scale variations in Co grade in nodules is analysed at some length by Ohta *et al.*, (1999) who focus on Ce (or rather Ce anomalies versus other REE) as a prime indicator. Unlike the other REE, which are mostly restricted to a 3+ valence, Ce has 2+ and 4+ states and thus reacts differently in some chemical situations, e.g., change in oxidation conditions. Positive, but often erratic, Ce anomalies have thus been related to Fe/Mn and Co trends at the larger scales, as these contrast with normally negative cerium anomalies in sea-water, e.g. (Bau and Koschinsky, 2009; de Baar *et al.*, 2018). For the purposes of this analysis, it is noted that at the regional and local scales, Ce and Ce anomaly relate similarly to Co, albeit with slightly higher scatter for Ce (Figure 4-44; r^2 of TOML/NORI/ MARA samples of 0.58 vs 0.70).

One of Ohta *et al.*, (1999) conclusions, is that the inter-province scale Co-grade trends are a consequence of oxidative uptake of Co. This is overprinted onto other metal uptake, that is perhaps more directly related to overall primary productivity. They propose that the control for the oxidative uptake is related to interprovince scale variations in particle size distributions and consequent suspended residence time prior seabed deposition (something that is neither supported nor falsified here). Ce partitioning out of very old deep seawater in the central North Pacific Ocean (i.e. North Pacific Deep Water layer at 28° N, that is fed by the Antarctic Bottom Water) is also attributed to oxidative processes by de Baar *et al.*, (2018), with Mn-oxides the mostly likely scavenger.

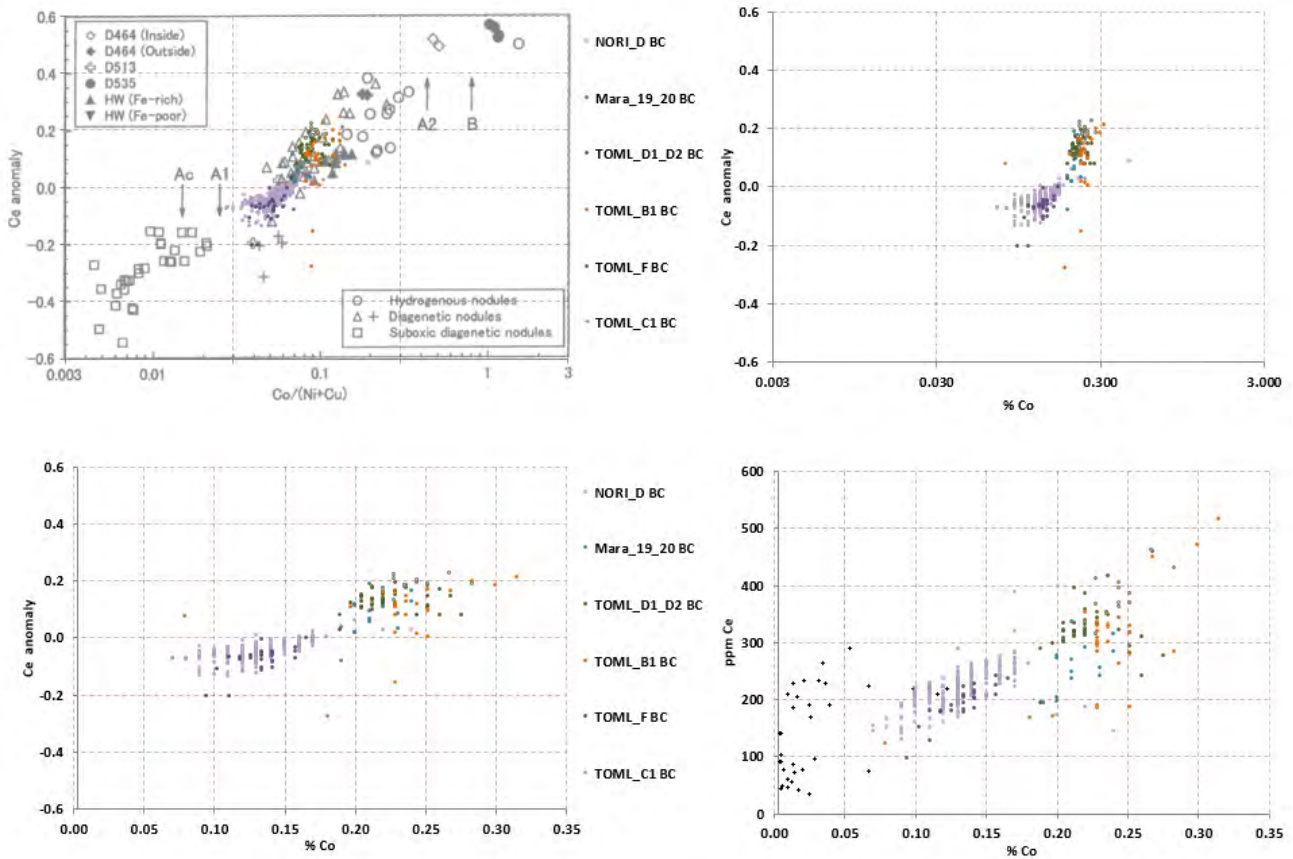


Figure 4-44: Relationship between cobalt – cerium anomaly and cobalt – cerium

Background chart at top left after Ohta *et al.*, (1999) and refer to that reference for the various data sources. “Ce anomaly” is calculated as $\log(\text{Ce}/\text{Ce}^*) = \log(\text{Cen}) / 2\log(\text{Lan}) + \log(\text{Ndn}) / 3$, where the suffix of “n” denotes the chondrite-normalized REE content (Anders and Grevesse, 1989).

When considering the regional scale cobalt variation, there are also a number of oceanographic differences per Table 4-12.

Table 4-12: Regional indicators and cobalt.

	Co %	Ce ppm	Ti %	Ba %	Depth mbsl	SPP g/m ³ /a.	Sil250 m	Sil1000 m
TOML C1	High 0.22-0.27	High-vhigh 320-450	High 0.3-0.38	Low 0.18-0.22	Low 4850-5000	Vlow 50-60	Mod-high 29.5-38	Mod-vhigh 97-107
TOML B1	High 0.18-0.32	Mod-vhigh 170-500	Mod-vhigh 0.2-0.5	Low 0.15-0.25	Low 4700-5200	Low 65-70	Mod-high 29.5-38	Mod-vhigh 97-107
TOML D1,D2	High 0.18-0.27	High 280-400	Mod-high 0.2-0.4	Moderate 0.25-0.4	Moderate 4400-4600	Low 66-68	Mod-high 28-39.5	Mod-high 97-102
Marawa 19,20	High 0.18-0.24	Moderate 200-320	Moderate 0.2-0.3	Mod-high 0.29-0.5	Moderate 4440-4650	Mod-high 71-80	Mod-high 28-39.5	Mod-high 97-102
NORI D	Moderate 0.07-0.17	Low-mod 120-300	Mod-high 0.18-0.35	Mod-vhigh 0.25-0.8	High 4100-4400	High 78-82	Low-mod 29-33	Low-mod 87.5-96
TOML F	Moderate 0.09-0.17	Low-mod 100-250	Moderate 0.18-0.28	Mod-vhigh 0.25-0.8	High 4300-4400	High 78-82	Low-mod 29-33	Low-mod 87.5-96
Peru Basin	Low-Mod 0.01-0.10	Vlow-High 30-300	Vlow-mod 0.01-0.25	Low-high 0.09-0.5	High 4100-4300	?	Vlow-low 24.5-30	Vlow 65-85

SPP (Surface primary productivity) is defined from satellite measurements of chlorophyll contents 2017-2020 in grams per cubic metre per year (Figure 4-48). Sil (Silicate) nearby levels from Garcia *et al.*, (2019) at 250 (sub-photoc) and 1000 mbsl (start aphotic) - in micro-moles per kilogram.

It is significant also, that Ni+Cu grades do not vary significantly between the areas (Figure 4-42) despite higher present and relict indicators of calcite (coccolith/foraminifera) primary productivity in the south-west. A relict indicator is the nodules' Ca content (Figure 4-46, Figure 4-47, Figure 4-48), something not known to be recognized in nodules before, and associated with the mixed calcium-sulphur phase identified by QEMSCAN in Figure 4-37. Note although, that Ba trends with water depth (and Co grade in Table 4-12), local scale Sr/Ba ratios also trend with Co (Figure 4-46). These are interpreted to mean that Barite preservation may not be an issue at either scale i.e. per van Beek *et al.*, (2003) and that the Ba trend in (Figure 4-46) is primary. Note also that the Marawa nodules have about 1% lower Fe, which may relate to a higher proportion of diagenetic growth. The Marawa area is known to have more extensive sediment drifts (Chapter 3).

A relationship with silicate (radiolarian/diatom) primary productivity e.g. (Loucaides *et al.*, 2012), could thus be important regarding cobalt content. The silicate portion of the so-called biological pump is often distinctly different to the calcite portion e.g. (Ragueneau *et al.*, 2000, 2006), and the CCZ is the point where the North Pacific Current (via California Current) joins the North Equatorial Current (National Oceanic and Atmospheric Administration, 2020). Silicate levels in the ocean need to be sampled via casting (Garcia *et al.*, 2019) and are seasonably variable e.g. (Costa *et al.*, 2018), so data is patchier than for calcite-chlorophyll based measurements. There are notable changes in diatom makeup in the California Current associated with climate change over just the last ~100 years (Barron *et al.*, 2013), so conditions over the growth period for nodules are not really constrained. Nonetheless, mid-water-silicate values are often significantly higher in the north-west of the regional area compared to the southeast (Table 4-12, Figure 4-42). In turn, these silicate values over the south-eastern portion of the CCZ, are significantly higher than over the Peru Basin (which contains low cobalt nodules Table 4-12). While not lending quantitative support to this study, it is also worth noting that cobalt is an essential element for diatoms via a requirement for the cobalamin Vitamin B12 (Bertrand *et al.*, 2012). Cobalamin is normally present in low concentrations in surface waters due to biological utilization, so a diatom bloom may result in a net increase in cobalt concentration.

CCZ clay-oozes are well known for containing significant proportions of biological opal e.g. (Kotlinski, 2003), but this is still less than found in sediments located further south near the equator (Figure 3-32). This indicates that biogenic silica dissolution near the seabed is also very important. The nodules themselves are not thought to contain much opal, based on the QEMSCAN results in section 4.4.3 and normative calculations for free opal (Figure 4-45). Thus, the silica correlation with cobalt in the TOML nodules may be due to the relatively common smectite seen in the QEMSCAN results above. There is unfortunately very limited information on the disposition of cobalt in the nodules as the cobalt analyses for the QEMSCAN were not reported. However, the cobalt disposition in the micro-probe scan of a single nodule (Figure 4-33) shows a close correlation with some of the Si-Al phase texturally associated with smectite in the buserite layer above a vernadite layer. While this is clearly a subject for more comprehensive future work, it seems possible that some cobalt grades in CCZ nodules may be associated with diatomaceous blooms, forming at the start and during a sub-oxic phase (glacial period).

While the correlation of Ce with Co can be taken to be related to oxidative uptake as discussed above, the reasons for the positive correlations of Co with Th, Ti and Al (Table 4-11, Figure 4-46) remain somewhat problematic.

Almost all Th in nature is ²³²Th (Wickleder *et al.*, 2006), so the chemical analyses referred to in this thesis are assumed to be entirely of this radioisotope. This also implies that age of bottom water (<1000 a) is not relevant, although pore-waters in clay-ooze may be significantly older (Church and Bernat, 1972). ²³⁰Th

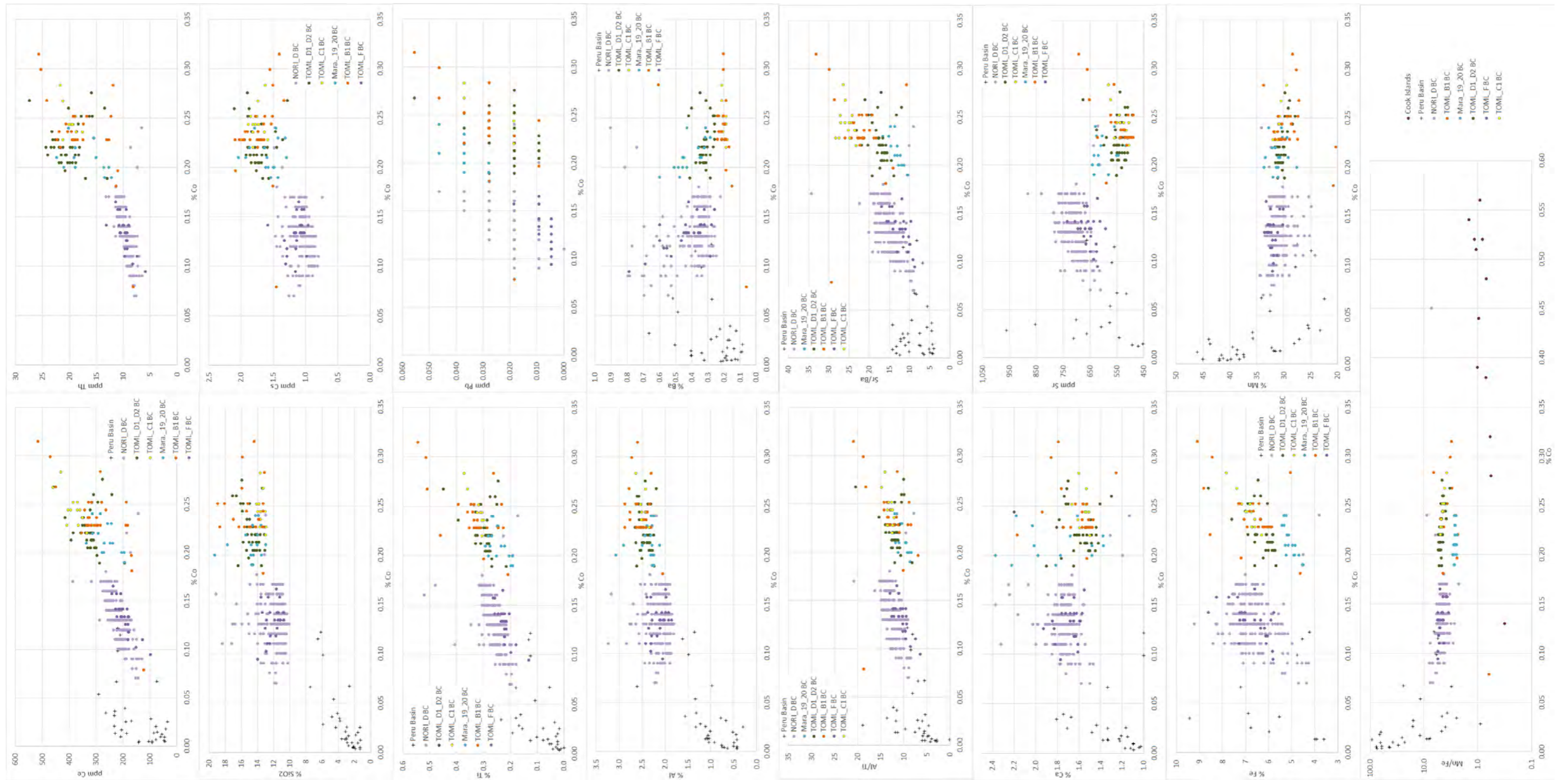


Figure 4-46: Select Co-“harker” and some non-Fe ratio diagrams for polymetallic nodules

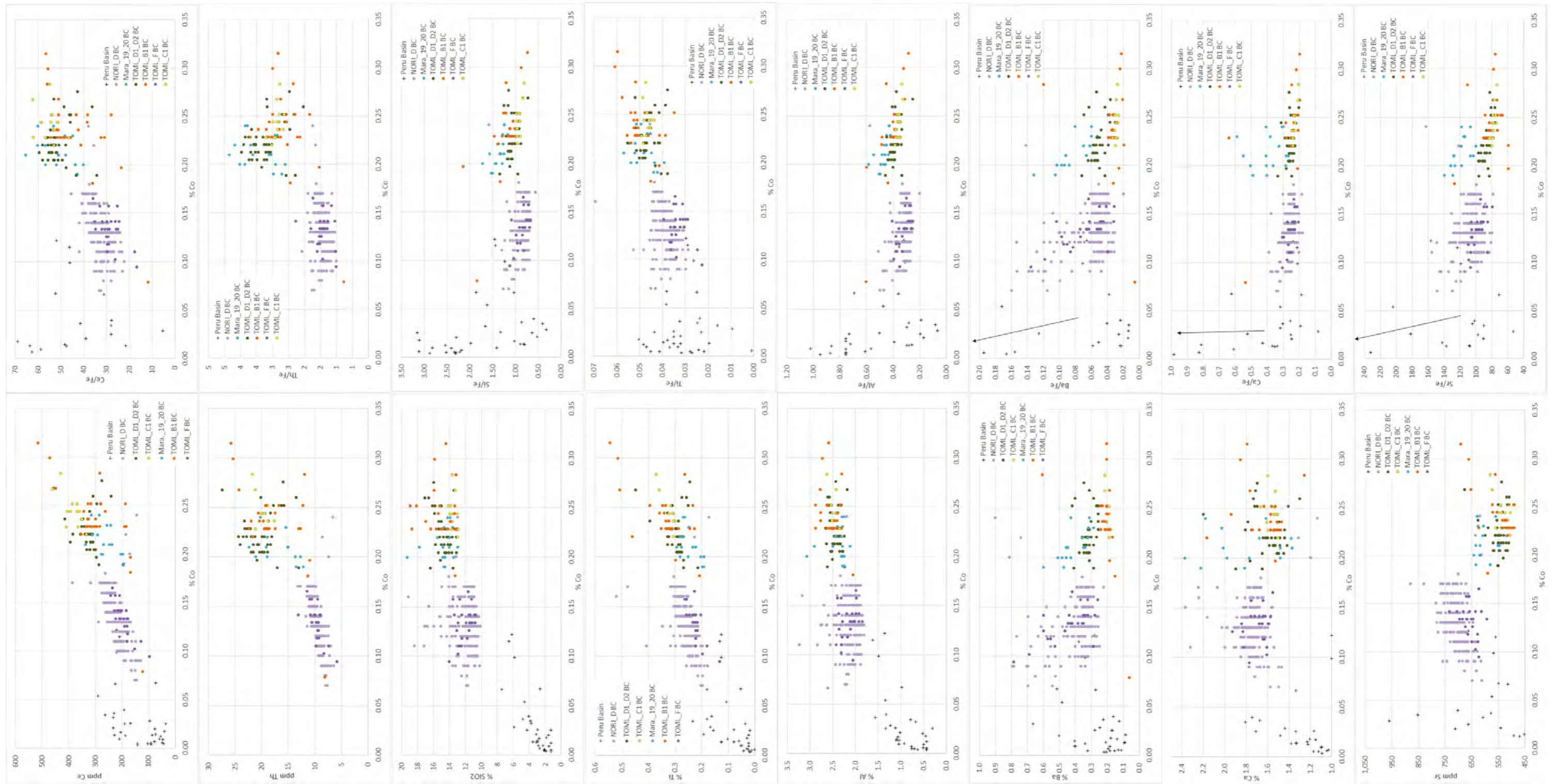


Figure 4-47: Select Co-“harker” and associated Fe ratio diagrams for polymetallic nodules

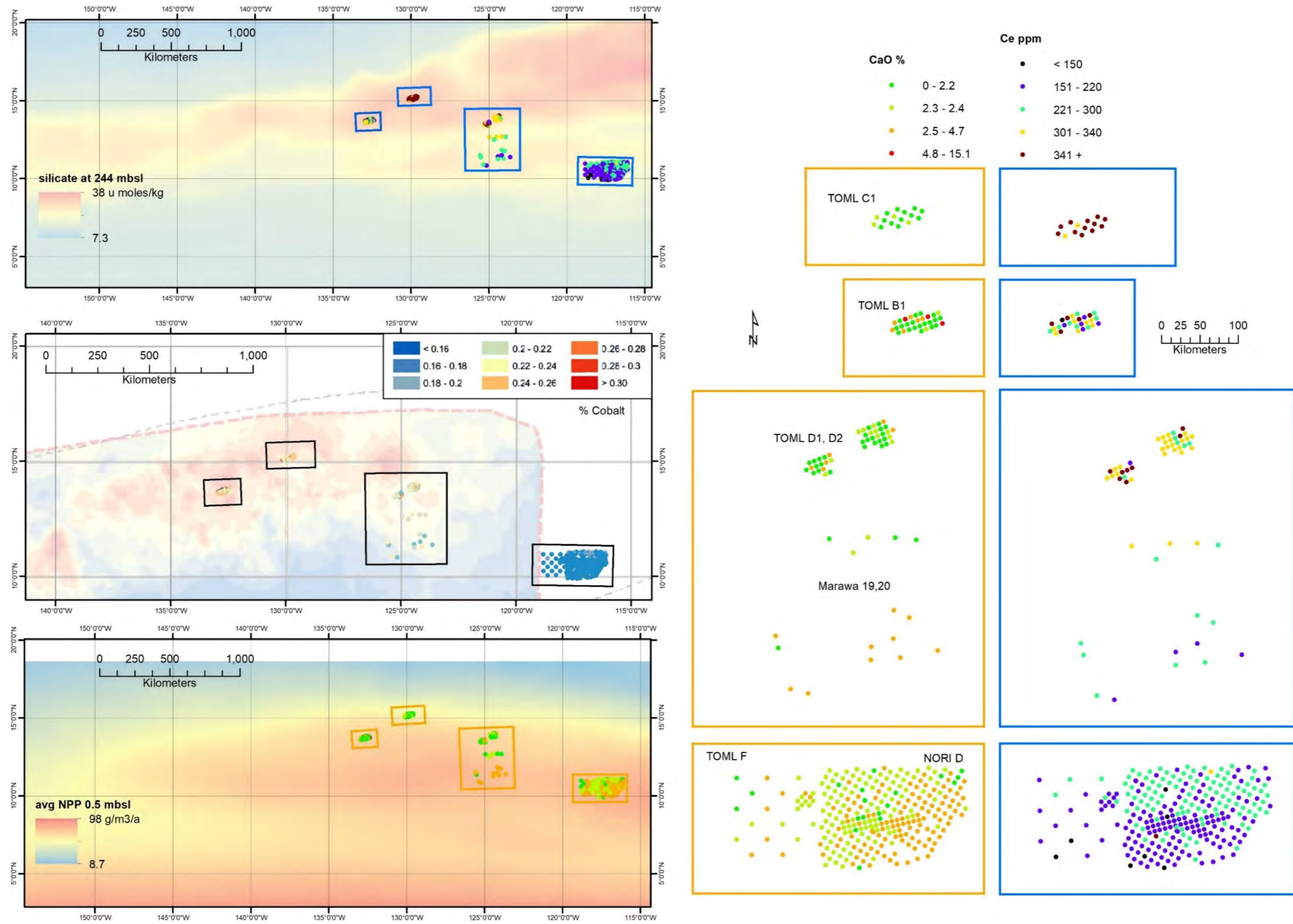


Figure 4-48: Ce and Ca spatial trends over calcite primary productivity and ocean silicate

Silicate values (average 2018) and net primary productivity (NPP; average 1993-2018) from Mercator Ocean International (2020) and processed by Joao Carvalho (ISQ); cobalt map from International Seabed Authority (2010b)

4.5.2.4 Local scale chemical trends and differences

Some local scale trends can be seen in Figure 4-48 above, and some have attributes in common to the regional and trends mentioned above in sections 4.5.2.2 and 4.5.2.3. Locally however there are some distinctly different local scale chemical trends as emphasised here.

The most striking local scale trends are in NORI D / TOML F (Figure 4-50), where there is a broadly south to north ($\pm 45^\circ$) trend for several elements with decreases in Ca and Fe and increases in Ce, Co, and Ti. These are interpreted to primarily reflect progressive changes in metal source from siliceous organisms to calcic organisms, as discussed above on the regional scale in section 4.5.2.2, coupled with local variations in the proportions of hydrogenetic versus diagenetic formation (note the somewhat tentative size association in Figure 4-49).

Significantly these changes correlate to some extent with nodule type (facies; Figure 4-51) and MBES backscatter response as discussed in section 3.4.11, as well as sediment chemistry as discussed in section 4.5.2.5. The RS type nodules of type/facies 2 have notably more copper and less cobalt and iron, but the Ce and Ti responses are relatively muted (Figure 4-51).

Note that in Figure 4-50, some possible minor lab batch effects may exist between historical data, first generation NORI (DSAO) data and second-generation NORI /TOML data (the latter two being from ALS Brisbane).

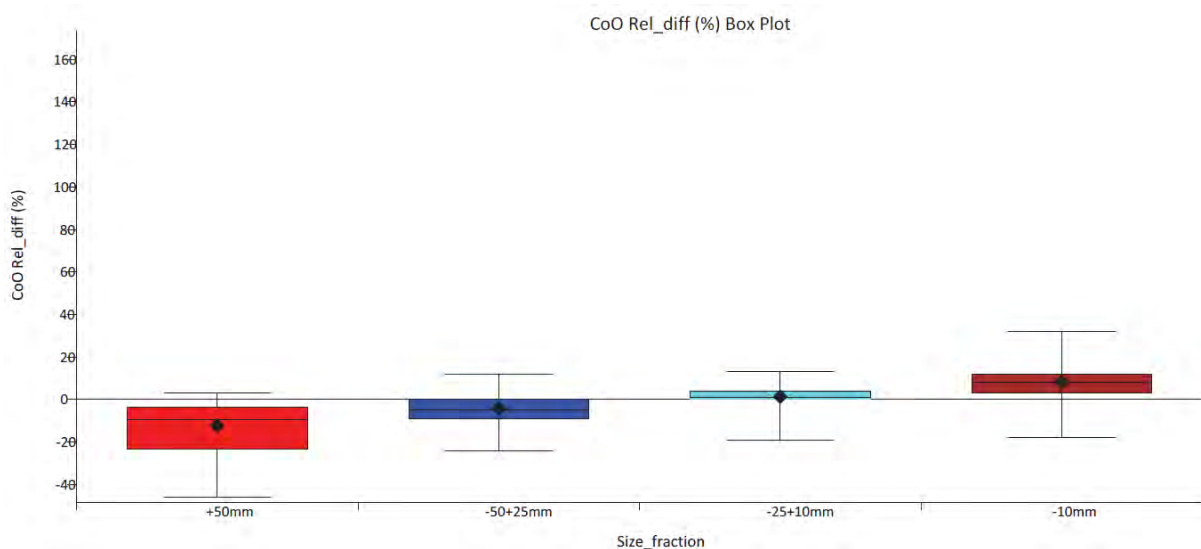


Figure 4-49: Cobalt grade changes with nodule size

Reproduced from Lipton *et al.*, (2021) Sample source: 24 box-core samples from NORI D.

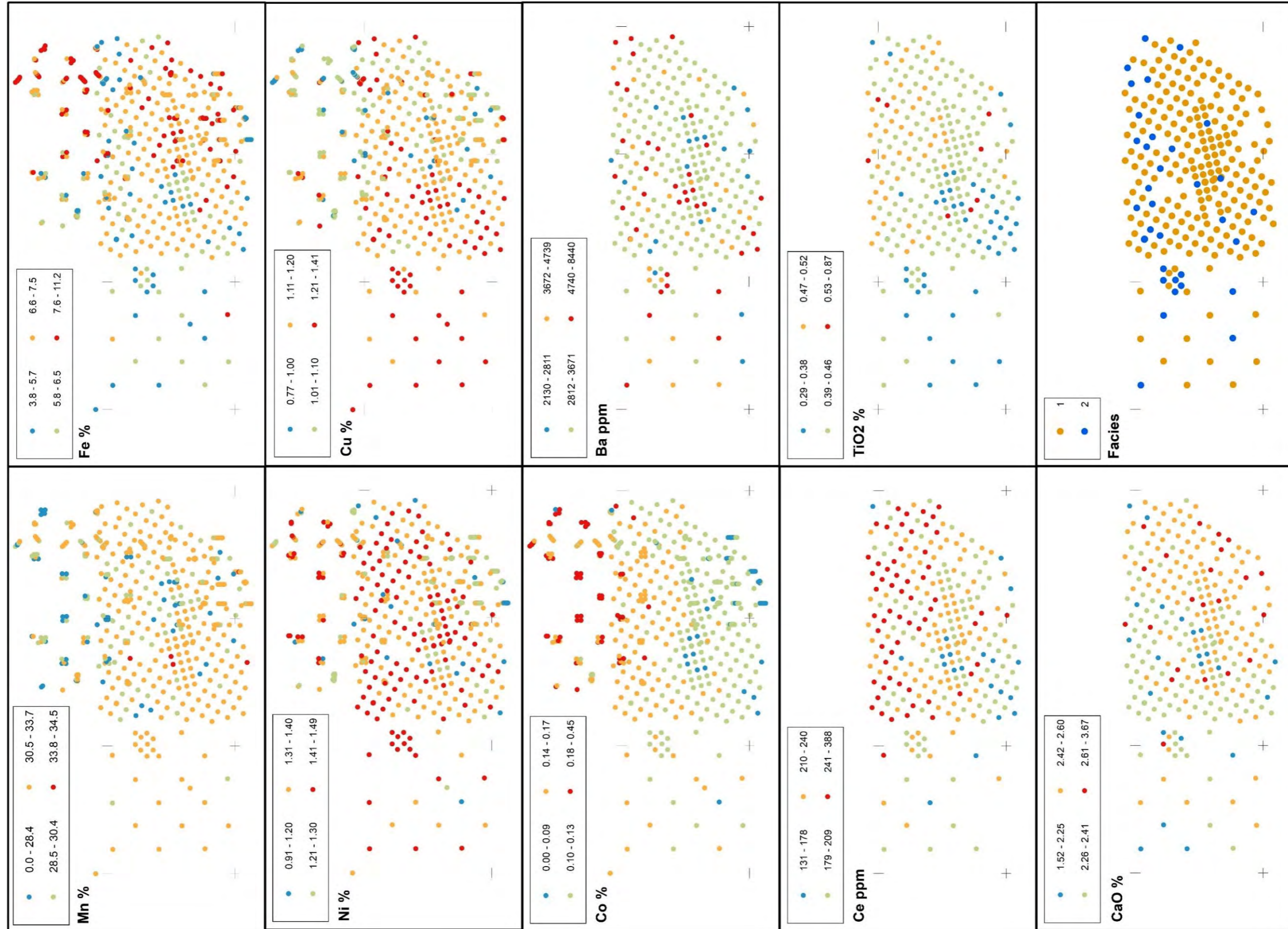


Figure 4-50: Nodule grade and facies trends in TOML F / NORI D

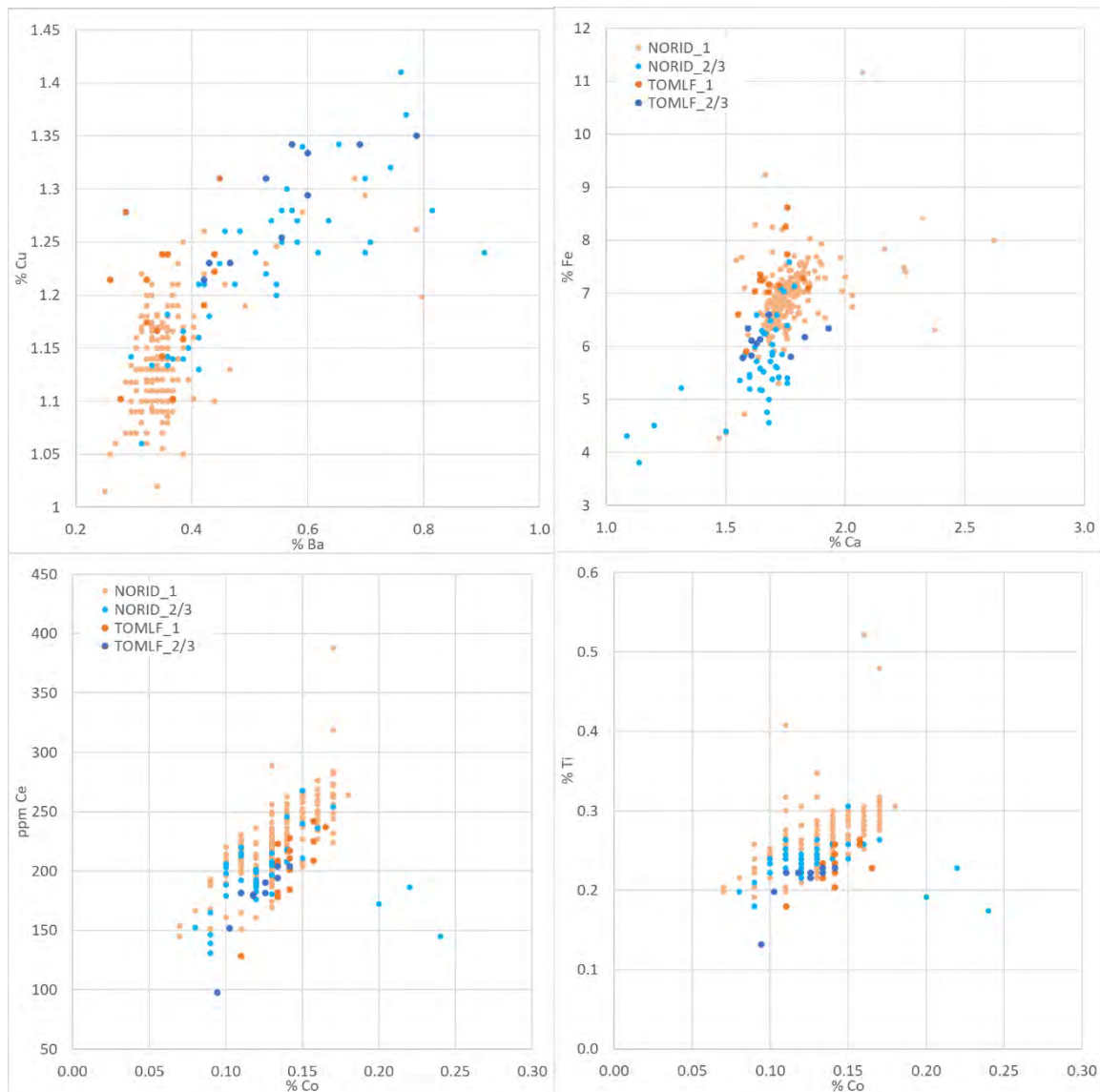


Figure 4-51: Nodule grade differences and trends against facies in TOML F / NORI D

As already mentioned in section 3.4.2, another distinctive trend lies within TOML B whereby the northern parts of the area are characterized by distinctly lower Mn, Ni, Cu but slightly higher Co (Figure 4-52). This area is only covered by historical data so there are no other element analyses available to better characterize the trend. It is notable that the area north of NORI B i.e. to the NW of TOML B does not show the lower Mn, Ni, Cu but does show the higher Co. A clue might be found in four of the box-core results from TOML B1, which have lower Mn, Ni, Cu (but not higher Co). CCZ15-B12, 13, and 17 are all thought to contain a variable component of volcanic rock (due to elevated Al and Si) and B08 a component of chalk due to high Ca. Box-core B13 (Figure 4-53) has distinctly irregular nodule forms supporting such an origin.

The northern part of TOML B has distinctive low backscatter volcanic units (?breccia dominated; section 3.4.2) so locally high amounts of pumice, coupled with the regional trend for higher silicate primary productivity could explain the trend.

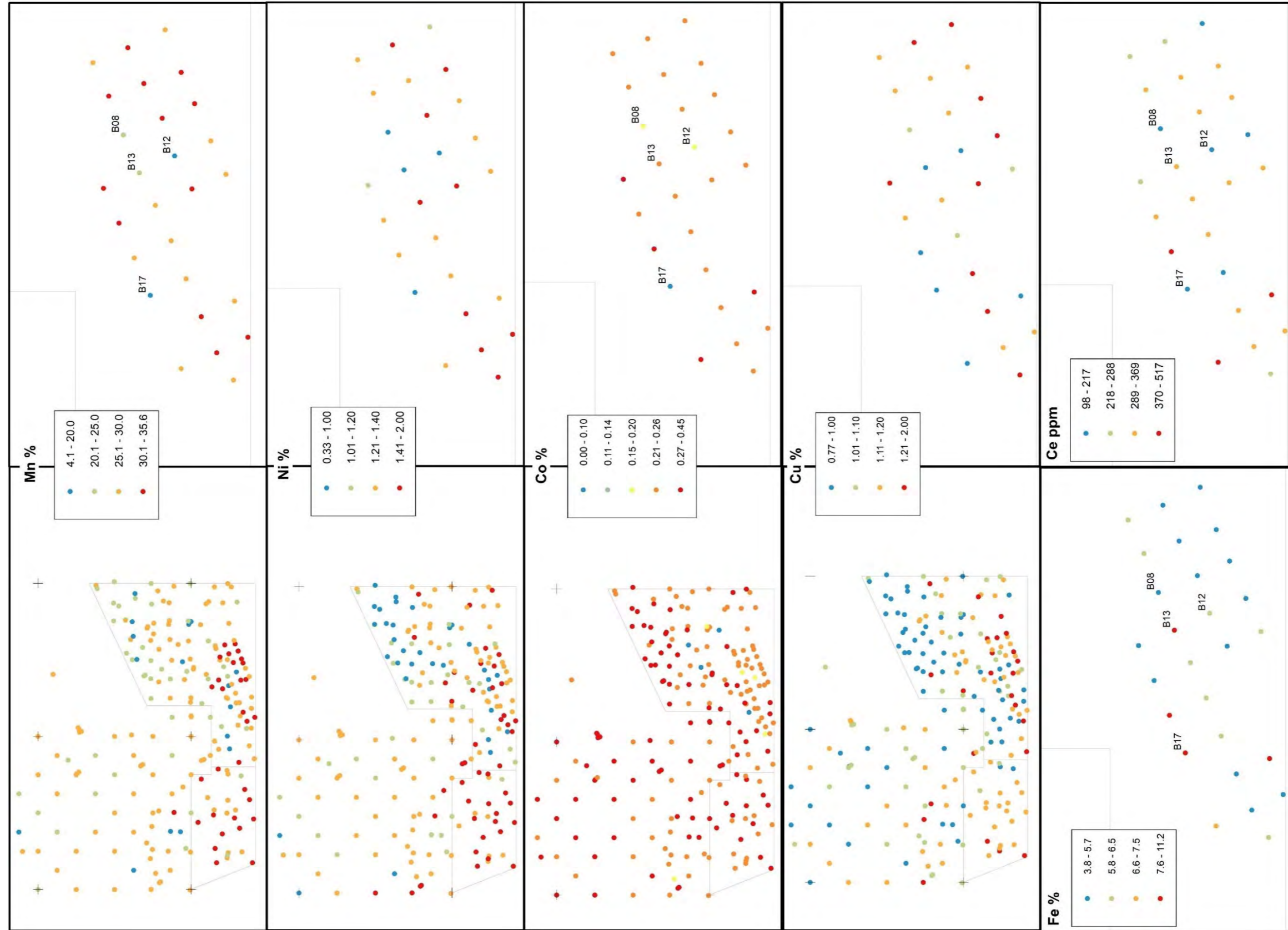


Figure 4-52: Nodule grade trends in NORI B and TOML B

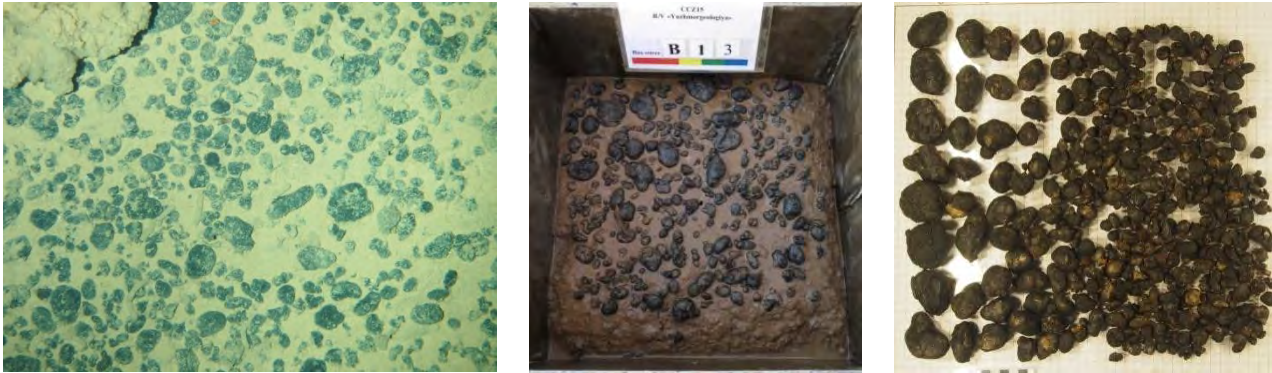


Figure 4-53: Photos of box-core CCZ15-B13 from TOML B

Photos are all about 50 cm high (the box-core top shot being slightly less with perspective)

A north-south trend amongst the Marawa box-cores is essentially conformable to a regional trend discussed above with Ba, Ca, P, Sr increasing to the south and Ce and Ti increasing to the north. For reasons unknown, Marawa has some of highest Mo grades of the areas (average of 659 ppm versus 607 to 636 for the various TOML areas and NORI D), and there is an increase in Mo grades amongst R-type nodules in the central eastern side of the contract area (709-792 ppm; Figure 3-73). Nearby RS type nodules average a more typical 628 ppm. Molybdenum is described as the best example of a ‘conservative-type’ seawater element by Bruland and Lohan (2003), as is tungstate (WO_4^{2-}). This group of elements are not prone to being scavenged by particles (e.g. Mn), nor concentrated by biological activity (e.g. Ni, Zn). Nonetheless Mo, W, Mn, Ni and Zn all correlate in nodules (Group 1 in Table 4-11). The higher Mo R-type nodules in the Marawa area do weakly correlate by type with Mn and Cu grades per Figure 4-54 (also generally per Table 4-11).

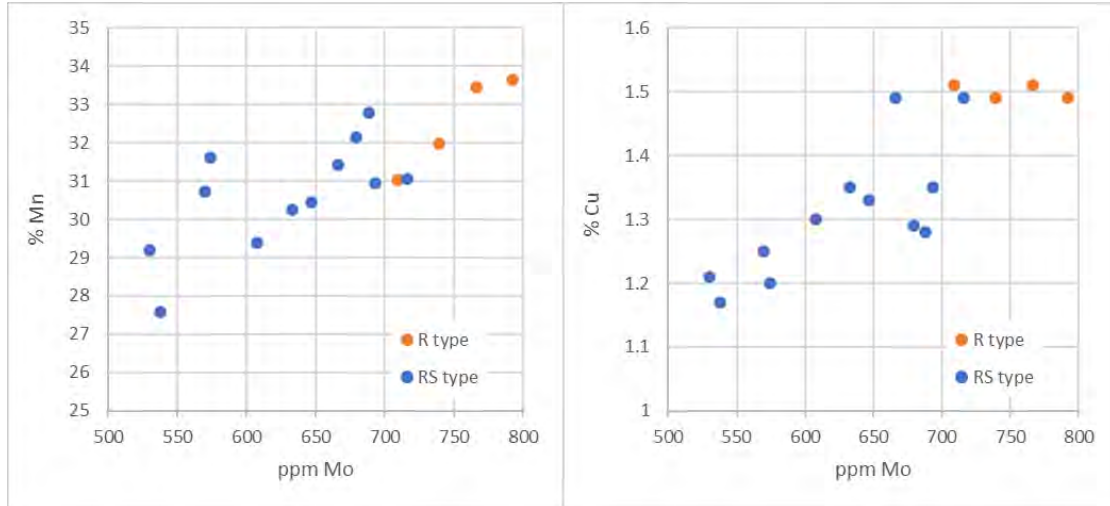


Figure 4-54: Mo, Mn, Cu grades in Marawa box-core samples

4.5.2.5 Nodule - clay-ooze chemical trends and differences

The only total sediment analyses available are from the NORI D area. The uppermost layer, sampled from box-cores, are normalised against nodules in Figure 4-55. The ratios were compared with those of Pattan and Parthiban (2011) from the Indian Ocean Nodule Field who analysed 11 samples of siliceous clay-ooze and 2 of calcareous clay-ooze. The results from NORI D are similar with the following exceptions Mo (~1/4), Mn (~1/2) and Ba (1/3). As QA/QC from the NORI sediment data has not been sighted, these elements are not discussed further although the ratios are included in Figure 4-55.

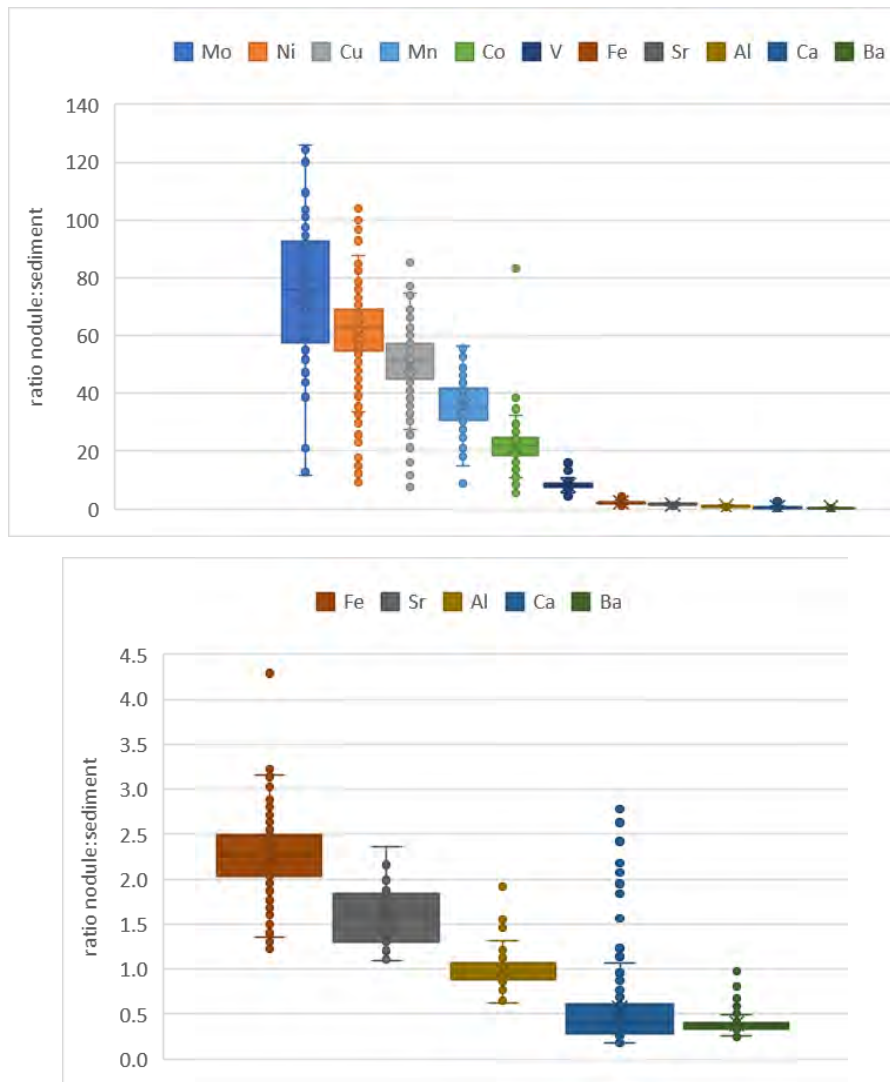


Figure 4-55: Ratios of nodule grades to sediment grades NORI D

Data are as dots, boxes are to 25th and 75th percentiles, whiskers are to the outmost datum within the interquartile range outside the boxes.

Spatial correlations are illustrated in Figure 4-56. Ca shows the same clear regional trend in sediment chemistry as it shows in nodule chemistry with a SE to NW trend. There is a negative correlation with sediment iron that does not manifest in nodules, but there is a suggestion of a negative correlation with copper in nodules that does not manifest in the sediment. There is also a very significant inverse correlations between the mineral resource block nodule abundance, as modelled by Lipton *et al.*, (2021), and the manganese and calcium contents of the sediment. Significantly, this supports the model that oxidation of organic material related to primary productivity can drive (or at the very least help) the formation of ferro-manganese minerals (+ zeolite and smectite), e.g. (Bischoff *et al.*, 1981).

Also of note is that: the north-south trend in nodule cobalt grades discussed above, also manifests weakly in the sediment; and a negative correlation that is seen in sediment manganese that does not manifest in the nodules. There is no sign in the sediment analyses of the higher copper and lower manganese associated with the type 2/3 nodules, but this may be an issue of scale (facies scale resolvable by AUV being smaller than local scale resolvable by grid box-core sampling).

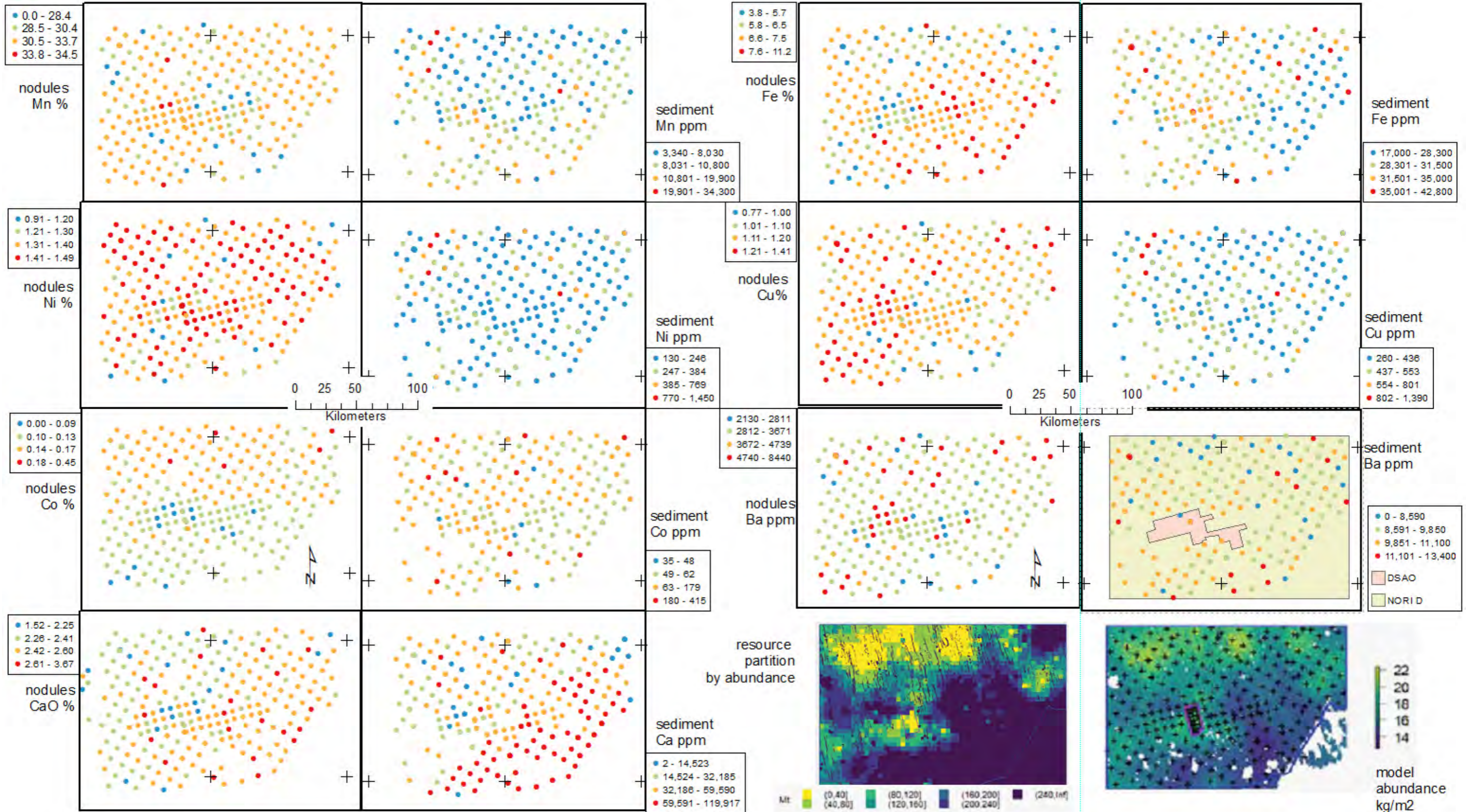


Figure 4-56: Spatial arrangement of nodule grades and sediment grades NORI D

Abundance and resource partition plots from Lipton *et al.*, (2021).

4.5.2.6 Diagenetic crust chemical trends and differences

Dredge samples in TOML D (D4, D6, D8 from the CCZ13 expedition) and TOML A (CCZ15-D01 from the CCZ15 expedition) returned significant amounts of diagenetic crust (of the “massive type”; section 4.3.3). Alongside nodules from these dredge samples, these crusts were subjected to major element chemical analysis to test variance. The variance sampling involved random selection of ~30 examples (typically ±20 g fragments) from the dredge pile for individual analysis. Results are shown in Table 4-10, and Figure 4-57. Minor amounts of “crustal fragment type” crust were also found in the samples, but were not analysed.

Per Figure 4-57, the following is noted:

- Crust grades vary from very low nickel, copper, manganese and cobalt to overlapping with nodules. No doubt this is due to inclusion (“mixing”) between ferro-manganese material and host clay-ooze, and implies that the ferro-manganese material can be of very similar or identical grades to the nearby nodules and likely formed from the same processes.
- The crusts all have similar progressive increases in SiO₂ and Al₂O₃, but not of CaO, supporting the above interpretation of inclusion of varying amounts of clay-ooze (siliceous type).
- There is a distinctive population of nodules from TOML A (dredge CCZ15-D02) that are crust-like in terms of some elements (e.g. the above mentioned) but not in terms of others (Ca, Fe, P), along with the dredge sample from TOML A, this is interpreted to be due to inclusion of significant amounts of biogenic apatite (teeth enamel) and a more hydrogenetic origin for these nodules.
- Similarly, the diagenetic crusts collected from TOML A and TOML D shows them to be quite distinct, with the TOML A crusts containing higher Ca, P (i.e. likely contributions from biogenic apatite (teeth)) and Ti (exotic mineral component), while the TOML D crusts have higher Ba (perhaps reflecting the regional Ba trend related to type of primary productivity; section 4.5.2.3).

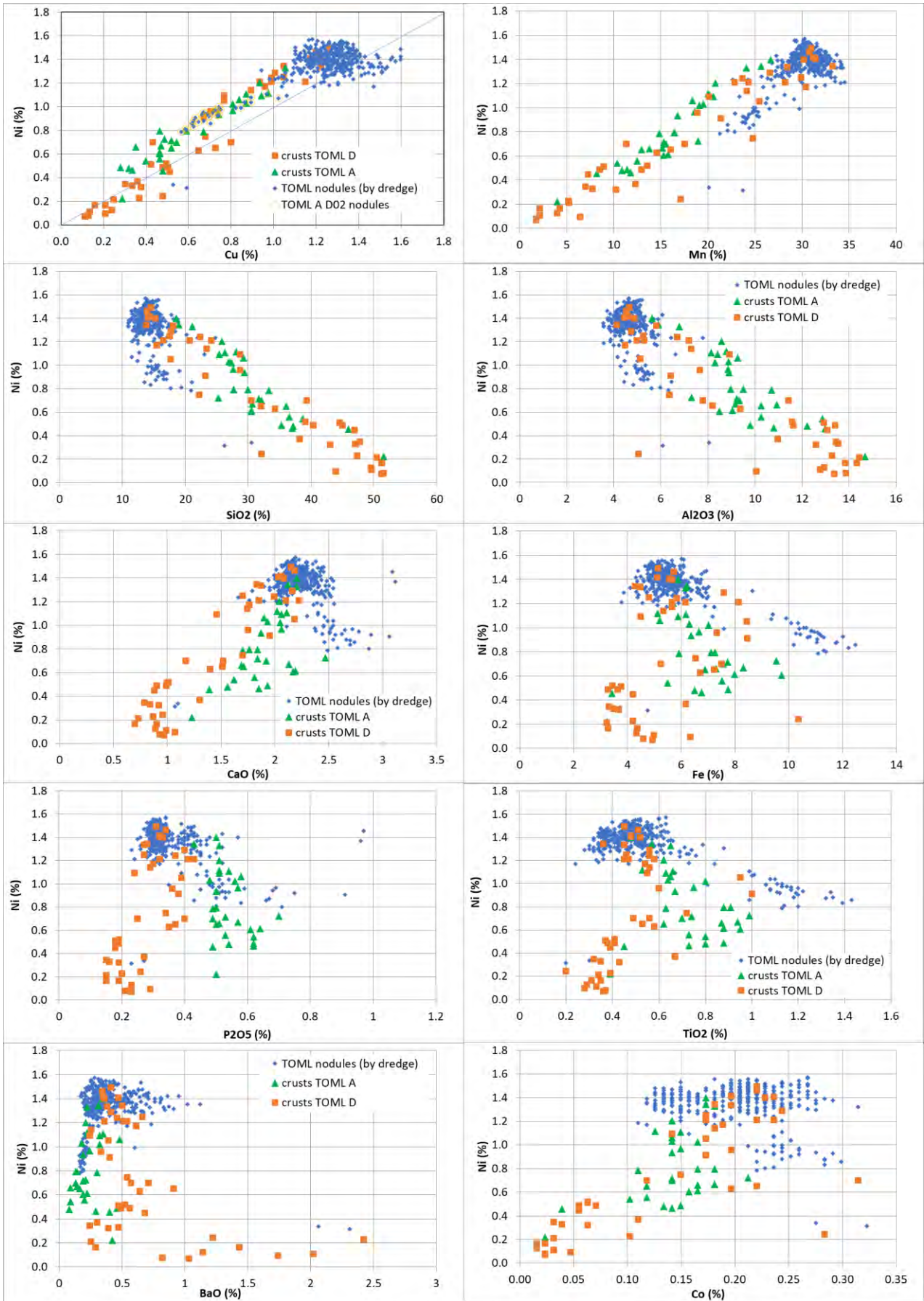


Figure 4-57: Major element chemistry of TOML A and TOML D crusts versus dredged nodules

4.6 Nodule and clay-ooze density

Accurate nodule densities and moisture levels are essential to estimate the tonnage in a Mineral Resource. Compared to many other mineral types, polymetallic nodules are of relatively low density $\pm 2 \text{ g/cm}^3$ (wet basis).

Along with vane shear data, e.g. (Lipton *et al.*, 2016), surface clay-ooze density measurements are part of the equation for understanding the bearing capacity of the seabed for mining equipment. These saturated and often poorly consolidated sediments are of lower density than the nodules they support, i.e., $\pm 1.2 \text{ g/m}^3$ (wet basis).

4.6.1 Methods for Density Determinations

Samples of polymetallic nodules and seabed clay-ooze were collected from the TOML exploration areas during the 2015 expedition using a box-corer. Details of the sampling program are included in section 4.2. Liam Johnston assisted with some of the measurements under the supervision of the author.

Once landed on the expedition vessel, the nodules were washed in sea water, and after weighing and sub-sampling for other purposes (e.g., grade determination), sealed in plastic bags and then in plastic tubs for transport to the lab. Clay-ooze samples were scooped by hand from the box-core at three levels and simply sealed in plastic bags. The clay-ooze sample levels varied, mostly due to the depth of penetration of the box-corer (9.19 Appendix 4E: Density measurements and calculations) but are generally: 0-10 cm; 10-20 cm and 20-40 cm.

Both nodules and clay-ooze densities were measured using constant volumes of water in a container, an electronic scale (specs) and Archimedes principle reformulated for a fully submerged object i.e.

$$D = \left(\frac{w_1}{w_1 - (w_2 - w_0)} \right) \times \rho \quad (1)$$

Where D = density of sample; w_0 = weight of water in full container; w_1 = weight of sample in air; w_2 = weight of sample and water in full container; ρ = density of water used in container (taken to be $= 0.99669$ at 25°C ; (United States Geological Survey, 2021)).

Nodules were weighed in air, then placed by hand into a container which was filled to a standard level then weighed again. The immersed weight was then compared against the same container filled to the standard level only with water. Some samples involved several nodules and some involved single nodules. Clay-ooze samples were collected using a sub-corer (hollow 3 mm walled 5 cm diameter pipe with top plug) and measured the same way. Clay-ooze sample weights (Figure 4-59) were typically around 1 kg but varied between 117 g and 1.7 kg, earlier samples used a smaller container for displacement, moving to a larger container/samples (over concerns regarding accuracy) did not seem to change the results. Condition of the clay-ooze was recorded (i.e., if the clay-ooze in the bag was damp (as sampled originally), had free surface water (implying some consolidation) or had minor drying cracks on the surface (included in supplementary data). Overly dry samples were not tested. Efforts were made to measure all three clay-ooze levels from a number of different TOML areas, and for some samples, a top-most layer with free water at surface was the only option. This topmost layer is often extremely wet and slushy anyway, but the implication nonetheless, is that the density measurements of these samples might be a little high.

Errors in the measurements (water level and scale) were reduced by using three containers of different size depending on the sample being measured, i.e. small nodule samples were measured in a small plastic cup (88 ml), medium sized in a glass (295 ml) and large in a pyrex bowl (2482 ml). Errors associated with

temperature and water quality (United States Geological Survey, 2021) are expected to be minor and thus disregarded (temperatures were between 17-26°C, elevation was ~8 m above sea level and potable tap water was used). Errors related to depressurization and disturbance of the sample from site to lab are also not accounted for but are also expected to be minor.

4.6.2 Results of Density Determinations

Polymetallic nodules have an average wet density of about 2 g/cm³ (Table 4-13; Figure 4-58). These are similar to results from the north Pacific (Hessler and Jumars, 1974).

The density measurements were done for both single nodules and for nodules in bulk, the later would include fragments and nodule-sand resulting from attrition during transport and handing. The results from both sample types are similar, except that the mean of the single nodules is on average ~ 2.8% lower than that of the bulk measurements. This might be due to air or water filled expansion cracks in the single nodules (that were collected ~7 months before the density measurements were made). The bulk nodule samples contained many more fragments that presumably often formed along these expansion cracks. The bulk nodule measurements are also preferred over the single nodule measurements, as they are likely more accurate due to a larger sample size; these results also have a lower standard deviation.

Also noted, is that Area F nodules might be slightly less dense than for the other TOML tenement areas (Table 4-13; Figure 4-58). This is of the order of 2 - 4% of their respective average densities, being slightly more pronounced in the single nodule estimates.

Table 4-13: Nodule Density measurements TOML Areas A, B, C, D and F

	Count	g/cm ³					Standard deviation
		Min	Median	Mean	Max	Range	
Single nodules TOML B,C,D	34	1.78	1.95	1.95	2.38	0.60	0.11
Bulk nodules TOML B,C,D	27	1.94	2.01	2.01	2.07	0.13	0.03
Single nodules TOML Area F	9	1.83	1.91	1.90	1.99	0.16	0.06
Bulk nodules TOML Area F	6	1.94	1.97	1.97	2.01	0.07	0.02
Bulk nodules TOML Area A	3	1.94	-	2.01	2.06	0.12	-

Table 4-14: Clay-ooze density measurements TOML Area B, C, D and F

	Count	g/cm ³					Standard deviation
		Min	Median	Mean	Max	Range	
TOML B1	26	1.168	1.262	1.256	1.394	0.23	0.046
TOML C1	17	1.173	1.226	1.231	1.283	0.11	0.032
TOML D1/D2	34	1.141	1.224	1.214	1.281	0.14	0.036
TOML F/F1	46	1.121	1.174	1.176	1.241	0.12	0.028

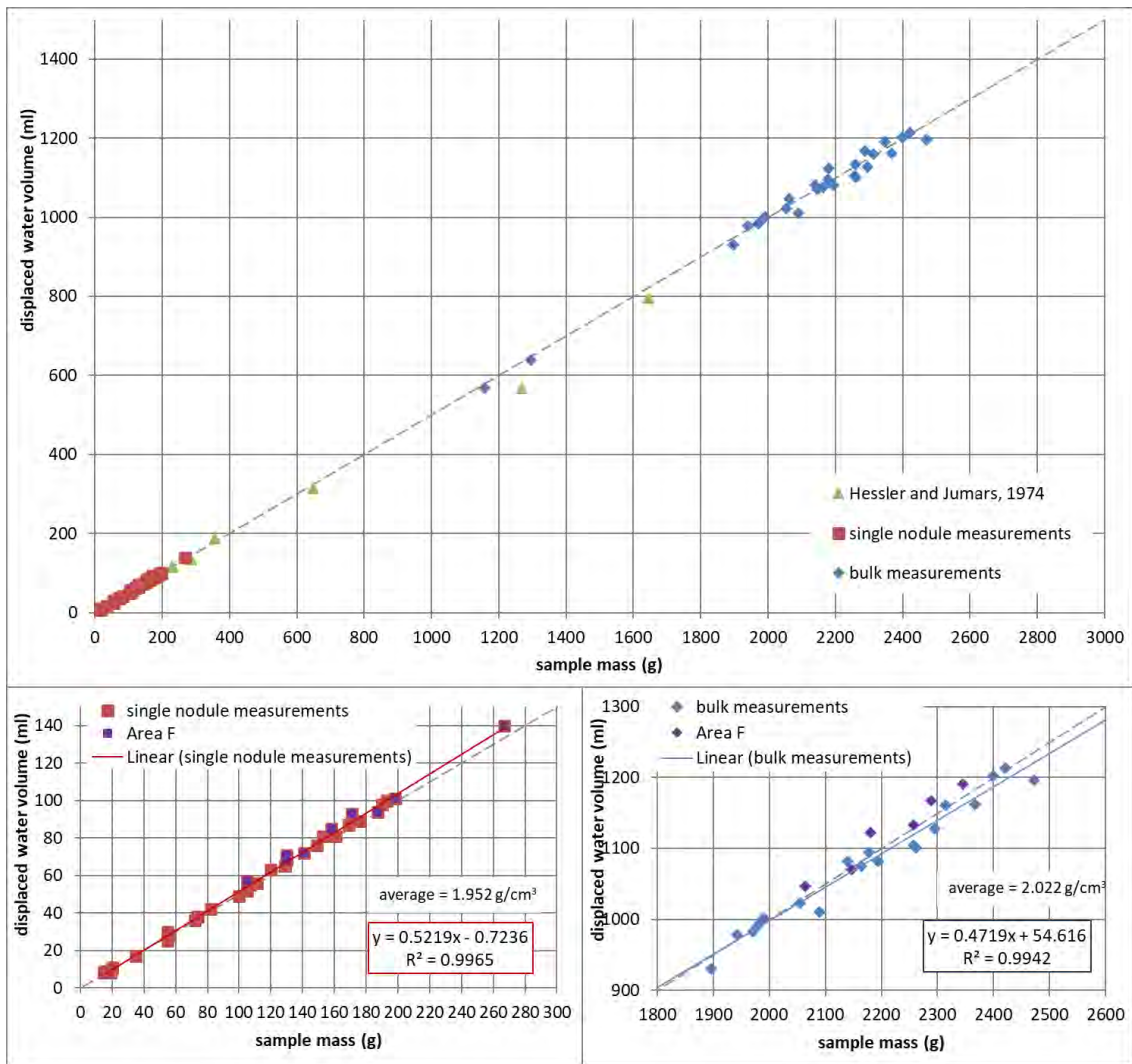


Figure 4-58: Nodule densities of samples from TOML areas B-D, F and central north Pacific

Clay-ooze density test results are summarized in Table 4-14, Figure 4-59 and Figure 4-60. While there is considerable variability between samples for any given depth, there is a clear trend from the NW to SE. The more north-westerly areas (TOML B1 and C1) have clay-ooze that increases the most rapidly with depth and have the highest overall densities. The most south-easterly area (TOML F/F1) has almost no change in density with depth (at least to ~32 cm) and has the lowest overall densities. TOML D1/D2 is located between them, both geographically and in terms of clay-ooze density results.

This geographically based trend reflects the level of surface (chlorophyll) primary productivity (e.g. Figure 4-48) over the areas, and is thus interpreted to be a result of rate of net calcite sedimentation rate. Exactly how this would be the case is unclear. Calcareous clay-ooze has in some cases been found to be denser than siliceous clay-ooze (e.g. 1.5-1.6 versus 1.2-1.3 wet bulk density in Marshall (1975)). But higher primary productivity may relate to higher overall sedimentation rate (less time per cm for sediments to consolidate) and higher organic export to the seabed (higher active biomass and thus higher rates of bioturbation).

A similar geographically based trend exists in the vane shear determinations conducted on the TOML samples (Lipton et al., 2016). Sampling and over-consolidation issues aside e.g. (Wiemer *et al.*, 2017) the combination of density and shear strength are the two key factors behind bearing load and thus an important consideration in seabed mining equipment design.

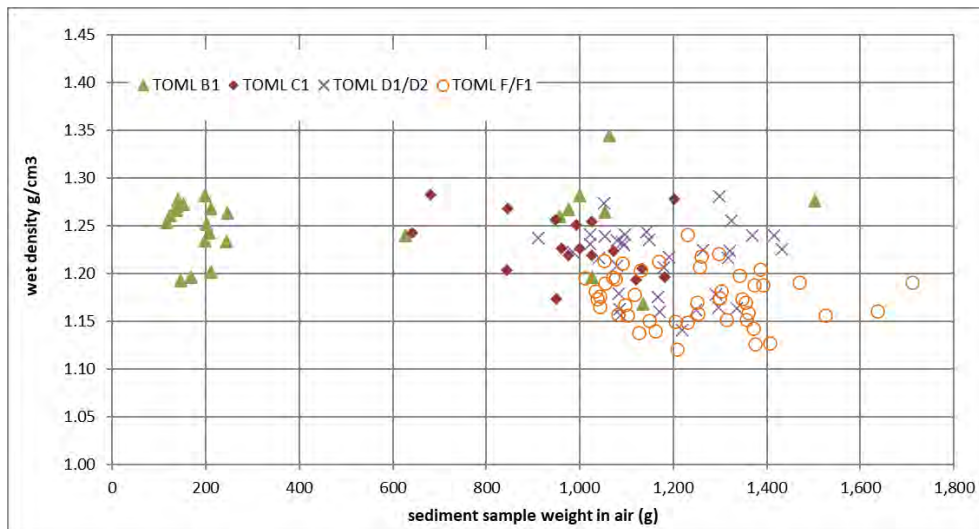


Figure 4-59: Clay-ooze-density with sample weights

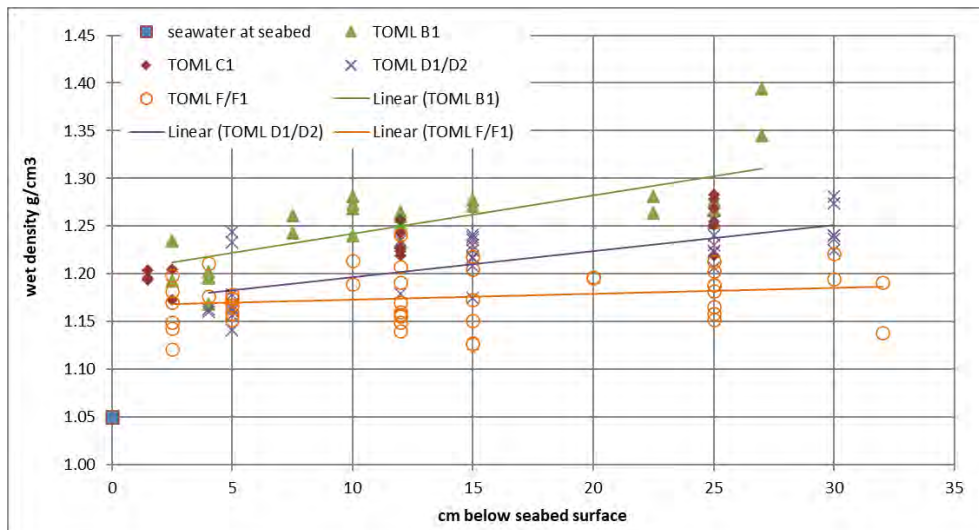


Figure 4-60: Clay-ooze density results with depth

4.7 Moisture Content

Water is the largest single component of polymetallic nodules, totalling ~44% by weight (on a wet basis; Figure 4-61). Significant amounts of free water and water of crystallization are both present.

1. **Water of crystallisation** is included within manganese and iron oxide minerals. This was determined in the test work to consistently be about **15%** by wet weight (including other likely trace levels of unknown volatiles). This water of crystallisation likely starts being removed at temperatures as low as 50-70°C through a transformation of the manganese mineral buserite into birnessite (section 4.4.1).
2. **“Free” water** included within pores and other cavities within the nodules including water adsorbed onto minerals – this is interpreted to be around **28%** by wet weight depending on the micro and macro void space in the nodules. Air-drying may remove approximately 16% of this with the rest by oven drying (up to 105°C).

Free water might be added or removed from nodules as the nodule decompresses and expands. Presumably involving some filling of pore space and the development of cracks and micro-cracks. For the purposes of this study, we only consider these effects from the point that the nodules were lifted onto the boat. After four months about 3% free water is added into the soaked samples (this ~3% is not included in the totals indicated above).

In estimation of moisture (or other component) content **wet basis** is taken before any air drying or soaking, **dry basis** is taken after oven drying to stable weight at 105°C and **volatile free basis** is taken after volatiles loss on ignition (LOI) in a crucible at 1000°C (Figure 4-61). Other bases are mentioned in the text with the temperature specified.

There are at least two key implications from the above points:

1. Drying of nodules for grade determination requires removal of as much free water and as little water of crystallization as possible. Mineral metal grades are normally done on a dry basis and comparison of samples also requires a standard drying approach.
2. Nodule mining and metallurgical processing economics rely on moving large volumes of material, thus managing the water content of the nodules would likely be very material if commercial mining proceeds.

Published estimates of nodule moisture content are compared with these results in Table 4-15.

Table 4-15: Comparison of nodule moisture content estimates

Source	Total Moisture	Free Moisture	Water of Crystallisation
(Mero, 1965) p233		30-36*	
(Fuerstenau et al., 1973)**	>22.66%	13.1%	>8.74%
(Haynes et al., 1985)	45-50%	35-45% with about ½ dried in air	5-10%
(Wiedicke-Hombach et al., 2012)	44%	Not specified	Not specified
This chapter and Lipton <i>et al.</i> , (2016)	44%	28% with about 60% of this dried in air	16%***
NORI A, B dredge samples (DeWolfe and Ling, 2018)		26.6 to 31% after 12 hours at 120°C	
Marawa box-core samples (n=16)		33.1% (31.7 to 35.5) method unknown	

* drying temperature not specified, so may include some water of crystallization; ** used in Nimmo *et al.*, (2013) to characterise moisture; *** includes ~2 % water of crystallisation lost before 105°C

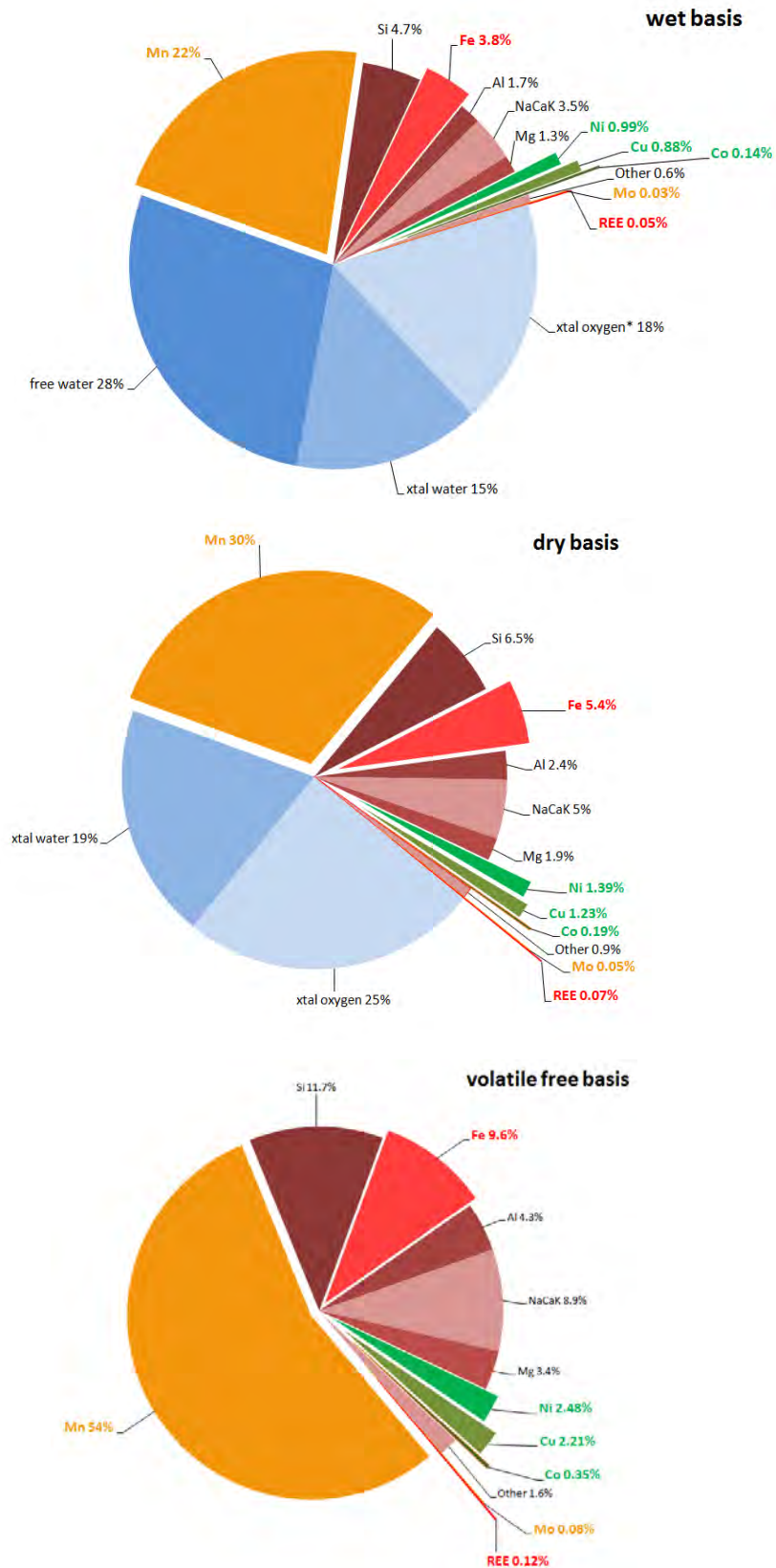


Figure 4-61: Bulk nodule composition on a wet, dry and volatile free basis.

Notes: Based on average grades of dredge samples collected during CCZ13. *A minor amount of oxygen of crystallisation may have been added or removed as a consequence of the XRF analytical process. The volatile free composition shown is theoretical and does not, for example, consider partial reduction or addition of reductant or flux. Xtal water is water of crystallisation also known as interlayer water. Xtal oxygen is stoichiometric oxygen in the mineral structures.

4.7.1 Methods for Moisture Content Determination

Nodule samples were collected by epibenthic sled and galenta dredge (between 4,200 and 4,700 mbsl) from TOML B, D and F (section 4.2.1.1, Figure 4-62).

All samples were tested within 6 months of being collected, except for the long-term tests. Nodules almost certainly experience some mineralogical and or macro restructuring due to decompression after collection from the sea floor (they formed at ~44,000 kPa, versus ~100 kPa air pressure at sea level). If no moisture is lost to ambient air, then the weight of the nodules should not change from the point of recovery on deck until testing. Soaked samples (samples submerged in water) on the other hand can take in water into cracks, micro-cracks and any decompressed mineral structures. Several samples with minimal interaction with ambient air or free water were also dried to try and ascertain the scale of this issue.

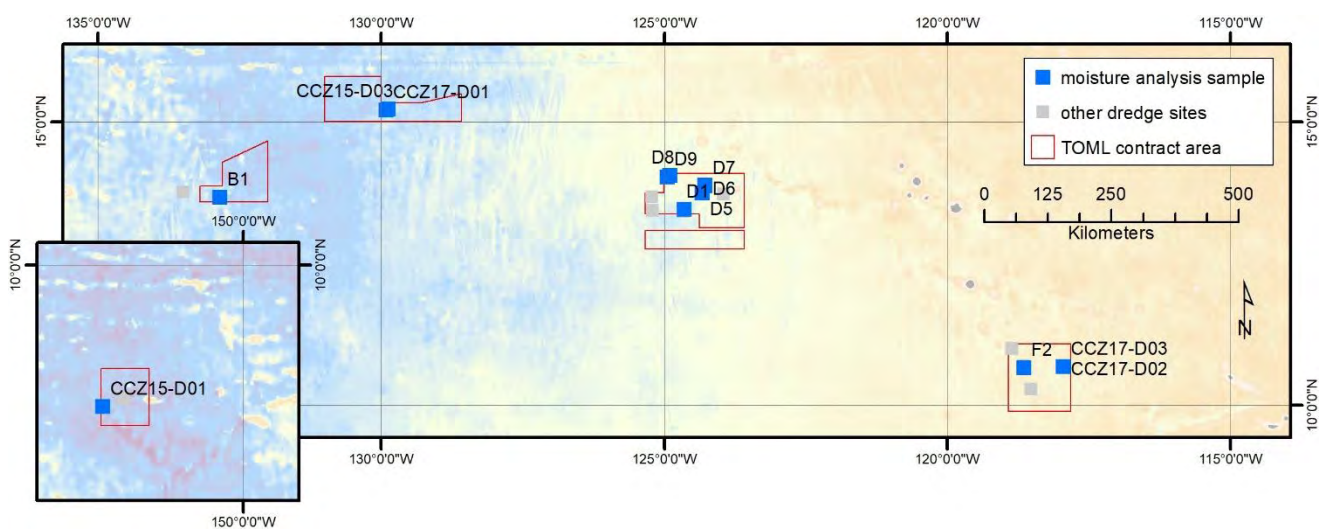


Figure 4-62: Location of samples used for moisture determination.

The samples were subjected to air and oven drying experiments to determine amounts of free and water of crystallisation and release rates over time and temperature. Apart from the long-term drying tests, the work was done at ALS laboratories Brisbane by Kieran Schneider per a work program designed and managed by the author. The long-term tests were done by the author.

It was also re-discovered that dried nodules are hygroscopic (reabsorb water after drying; (International Association of Geoanalysts, 2021)) and additional test work was included to better understand how significant this effect is. Samples at various states of drying were left to absorb moisture from the ambient air (typically for one hour but for up to six days) and reweighed and redried.

Several sets of samples were eventually tested, after early experiments suggested necessary refinements to the methodology. These methods are summarized in Table 4-16.

Table 4-16: Nodule batches for drying

Batch	Description <i>Note dredge samples from CCZ13 are named by TOML area</i>	Number of samples	Air drying steps	Oven drying steps
1	Whole oblate to slightly prolate nodules (7-13 cm horizontal diameter and 3- 8 cm vertically) from outset soaked at outset. All single nodules of 150 to 680 g. soaked in salt water (3 months) dredge samples from CCZ13: F2, 25157, stongly oblate (8x3 cm) RS, 10.67°N, -118.65°E, 4400 mbsl D5, 25158, oblate (11 x 6 cm) RS with distinct dome and equatorial zone, 13.75°N, -124.33°E, 4600 mbsl D7, 25159, prolate (13 x 10 x 8) RS, 13.87°N, -124.28°E, 4400 mbsl D6, 25160, slightly prolate (8 x 6 x 3 cm) diagenetic, 13.88°N, -124.28°E, 4400 mbsl D8, 25161, prolate (10 x 7 x 4) RS with equatorial zone, 14.06°N, -124.9°E, 4400 mbsl D9, 25162, slightly prolate (10 x 8 x 5 cm) diagenetic, 14.03°N, -124.95°E, 4400 mbsl B1, 25163, slightly prolate (8 x 7 x 4 cm) diagenetic with keel, 14.75°N, -133.5°E, 4800 mbsl	7	primarily an air-drying experiment Soak samples in seawater for at least 48 hours. Shake gently by hand for 10 seconds. Weigh. Immediately. Reweigh at the ten progressive longer time intervals per the table of results below. Measure room temperature and humidity each time the sample is weighed	Placed in an oven at 90°C and weighed and reweighed until the weight had effectively stabilised (<0.3g change) this involved 17 "weighings" over progressively longer periods totalling 77 hours. Repeat at 105°C (twice in 44 hours), 120°C (3 times, 14 hours), 140°C (4 times, 25 hours) and 160°C (4 times 40 hours); the timing of "weighings" being to fit in with other lab work, ie not equal intervals. The samples were then left for 6 days and then coarsely crushed to <1 cm and reweighed. They were then redried at 160°C and reweighed. Finally pulverised and a subsample pre-dried to 105°C, weighed then subjected to LOI at 1000°C
2	Fragmented nodules (< 3 cm diameter) from outset soaked at outset. Each sample 15 to 300 g. soaked in salt water 3 months, then left in air 1 month then resoaked in fresh water for 1 hour dredge samples from CCZ13: D5, 25169, 13.75°N, -124.33°E, 4600 mbsl D6, 25167, 13.88°N, -124.28°E, 4400 mbsl D7, 25166, 13.87°N, -124.28°E, 4400 mbsl D8 x 2, 25164 and 25165, 14.06°N, -124.9°E, 4400 mbsl F2, 25168, 10.67°N, -118.65°E, 4400 mbsl	6	primarily an oven drying experiment Soak samples and drain excess water off tray. Weigh (and measure ambient air temperature and humidity). Leave for 48 hours then weigh again (and measure ambient air temperature and humidity). Repeat the step above a further four times. Roughly split each sample into splits a) and b) per supplied fragments (no need to crush) for oven drying experiment	Split a) Sequentially oven dry – 50°C, 70, 90, 105, 120, 140, 160, LOI (per batch 1) Between each oven stage weigh immediately on removal weigh after 30 mins dry again to same temp weigh immediately on removal and transfer to over prepared at next temp. Split b) Oven dry – 50°C Pulverise entire sample Oven dry – 70, 90, 105, 120, 140, 160 , LOI Between each oven stage weigh immediately on removal weigh after 30 mins dry again to same temp weigh immediately on removal and transfer to over prepared at next temp.
3	Fragmented nodules (< 5 cm diameter) from outset never soaked since collection. Each sample 80 to 190 g. stored in closed plastic bags for 4 months with 2 transfers after 1 month and 2 months later dredge samples from CCZ13: D1 x 6, 25170-75, 13.46°N, -124.68°E, 4600 mbsl	6	not subjected to any air drying but went directly into the oven.	Weigh (and measure ambient air temperature and humidity). Break into sub 2 cm pieces in bag and weigh again. Use supplied fragments (no need to crush) for oven drying experiment (50, 70, 90, to 105 deg C).
4	Bulk nodules for long term air-drying CCZ15-D01 (28573) CCZ15-D03 TOML C1 (28572) CCZ17 D01 (26521) CCZ17-(D02/D03) TOML F1 (26522)	4	All samples were collected by YMG Galatea dredge and stored firstly in non-airtight bulker bags then in non-airtight plastic tubs for 3-5 years. The sample from CCZ17-D02/D03 (two nearby dredges) was not discriminated prior shipment. ~ 5 kg weighed, Nodules were soaked in tap water for minimum 2 days, drained through a 250 micron sieve for several minutes. re-weighed	None

4.7.2 Results of Moisture Content Determination

Full tabulated results and associated calculations are in 9.20 Appendix 4F: Sample moisture test results and calculations, and sample photos in 9.21 Appendix 4G: Photos of moisture determination samples.

Key to understanding total moisture content in this report, is the results from the samples from batch 2 which were air then oven dried over a period of over 1200 hours. The results from batch 1 and 3 are compared to batch 2 to try and answer specific questions. The drying curve has three discrete steps that relate to the stages of drying and sintering.

Stage one (batch 1 and 2), is air drying at up to 260 hours at ambient temperatures of 22°C to 25°C and humidity of 50% to 60% (Figure 4-63). Moisture content lost by the time of stabilisation (around 200 hours at these ambient temperature and humidity), varies between 12% and 19%.

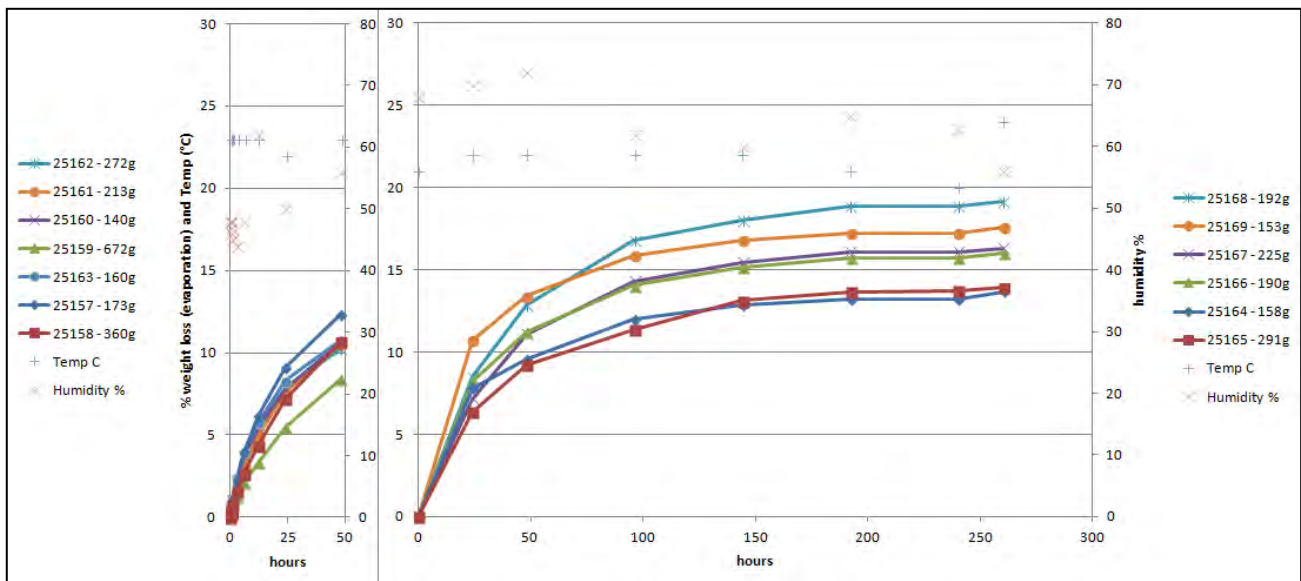


Figure 4-63: Air drying results for batch 1 (left) and batch 2 (right)

Stage two (batches 1,2 and 3), is oven drying at up to 978 hours in seven temperature steps. From Figure 4-64 the moisture content lost is a very consistent 15% to 16.5% at 105°C and 18% to 19.5% at 160°C.

Between each oven drying temperature the samples were left exposed to ambient air for one hour to measure hygroscopic weight increase.

Stage three (batches 1 and 2), is loss on ignition (LOI) where samples are pulverised and effectively sintered at 1000°C, driving off all moisture that might include other types of "combined water" (hydrates and labile hydroxy-compounds) and carbon dioxide, although the latter is thought to be minimal in nodules.

From Figure 4-65 the LOI from 160°C is remarkably constant for the test samples between 14% and 15.2% which equates to:

- - 10.6% to 11.8% from 160°C on a starting wet basis.
- - 16.8% to 18% from 105°C. The results are comparable with figures from some sources:
- Mero (1965) reports LOI (1100°C) of 15% to 39% averaging 25.8% but from nodules at an "air dried" level.
- The TOML nodule samples analysed for major and minor chemistry (4.4) using XRF also had LOI determined. These averaged LOI from 105°C of 17.9%.

- Reference material CGL131 (a nodule standard from the eastern German area in the CCZ averaged an LOI of 16.98% from 16 laboratories, although the figure is not certified)

Other workers report higher LOIs (20% to 25%) but do not specify the drying method in enough detail. The chance of hygroscopic absorption of moisture also cannot be discounted.

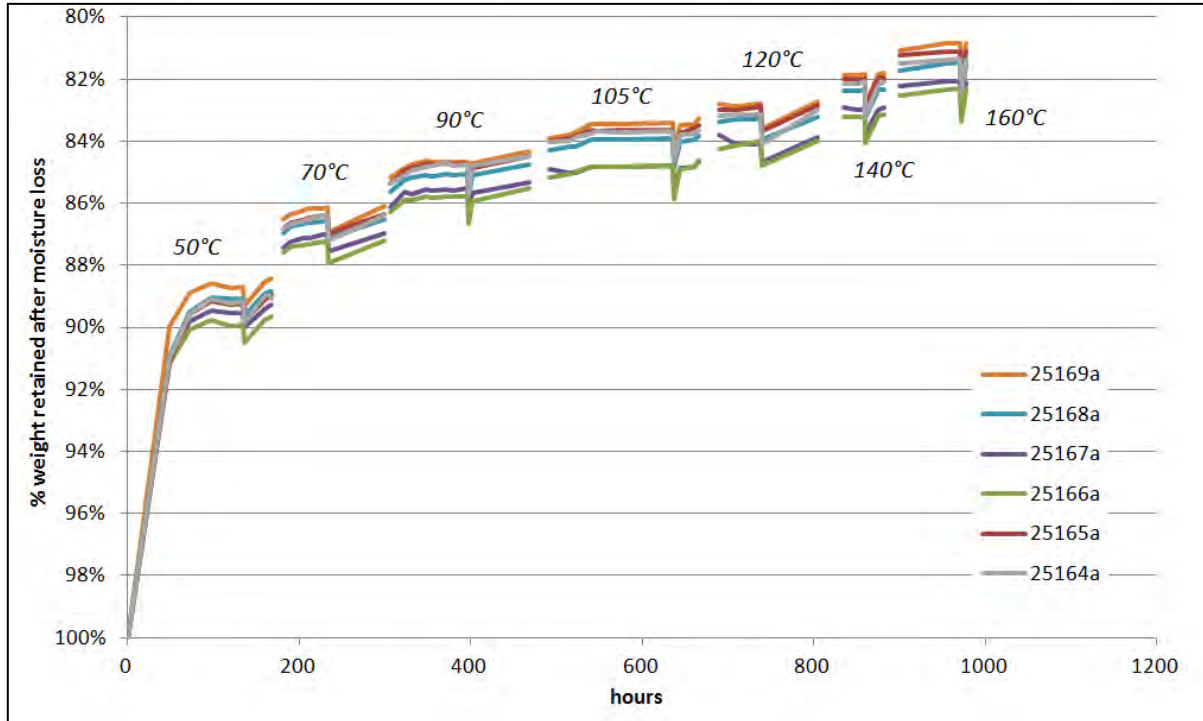


Figure 4-64: Oven drying results for batch 2 nodules

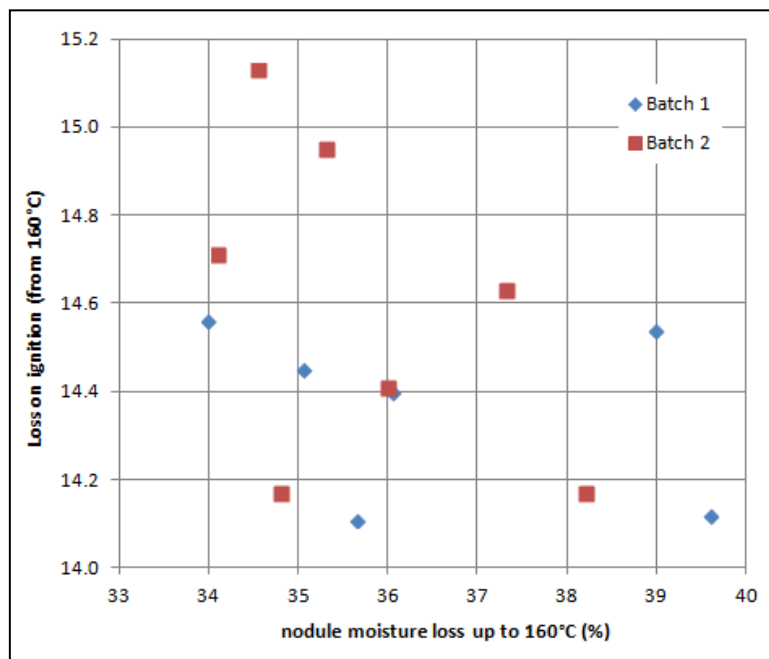


Figure 4-65: Loss on ignition (1000°C) for batches 1 and 2

A combined drying curve is summarised in Figure 4-66. Average total moisture content is 47% with most of the variance in total moisture apparent from the earliest stages of air-drying (48 hours at ambient temperature).

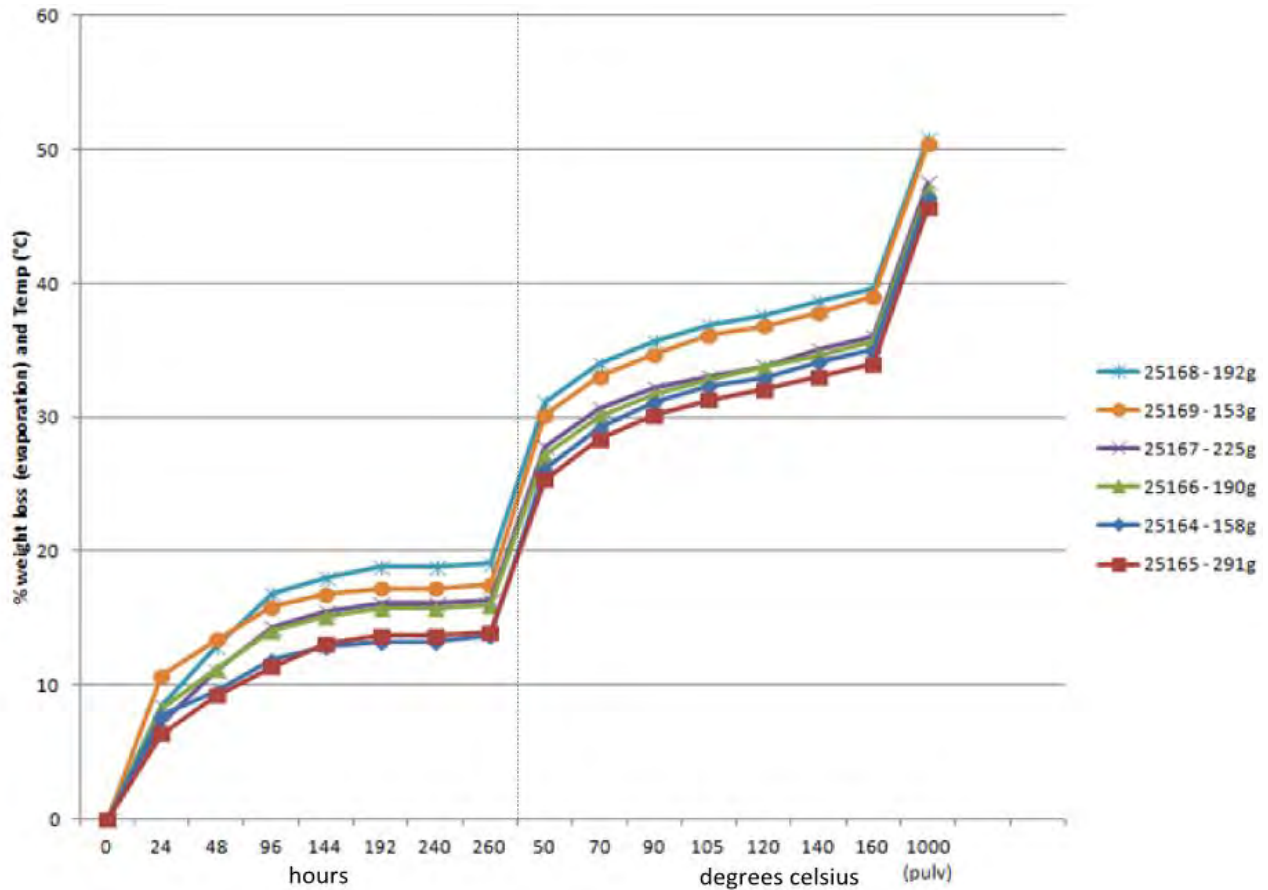


Figure 4-66: Drying curve for polymetallic nodules

The nature of this subject lends that the results of the determination are presented as a series of questions and answers. Specifically:

- What is the total moisture content of nodules?
- What is proportion of free and water of crystallisation?
- How quickly does free water dry off the nodules in air?
- Do smaller nodules dry more quickly than larger ones?
- How hygroscopic are nodules?
- Do soaked decompressing nodules absorb more water?
- How should nodules be dried for grade estimation?

4.7.2.1 What is the total moisture content of nodules?

Sequential air and oven drying of nodules indicates that they contain approximately 44% total moisture (wet basis), with:

- Inclusion of loss on ignition figures (typically 14-15%).
- An average of 47.47% within a range of 45.6% to 50.8 % (Figure 4-67).

- Consideration (and subtraction) of water (~3%) that was absorbed into depressurization cracks after collection (see below).

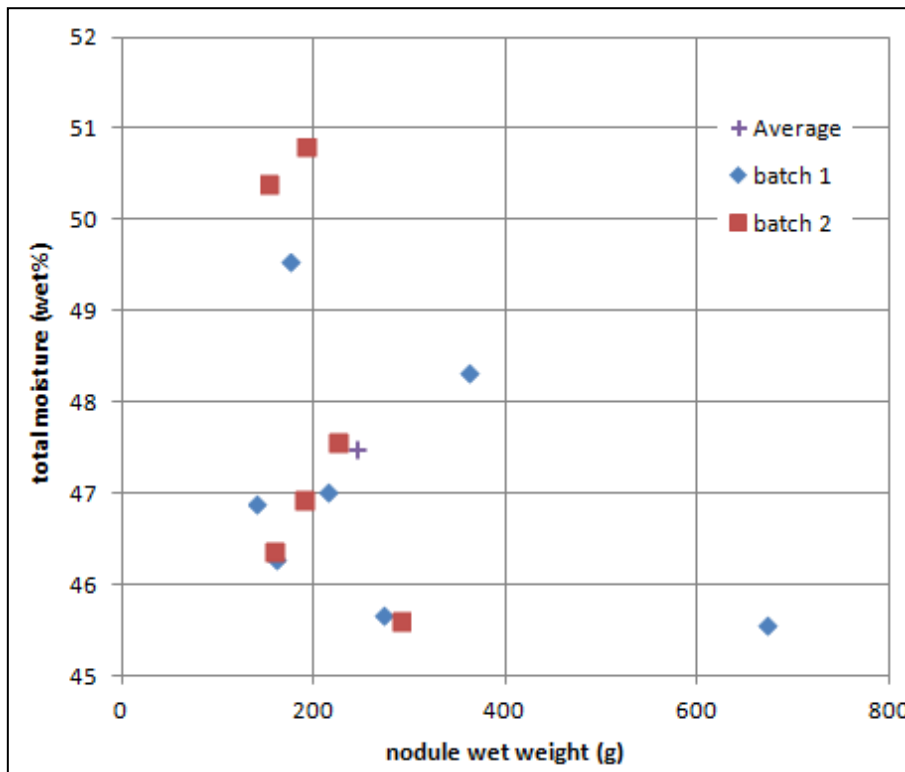


Figure 4-67: Total moisture content nodule batches 1 and 2 (includes 1% to 6 % added water from storage)

There does not seem to be any relationship between relative moisture content and nodule size.

4.7.2.2 What is the proportion of free water and water of crystallisation?

CCZ Nodules are understood to contain 7 minerals (manganese and iron oxides) that contain water of crystallisation (section 4.4). During drying of the mineral buserite readily dehydrates to birnessite at part of the temperature range typically used to drive off free water in rock samples (section 4.4). This is reflected in Figure 4-66 where the drying curve between 50 and 160 °C climbs constantly through the temperature range, i.e. suggesting that progressively more water of crystallisation is being driven off rather than a halt and step change between free water at a lower temperature and water of crystallisation at a higher temperature.

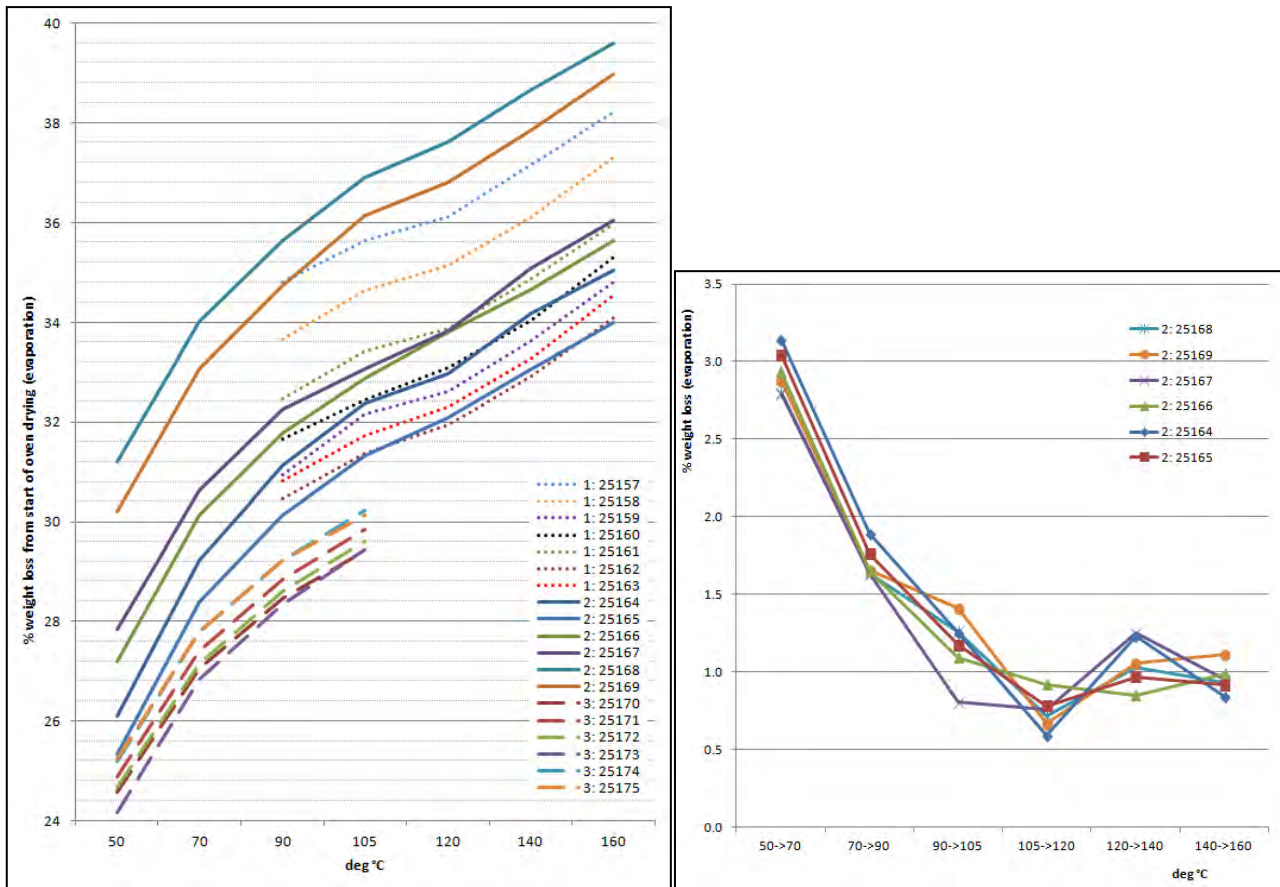


Figure 4-68: Oven drying curves batches 1 to 3 (left) and step changes for batch 2 (right). refer to Figure 4-63 for extent of prior air-drying which is less for batch 1.

From Figure 4-68 it is clear that the rate of drying decreases significantly from 90°C and by 105°C comprises about 1% moisture or less per subsequent 20°C step. In conjunction with the discussion above, this is interpreted to mean that by 105°C all free water has essentially been driven off. Also, an additional 1 to 2% moisture as water of crystallisation has also been driven off.

With reference to the drying curve in Figure 4-66 and the results from all three batches, the proportion of different water types is estimated as follows:

- Free water **28%** absolute wet basis (batch 1 and 2 average is 33.4% minus 2% for water of crystallisation and 3% for free water absorbed into decompression cracks; batch 3 average is 29.8 minus 2% for water of crystallisation plus ~0.6% for air drying). i.e. 64% relative.
- Water of crystallisation **16%** absolute wet basis (batch 1 and 2 average is 14.1% for 105°C to LOI, while average for 272 samples for 105°C to LOI is 13.9% from a 28.4% wet base plus 2% from sub 105°C losses). i.e. 36% relative.

The test work discussed above does not include any mineralogical tests, which could be fundamental in any future advances in our understanding of mineralogical changes with depressurization and drying.

4.7.2.3 How quickly does free water dry off the nodules in air?

Air drying of nodules is slow (Figure 4-66). Samples stored in open containers are dry to the touch after several months and after several years can lose as much as 14% (Table 4-17), but a sample stored almost permanently for 4 months in plastic bags since collection lost at most only about 1% water. Nodules were resoaked before the testing then air-dried indoors at about 22° C and 60% humidity. For the air-drying:

- In the first hour nodules and fragments only lose approximately 1% by weight and it takes 3 hours to lose about 2% moisture.
- After 48 hours between 9% and 14% water loss (wet basis) is typical.
- Losses reduce after 200 hours with 12% to 18% water loss (wet basis). The variation seems to depend on the amount of water in cracks and larger voids in the nodules but also perhaps dependent on subtle differences in texture (Appendix 4F). This represents about half to two thirds of the total free water content.
- After several years of storage (different samples; Table 4-17) losses are lower to similar to the 200 hour figures with smaller nodules, especially the smooth types from TOML A, recovering less moisture on soaking than the RS type nodules from the central and eastern CCZ.

Airdried nodules can re-absorb water from the air; towards the end of the air-drying test a slight decrease in humidity from 62% to 55% resulted in the loss of approximately 2% more weight through moisture evaporation for some of the samples tested in the laboratory. This may also be a factor in some of the results in Table 4-17.

The remaining free water needs to be driven off by oven drying. Oven drying (fan forced at 105°C) is thought to be effective on nodule pieces in less than 24 hours, but this regime was not specifically tested.

Table 4-17: Long term air-dried nodule moisture loss estimate

Sample	Years left dry	Weight prior soaking (kg)	Weight post soaking and draining (kg)	% change*	Ambient humidity when weighed dry
CCZ15-D01 (28573)	4.5	5.15	5.50	+6.8	65%
TOML A		5.30	5.65	+6.6	65%
s-S type <20% fragments		4.90	5.15	+5.1	65%
CCZ15-D03 (28572)	4.5	5.05	5.50	+8.9	80%
TOML C1	2.0	4.85	5.60	+15.5	65%
m-RS type >90% fragments		4.45	5.10	+14.6	65%
ml-RS-type >80% fragments		4.15	4.80	+15.7	65%
CCZ17-D02/03 (26522)	2.0	4.05	4.75	+17.2	80%
TOML F1		4.15	4.95	+19.3	90%
l-RS type >70% fragments		4.30	5.15	+19.8	90%

*Note some absorbed moisture into dehydration/depressurisation cracks (min 3% from section 4.7.2.6).

4.7.2.4 Do smaller nodules dry more quickly than larger ones?

Yes, to a limited extent. Air-drying takes approximately 200 hours to finish depending on temperature and humidity, but at 48 hours whole nodules showed a weak relationship (Figure 4-69). Smaller nodules and fragments all dry at about the same rate with slight differences in permeability and mud content likely more important.

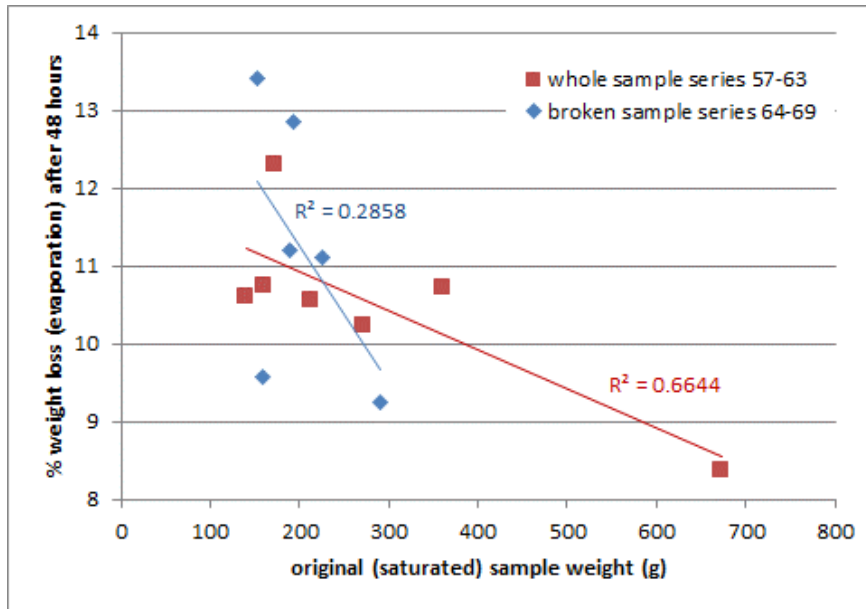


Figure 4-69: Weight loss against nodule size

4.7.2.5 How hygroscopic are nodules?

Dried nodules and especially dried pulverised nodules are highly hygroscopic absorbing around 10% water (dry basis) in 24 hours.

This was not a strong focus of the test work, e.g. water activity was not determined and exposure was only done for limited times to ambient air. A test on a single pulp supports this order of magnitude rate of absorption (Figure 4-70).

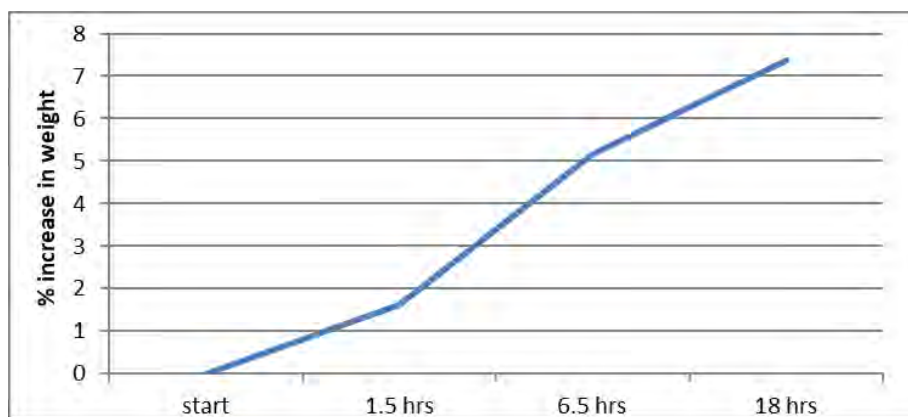


Figure 4-70: Nodule sample moisture absorption after drying to 105°C for 6 hours

At each stage of the oven drying test work (Figure 4-64) for batch 2 the samples were left out for roughly 1 hour and the resultant weight gain measured. For batch 2 a split was pulverised at 50°C and the pulps drying profile measured alongside the nodule fragments specifically with the aim of seeing the effect on hygroscopic behaviour.

From Figure 4-64, it is appears that roughly the same amount of water was reabsorbed at each temperature however a more detailed analysis (Figure 4-71) shows that:

- Peak water loss appears to vary slightly by temperature, however this is interpreted to be due to slight differences in the time the sample was left in ambient air.
- The lower absorption amounts for 50°C and 70°C however are thought to reflect incomplete drying by this stage.
- The consistent absorption amounts at higher temperatures suggest that the interpreted transformation of busserite to birnessite does not materially affect the hygroscopic behaviour.
- Pulverised samples are more (approximately 200% more) rapidly hygroscopic than nodule pieces.
- Larger samples absorbed a larger weight of moisture but smaller samples absorbed proportionally more moisture.

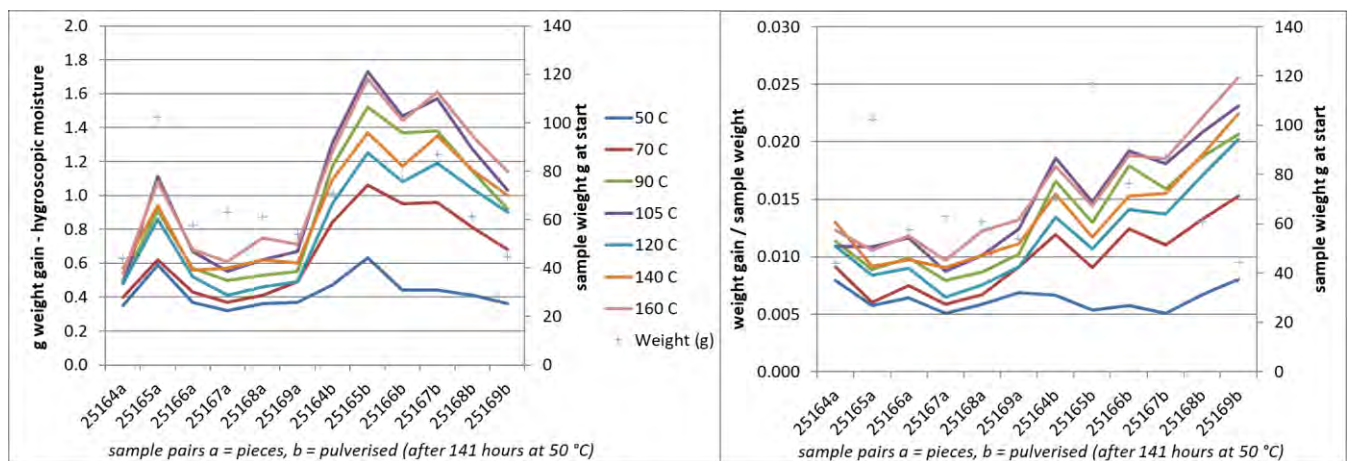


Figure 4-71: Hygroscopic absorption at progressive drying temperatures for batch 2

It was also noticed from the drying results that typically very slightly more moisture was lost after redrying (Figure 4-72). This is likely some kind of hysteresis involving free water rather than progressive loss of water of crystallisation as the effect is muted at higher temperatures.

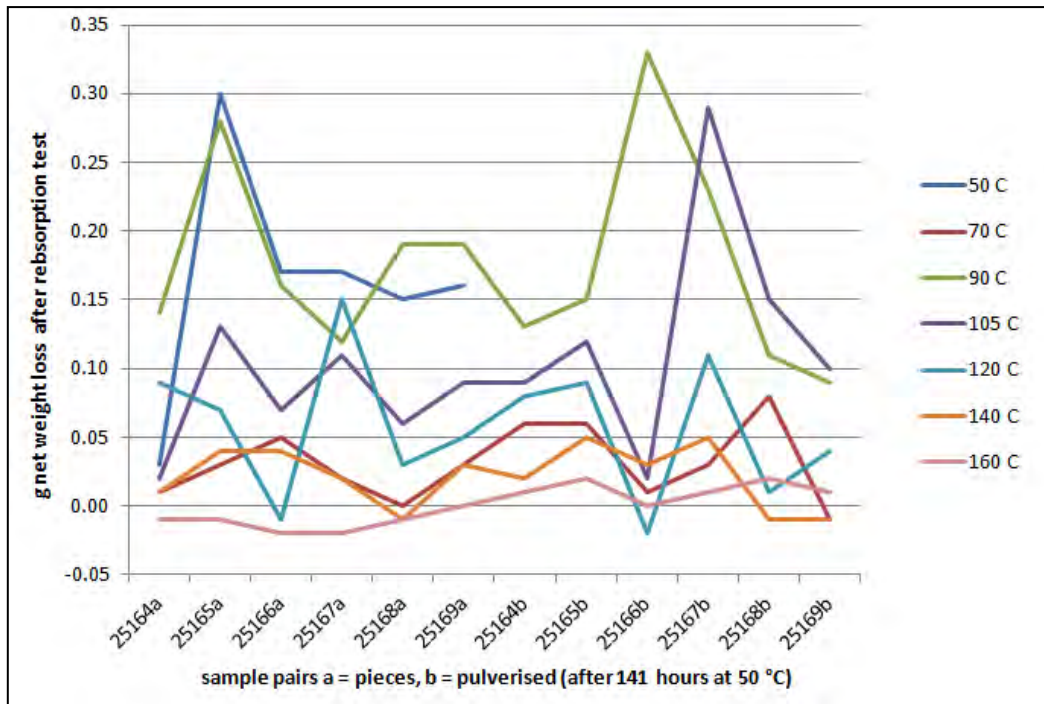


Figure 4-72: Additional moisture loss at a given drying temperature after hygroscopic test

4.7.2.6 Do soaked decompressing nodules absorb more water?

Nodules stored in water for several months after collection will expand and absorb approximately 1% to 6% additional water (wet basis).

Once nodule samples are lifted to the surface they start to decompress and changes even at the mineralogical scale are documented (e.g. ferrosulphate per section 4.4.1). The decompressing nodules will expand, initially presumably filling some of the pore space and then cracking. Hoffert (2008) discusses the cracking and fracturing in some detail (p 225) although he does not attribute decompression to the process or discuss it.

The samples in Batch 3 were oven dried alongside those in Batch 2 from 50°C to 105°C specifically to constrain the answer to this question. These samples are from a single sled sample that were never stored in water after lifting to the surface but stored in plastic bags, with exposure to ambient air for only minutes (1-30) at a time, in four events.

From Figure 4-68 and Figure 4-73 the batch 3 samples have:

- Generally lower moisture contents (1% to 7% of total nodule weight on a wet basis) than batches 1 or 2. This may be due to, in part at least, partial loss of moisture already in air and perhaps to no opportunity to absorb water during soaking.
- Tighter grouping of drying curves. This may reflect the common source of the samples but also supports a lack of absorbed water into any new cracks.
- Proportionally less moisture loss from 70°C to 105°C (up to 1% from start of drying); suggesting that less tightly held free water was available for removal by drying.

Note that in the air-drying test for batch 1 after an hour of air-drying the nodules had lost only 1% total wet weight. By three hours it was 2%.

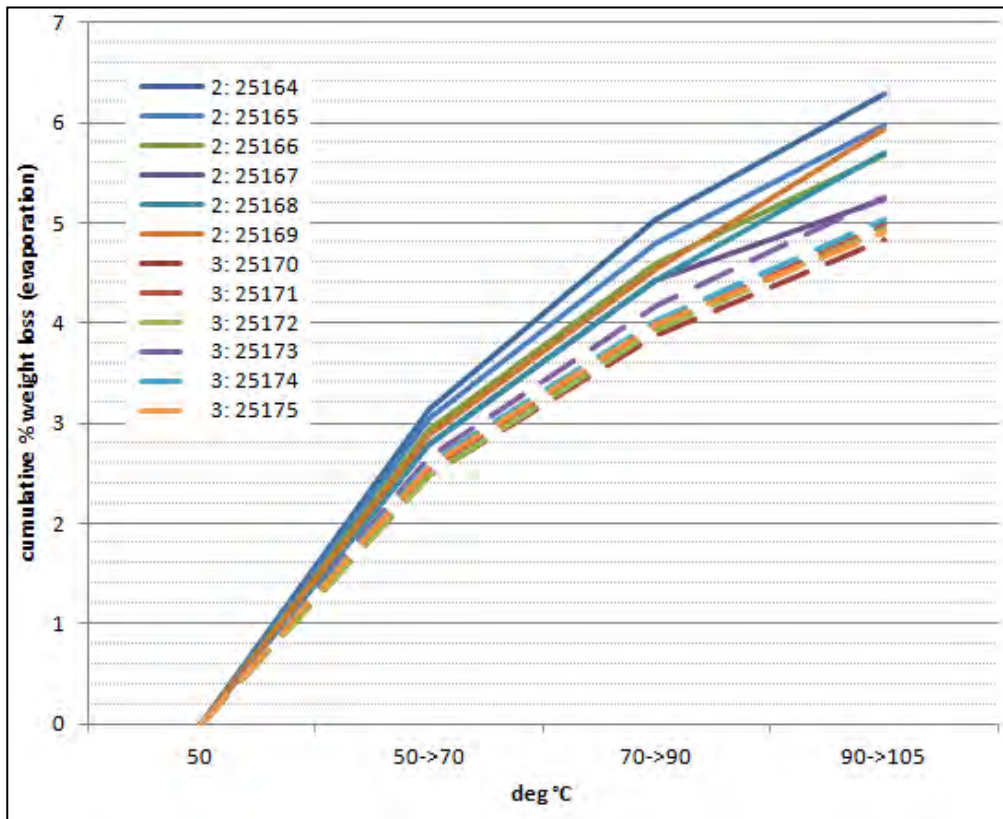


Figure 4-73: Moisture loss in oven drying (50-105°C) batches 2 and 3

It is interpreted that batch 3 had lost perhaps as much as 1% and at most 2% total weight in water to air prior to the oven drying, but that nodules in batches 1 and 2 had absorbed 1% to 6% total weight in water from having been soaked for several months before the drying test work. The difference between the average weight loss at 105°C of batches 1 and 2 versus batch 3 is 3.6% so for the total moisture estimates above 3% is subtracted. Note however that much of the range in total nodule moisture contents in batch 2 may be due to variable decompression cracking and water absorption.

With reference back to Figure 4-63 most of the 1% to 6% water likely absorbed by nodules due to soaking was probably lost back in air drying after 48 hours. This could only be really confirmed by specific and intensive tests (e.g. paired nodules soaked and not soaked then dried).

It is suggested that future nodule samples studied for moisture content should not be soaked but rather wrapped in temperature resistant plastic wrap immediately on collection. Alternatively, if the effects of vessel heave can be managed adequately, they should be weighed immediately after collection, stored in well ventilated ambient conditions and reweighed periodically.

4.7.2.7 How should nodules be dried for grade estimation?

An oven drying temperature of 105°C at 24 hours for grade estimation is supported for the following reasons:

- Loss of water of crystallisation is minimal (~1-2% of total wet mass).

- All free water is removed (at lower temperatures this is not the case).
- Higher temperatures simply remove water of crystallisation and not free water.
- Industry standard so grades can be readily compared.
- Drying times are quick so interlaboratory variance in drying time is not an issue.

Note that 24 hours is not enough time to remove all of the moisture possible at 105°C. Figure 4-74 shows that for batches 2 and 3 (pieces and pulverised samples) 24 hours at 105°C from 90°C is enough only to remove approximately half the total moisture that could be driven off after drying at 90°C. However, given that most of the moisture driven off between 24 and 72+ hours is likely water of crystallisation a slight underestimation is not significant. The additional 0.4% to 0.6% weight loss has to be considered against the 28% to 34% that has already been driven off by drying to that point.

Relatively rapid drying may also reduce the water of crystallisation driven off at temperatures below 105°C.

Note that in the process of subsampling and redrying, i.e. from 160° to ~25° to 105°C it is likely that some water of crystallisation remained permanently lost at 160°C and a measure of atmospheric water was reabsorbed at 25°C then lost again at 105°C. The relevant calculation in section 9.20 assumes the dried state of the sample pre-LOI was as at 160°C and the resultant figures agree well with LOI done directly from 105°C and the CGL131 standard also dried at 105°C.

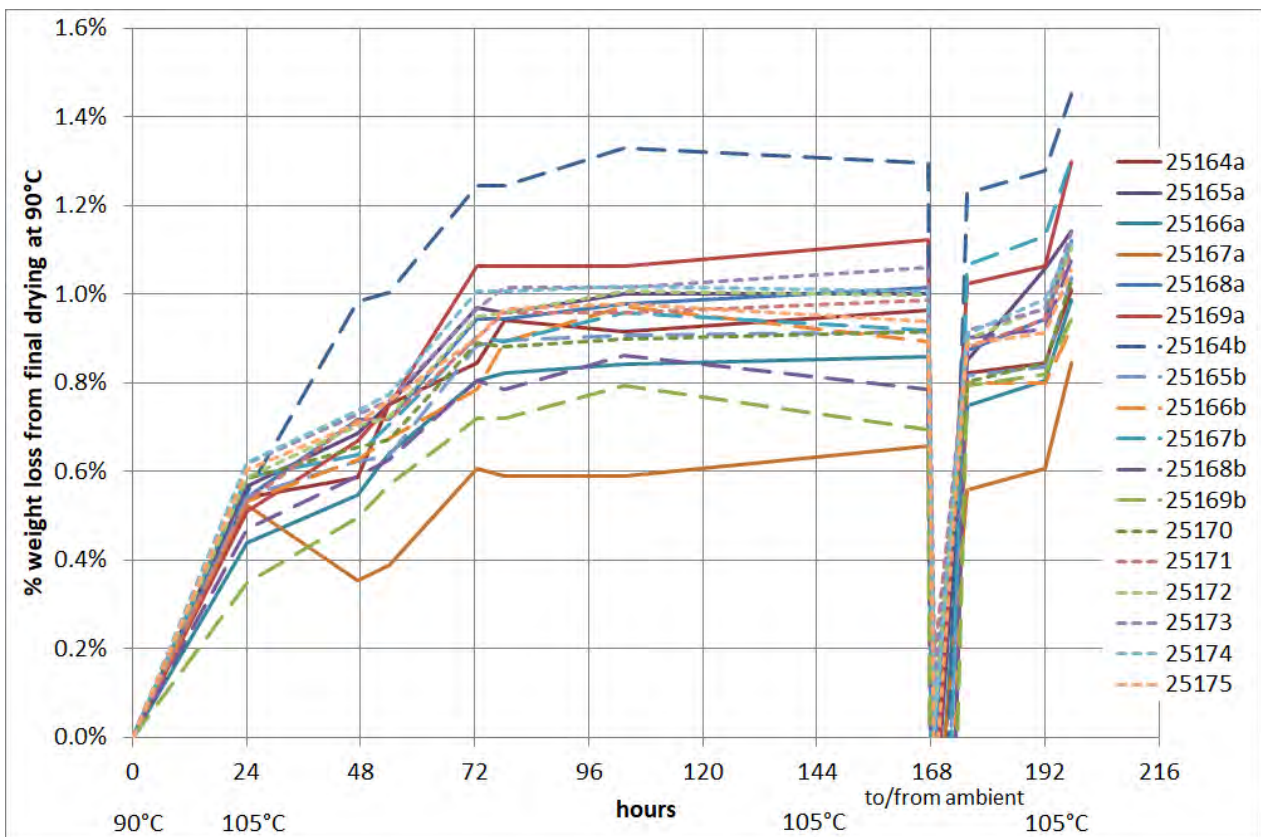


Figure 4-74: Moisture loss with time drying at 105°C batches 2 and 3
 Sample was exposed to ambient conditions at 168 hours for several hours.

4.8 Propensity to form attrition fines

4.8.1 Context and test program objectives

Liquefaction of mineral ores, including iron ore fines onboard cargo ships can result in cargo shift and loss of stability. In 2010/11 and 2013 there were a number of serious cases involving shipments of nickel-laterite ore which resulted in casualties and loss of the vessel and cargo. It is believed that the main cause of these events (and other near misses) is the poor compliance of shippers with testing and certification requirements, e.g. as set out in the IMSBC code for this liquefaction prone cargo. In response to these incidents shipping and insurance companies have upgraded their policies and policing of testing.



Figure 4-75: Sinking of the Trans Summer during Typhoon Utor, August 2013

Photo credit: Hong Kong Flying Service. Source (Schuler, 2013)

There are currently no testing or certification requirements for the transportation of polymetallic nodules, but the test work described here looks at some of their critical properties and how they change over a period of attrition. Nodules are quite soft rocks and prone to breaking or crumbling. Understanding their propensity to form attrition fines thus has significant implications. Unlike land-based ores, there is little potential to dry nodules prior to transport to a processing market.

Of relevance is that the International Maritime Organization (IMO) released a Marine Guidance Note related to the carriage and testing of iron ore fines as covered in the International Maritime Solid Bulk Cargoes Code (IMSBC) (Maritime and Coastguard Agency, 2014; International Maritime Organization, 2020). The note classifies cargo outlines test requirements for determining the Transportable Moisture Limit (TML) of bulk cargoes (Iron Ore Fines).

Manganese mineral fines and iron ore fines share some similarities (chemical form, surface area). This is as opposed to nickel laterite ore which contains a mix of ultrafine limonite clay (grading to goethite) and variably decomposed rock including talc and serpentine rich material (Golightly, 1981; Dalvi et al., 2004). Land based manganese ores are generally very hard and coarse grained and are not subject any special transport regulations with regards to fines. Most general bulk commodities that are at risk of flowing as fines

are subject to a transportable moisture limit (International Maritime Organization, 2020). This is typically at 5% and not applicable to highly porous materials like iron-ore fines (Holmes et al., 2016), nickel laterite and polymetallic nodules that typically have high vadose water contents ($\pm 30\%$ by weight).

The IMSBC code categorizes Iron Ore Fines cargoes into three groups – A, B and C:

Group A consists of the cargoes which may liquefy if shipped with moisture content in excess of their transportable moisture limit.

For Iron Ore cargoes to be classed as a Group A Cargo they must contain both 10% or more of fine particles less than 1mm in diameter and 50% or more of particles less than 10mm in diameter. The content of goethite shall be less than 35%. It is not specified but assumed that the % breakdown is by wet (decanted) weight.

For Group A cargoes it is normally the appropriate authority or competent authority in the country of loading/origin that sets out the test procedure for determining the actual moisture content and TML of such cargoes.

Group B consists of cargoes which possess a chemical hazard which could give rise to a dangerous situation on a ship. Polymetallic nodules are not thought to ever qualify as Group B due to their applicability of their process residues in agricultural uses e.g. (Wiltshire, 1997, 2017).

Group C consists of cargoes which are not liable to liquefy (i.e., Group A), and do not possess chemical hazards (i.e., Group B).

Thus, for Iron Ore cargoes to be classed as a Group C Cargo they must contain either less than 10% of fine particles less than 1mm in diameter, or less than 50% of particles less than 10 mm in diameter, or both, or iron ore fines containing 35% or more goethite. It is not specified but assumed that the percent breakdown is by wet (decanted) weight.

Nodule samples invariably start out as Group C like material, and should either easily pass (or not apply to) any of the three standard tests used for TML (i.e. flow-table, Proctor-Fagerberg, Penetration; (Holmes et al., 2016)). However, with abrasion and impact (mostly inter-particle) attrition fines are formed and when the sample:

1. Has particles <10 mm comprising more than 50% of the weight of the sample that sample has “exceeded the coarse threshold”;
2. Has particles <1 mm comprising more than 10% of the weight of the sample, then that sample has “exceeded the fine threshold”.

The sample thus needs exceed both the fine and coarse thresholds to pass from “Group C like” material to “Group A like” material.

The study presented here is entirely empirical and designed to inform future discussion on this subject e.g., with cargo shipping companies, their underwriters and relevant regulatory authorities. It is thus distinct from the sophisticated nodule fragmentation modelling presented by (van Wijk and de Hoog, 2020) that looks at the geo-mechanical detail of how nodules fragment with a specific view to performance in a hydraulic riser system. It is also worth noting that at the time of testing, the TOML mining concept (Chapter 6) did not involve a hydraulic riser system, and none of the testing involves the slurry densities expected in a riser (<20% solids by volume).

Thus, the test program had two main objectives:

1. To determine the time frame in which a transported nodule sample changed from “Group C like” to “Group A like” if they were subject to similar rules to those applied to iron ore fines.
2. To better constrain how water content impacts on formation of nodule attrition fines.

The fines generated were not analysed chemically but it is very unlikely that they are of the same composition as coarser fractions. Kim *et al.*, (2021) demonstrate via bulk chemistry and x-ray diffraction analysis that attrition fines from the KIOST exploration contract area in the CCZ are significantly higher in alumino-silicates. This is interpreted to be due to nodules preferentially breaking along clay-ooze filled growth seams or micro fractures (as seen in the microanalysis figures within section 4.4.3).

4.8.2 Methods for attrition fines testing

Tests were carried out at ALS Limited Laboratory, located in Brisbane, Queensland, Australia. Blaze Riada-Horn and Upkar Bagga conducted the tests under the supervision of the author. Review and adaptation of the program was required, and this was done after discussion between the team members. With the author, Blaze Riada-Horn led drafting of an unpublished technical note that included most of the results presented here.

The sample was 40 kg of a single dredge sample from TOML F; CCZ13 campaign D1 (Figure 4-76). This sample was selected as this nodules type (sm-S; or NORI Type 1) are softer than nodules from other sampled parts of the TOML contract areas and as this is a likely key nodule-ore type in proposed trail mining. The sample was collected using an epibenthic sled-dredge (per section 4.2.1.1).

The sample had been kept in two tightly sealed buckets and still retained most of its original moisture. The two halves of the sample were split into quarters using a riffle splitter for 8 x ~5 kg subsamples. Each subsample contained a range of large (+10mm), medium (-10+1mm) and fine (-1mm) nodules. These fractions were separated using 24” diameter sieves, each being shaken for approximately 4 minutes. The three fractions were weighed to obtain a starting weight (Figure 4-77). The sub-samples were then recombined and tumbled to incite attrition using an electric tumbler-mixer (Figure 4-78).

At typically 10 minute intervals, the sub-sample was re-sieved to the same three fractions and reweighed. This continued until the sample exceeded the above-mentioned thresholds. Sub-samples in tests that included added water were also sealed each time in a water-tight drum (narrower diameter than the tumbler but of similar height (Figure 4-79).

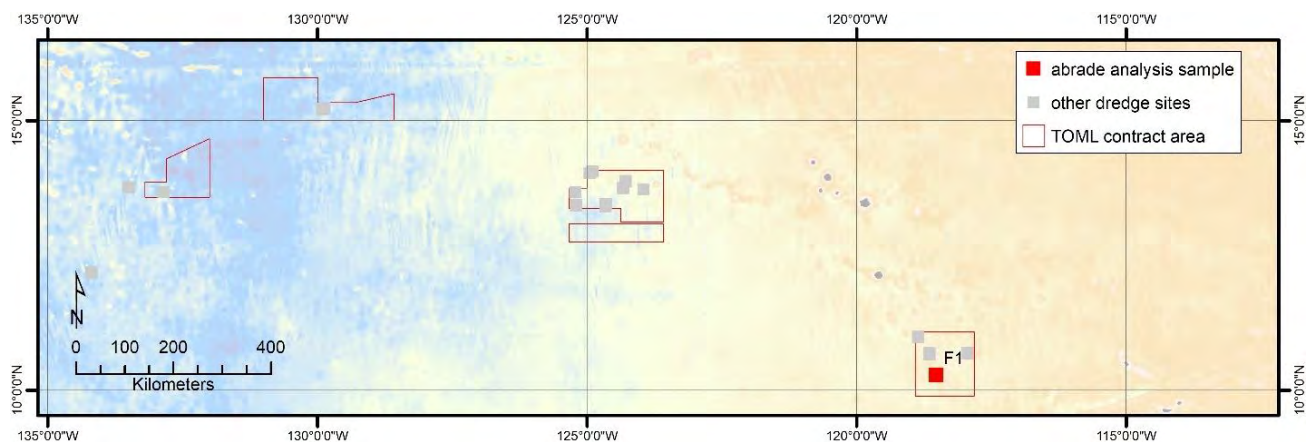


Figure 4-76: Nodule abrade test sample location



Figure 4-77: An example of sample fractions



Figure 4-78: Tumbler used during test work

A range of conditions (varying added water) were then tested as follows in Table 4-18.

Table 4-18: Nodule attrition tests

Test	% water added
1	0
2	0
3	20
4	50
5	80
6	200
7	400

During the test work some loss of fines was experienced. It has been assumed that all lost fines were <1 mm in size. Note however that in any commercial system material losses would need to be accommodated for, either with cleaning and recycling circuits or with discharge circuits. If discharge circuits are used (i.e. prove most cost effective and environmentally acceptable) then the test results without inclusion of losses may be more relevant. In any event, the amount of losses encountered in this attrition test-work may be of interest in its own right.



Figure 4-79: Wet sample bucket held in place with crates/padding and sealed with tape.

4.8.3 Results of attrition fines testing

Full tabulated results and associated calculations are in section 9.22.

4.8.3.1 Tests 1 and 2 – no water added

Testing was undertaken on two sub-samples of nodules without adding extra water. Test 2 is a more precisely measured repeat of Test 1 to ensure the results are accurate.

For test 1 (Figure 4-80) the -10 mm fraction exceeded the coarse threshold (50% of the total weight of the sample) after about 50 minutes. Note that the 4th step was 40 minutes instead of 10 minutes. The -1mm fraction exceeded the fine threshold (10% of the total weight of the sample) after 100 minutes if sample losses are included as fines, and after 136 minutes if they are excluded. Therefore, the sample exceeded both conditions to pass from Group C like to Group A like after minimum 100 minutes.

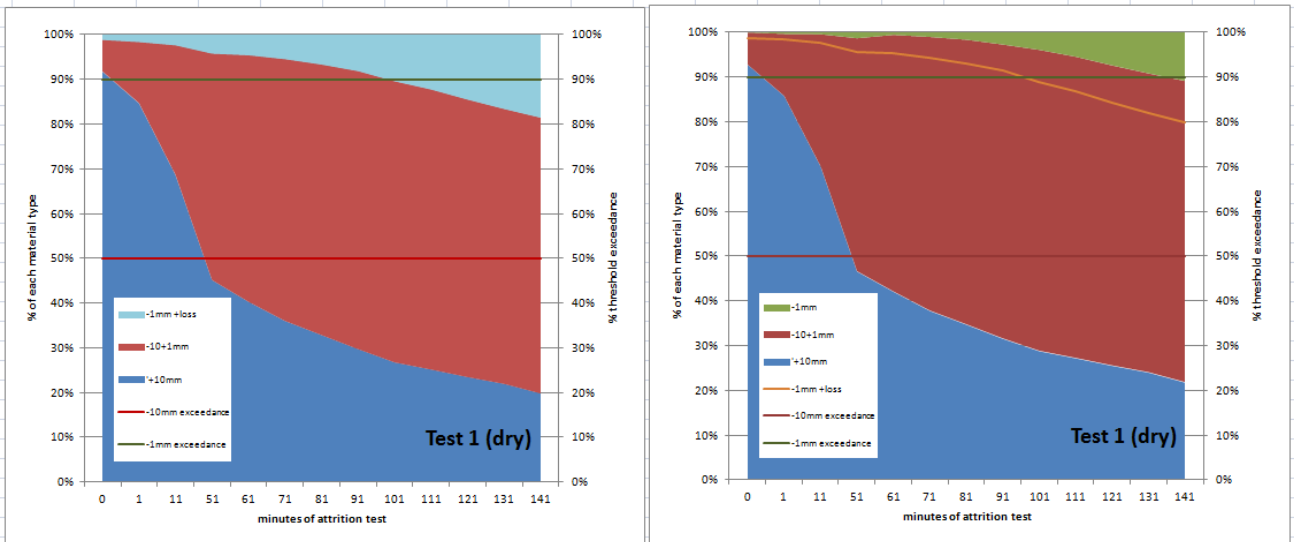


Figure 4-80: Consolidated results test 1.
The graph at left assumes all losses are – 1 mm fines.

Sample losses by the end of the program was around 10% through dust and grit sticking to the various surfaces involved in the test work and sample handling.

Results for test 2 (Figure 4-81) are effectively identical with test 1. The -10 mm fraction exceeded the coarse threshold (50% of the total weight of the sample) first after about 50 minutes. The -1mm sample exceeded the fine threshold (10% of the total weight of the sample) after 100 minutes if sample losses are included as fines and 130 minutes if losses are excluded. Therefore, the sample exceeded both conditions to pass from “Group C like” to “Group A like” after minimum 100 minutes.

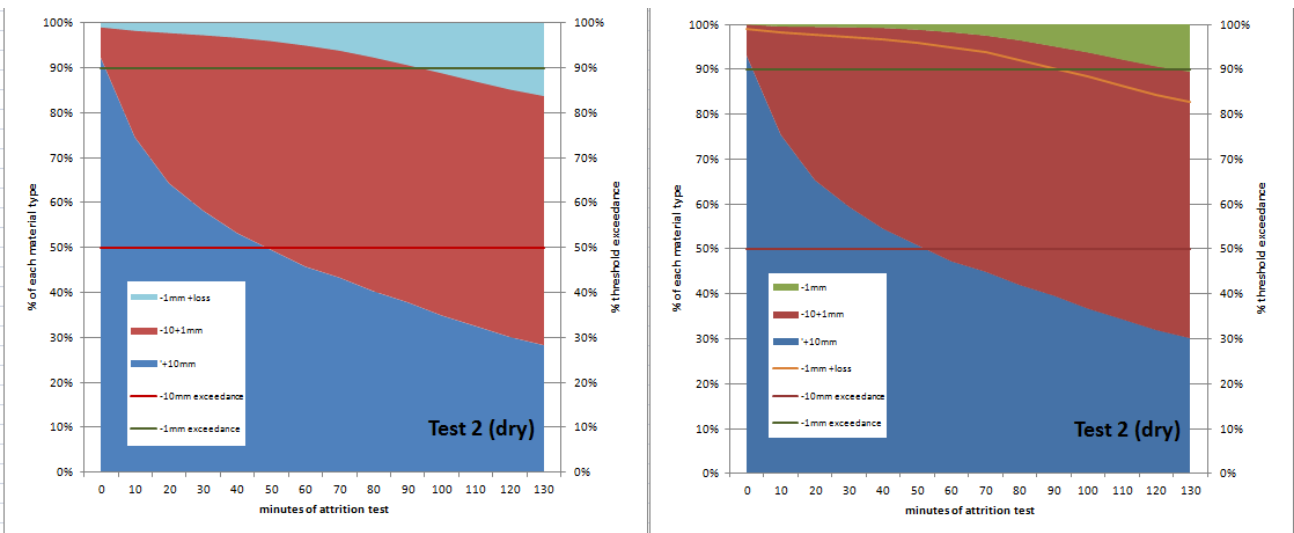


Figure 4-81: Consolidated results test 2
The graph at left assumes all losses are – 1 mm fines.

Sample loss by the end of the program was around 8% through dust and grit sticking to the various surfaces involved in the test work and sample handling. With the refinement in timing this is probably the best example of a dry test.

4.8.3.2 Summary of dry test results

The -10 mm fraction exceeded the coarse threshold (50% of the total weight of the sample) after 50 minutes (Figure 4-82). The outcome of test 2 is preferred that of test 1 due to the shorter measurement timing intervals.

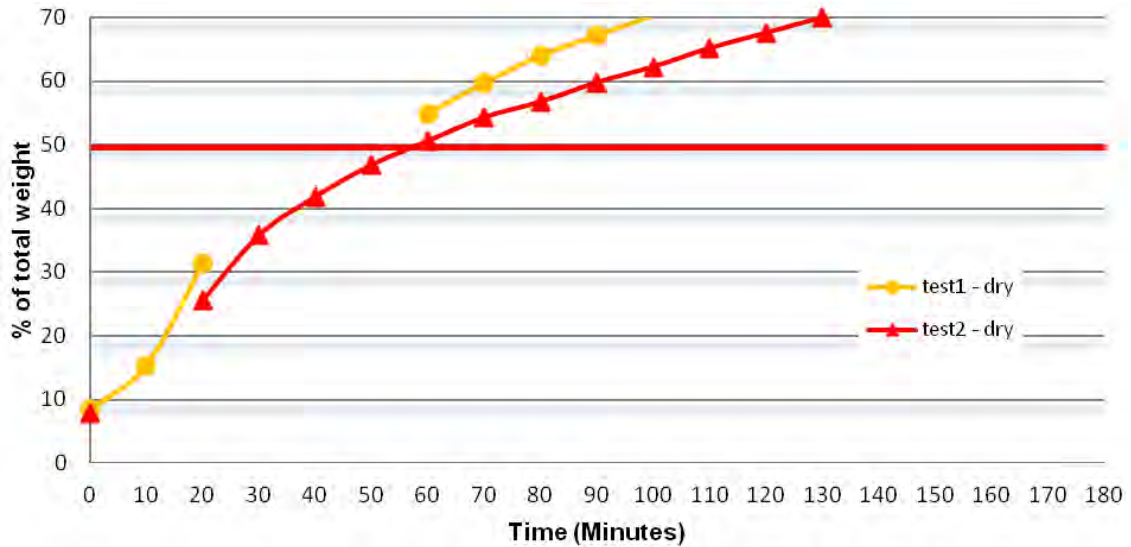


Figure 4-82: Tests 1 and 2, -10 mm sample results (losses included)

The -1mm fraction (including losses) then exceeded the fine threshold (10% of the total weight of the sample) after about 100 minutes if losses are included (Figure 4-83).

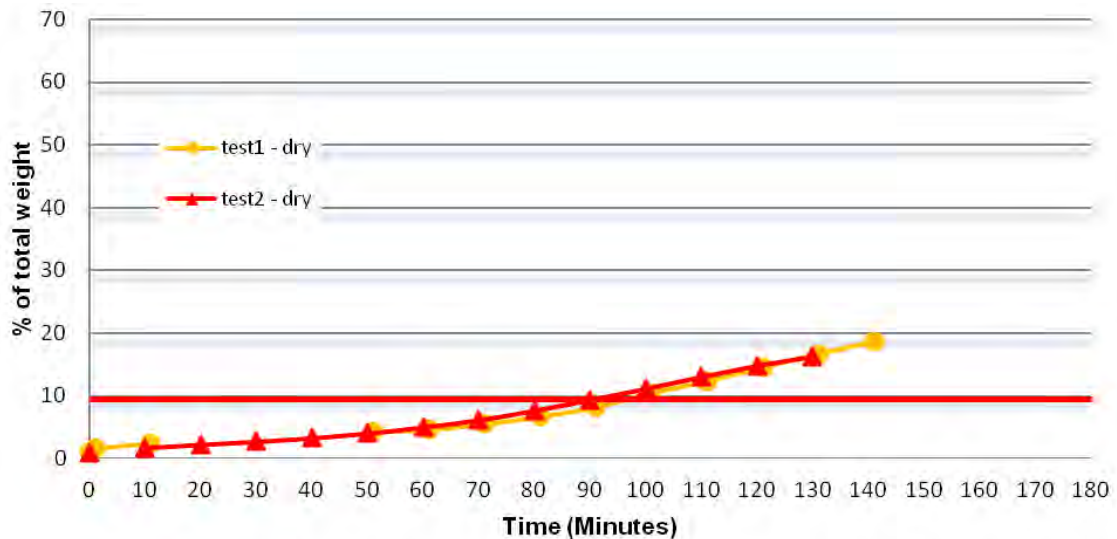


Figure 4-83: Tests 1 and 2, -1mm sample results (losses included).

The nodule samples thus moved from being Group C like to being Group A like after about 100 minutes of continuous dry attrition.

4.8.3.3 Tests 3 to 7 - variable water added

Test 3 had 20% of weight in water added. The -1mm fraction exceeded the fine threshold (10% of the total weight of the sample) after about 10 minutes if losses are included (Figure 4-84), but 45 minutes if losses are excluded. The -10 mm fraction exceeded the coarse threshold (50% of the total weight of the sample) after

about 80 minutes. Therefore, the sample moved from Group C like to Group A like after about 80-90 minutes.

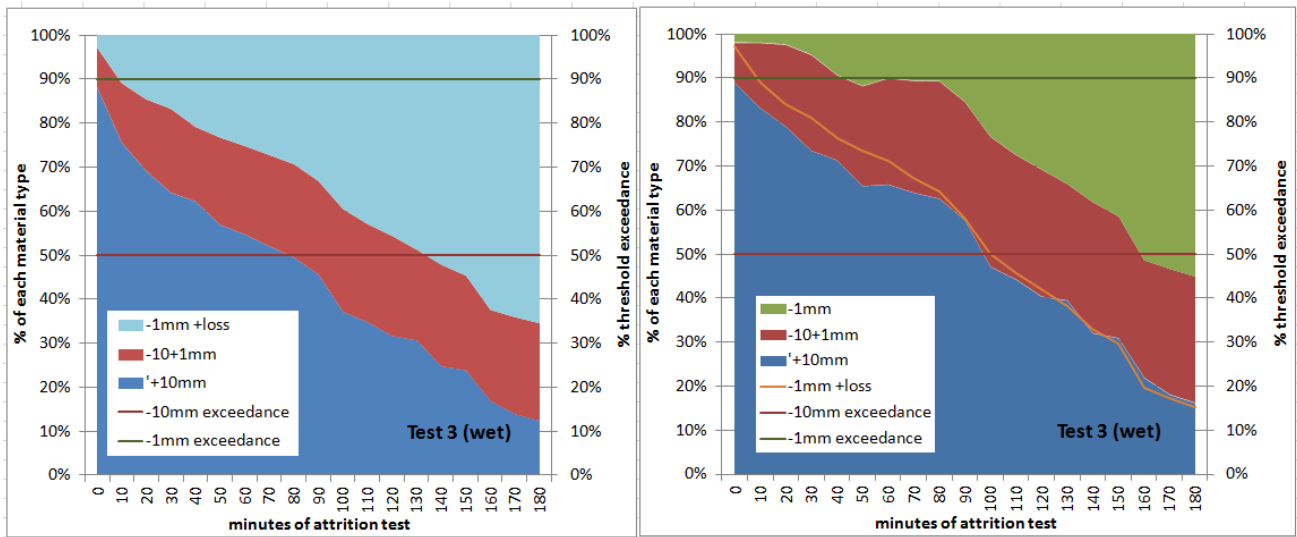


Figure 4-84: Consolidated results test 3

Sample loss by the end of the program was around 30% through fines in water being decanted.

Test 4 had 50% of weight in water added. For test 4, the -1mm fraction exceeded the fine threshold (10% of the total weight of the sample) after about 20 minutes if losses are included but 30 minutes if losses are excluded (Figure 4-85). The -10 mm fraction exceeded the coarse threshold (50% of the total weight of the sample) after about 120 minutes with losses included and looked to exceed this threshold as the test ended at 150 minutes with losses excluded. Therefore, the sample moved from Group C like to Group A like after about 120 minutes.

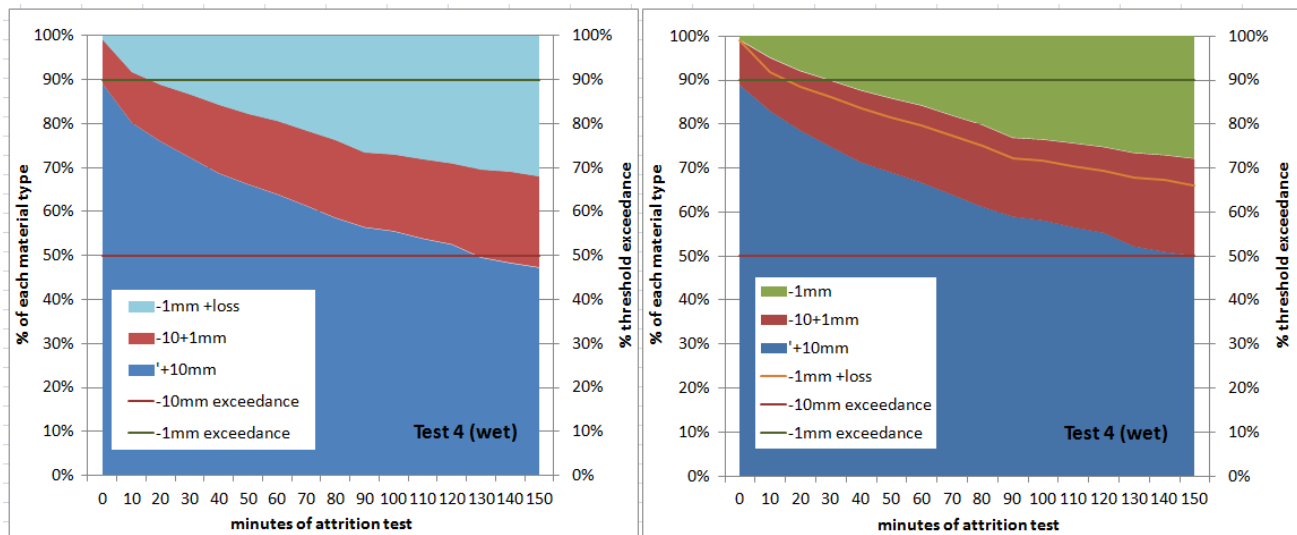


Figure 4-85: Consolidated results test 4

Sample loss by the end of the program was much less than in test 3, i.e. about 5% through fines in water being decanted.

Test 5 had 80% of weight in water added. For test 5, the -1mm fraction exceeded the fine threshold (10% of the total weight of the sample) after about 10 minutes if losses are included but 20 minutes if losses are

excluded (Figure 4-86). The -10 mm fraction exceeded the coarse threshold (50% of the total weight of the sample) after about 90 minutes. Therefore, the sample moved from Group C like to Group A like after about 90 minutes.

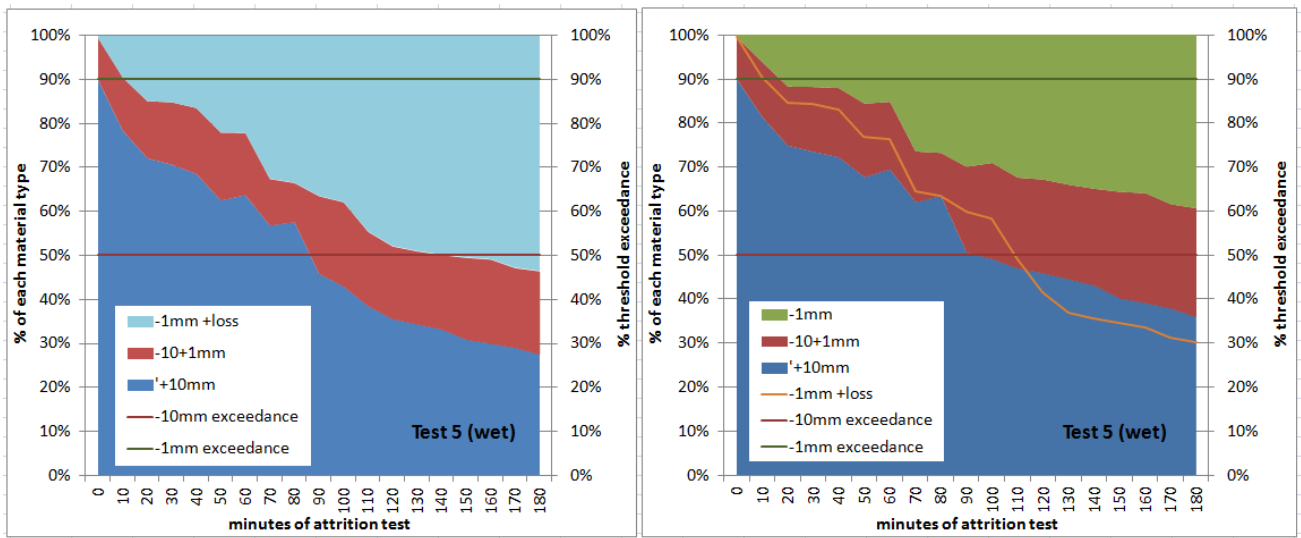


Figure 4-86: Consolidated results test 5

However, the results are at odds with the results of Tests 4 and 6, and include irregularities such as some increased proportions of coarser material, indicating measurement errors.

Test 6 had 200% of weight in water added. For test 6, the -1mm fraction exceeded the fine threshold (10% of the total weight of the sample) after about 20 minutes (Figure 4-87). The -10 mm fraction exceeded the coarse threshold (50% of the total weight of the sample) after about 140 minutes. Therefore, the sample moved from Group C like to Group A like after about 140 minutes.

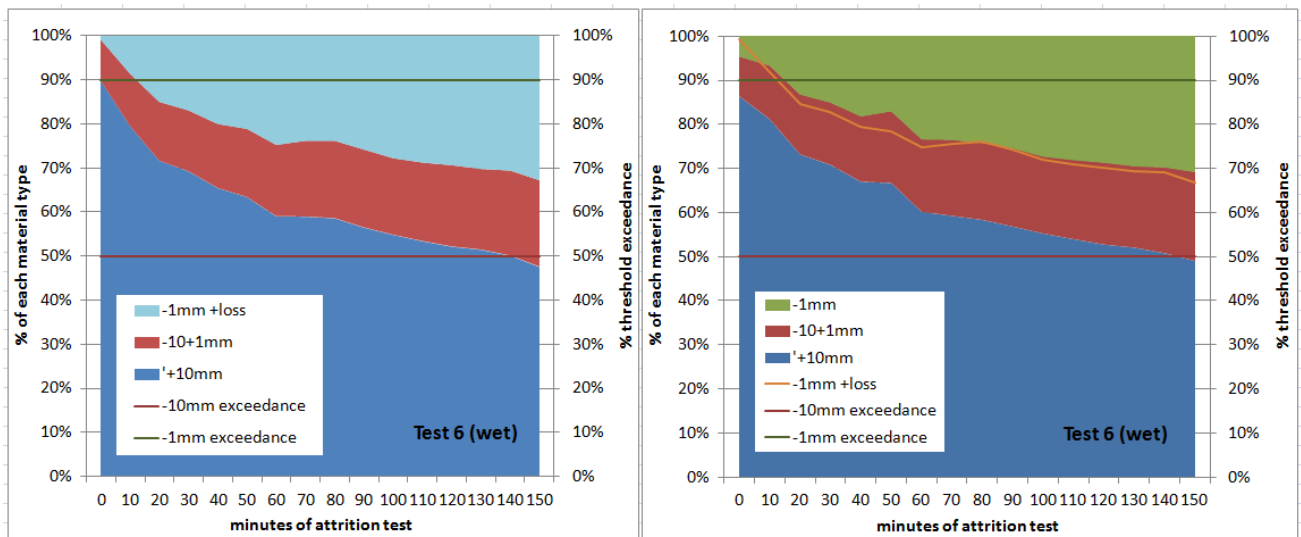


Figure 4-87: Consolidated results test 6

Like test 4 sample loss by the end of the program was only a few %, through fines in water being decanted. There is a minor irregularity in the weights at 50 minutes, but this is a good wet test to reference.

Test 7 had 400% of weight in water added. Test 7 was a simple 11-hour test to help constrain near “worst case” conditions, i.e. long term, high water content. Unfortunately, there was water leakage from the tumbler that probably increased the level of losses (~28% by weight; Table 4-19).

Table 4-19: Results for nodule sample with 400% of weight added in water – Test 7

Time in Tumbler (hours)	Sample Weight after Tumbling + Sieving (g)	Sample Loss (g)	% of total weight (without losses)		
			'+10mm	-10+1mm	-1mm
0	2930.1	-81	84.01	11.11	4.88
11	2095.5	834.6	31.44	43.58	24.98

Both the -1mm and -10 mm samples significant exceeded the fine and coarse thresholds during the overnight tumbling. The -10 mm sample reached 69% without losses and 78% with losses included. The -1 mm sample reached 25% without losses and 46% with losses included.

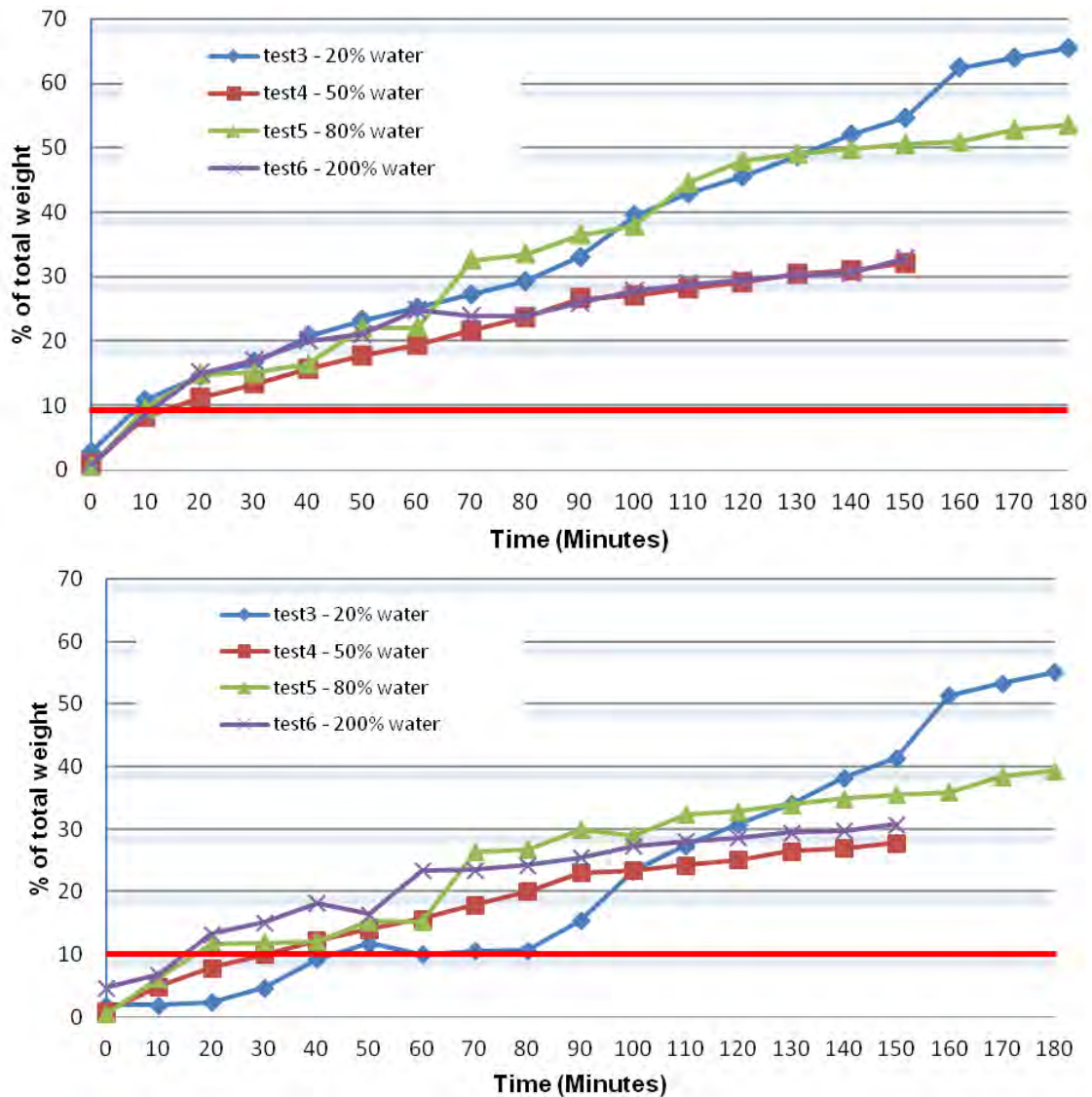


Figure 4-88: Wet test results for -1 mm fraction with and without losses

4.8.3.4 Summary of wet test results

The -1mm fraction (including losses) then exceeded the fine threshold (10% of the total weight of the sample) after about 10 minutes of tumbling if losses are included and from between 10 minutes and 40 minutes if losses are excluded (Figure 4-88).

The -10 mm fraction exceeded the coarse threshold (50% of the total weight of the sample) after 80 minutes of tumbling for the 20% added water sample (Figure 4-89), and about 130 minutes for the 50% and 200% added water samples. Test 5 at 80% added water has results closer to the 20% water sample but as noted above this test had some irregularities so probably should not be overly relied upon.

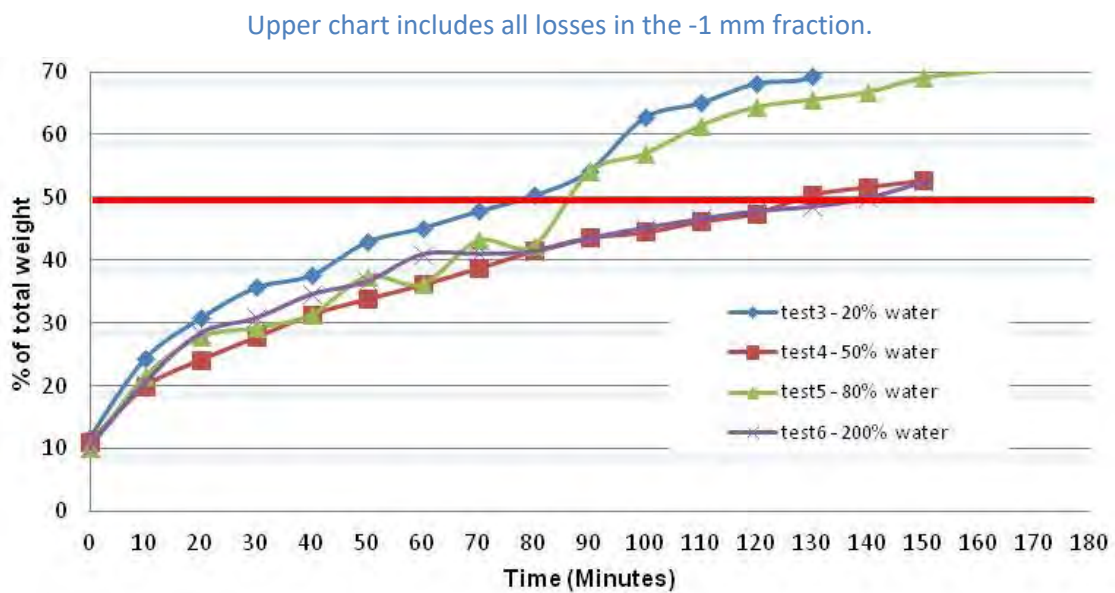


Figure 4-89: Wet test results for -10 mm fraction with losses included

4.8.4 Further Analysis of Results

The first objective of the attrition test work program was to determine the time frame in which the nodule samples change from *Group C like* to *Group A like*. This clearly depends on how the nodules are transported and some constraints are provided below.

4.8.4.1 Discrete dry transport

Dry transport is considered here to include relatively violent processes such as dumping and pneumatic conveying as this is what the testing attempted to simulate. Transportation in a hold is likely to be much less violent even in significant seas. As mentioned in the introduction, the samples as supplied had already been shipped, trucked and flown a very significant distance, which could be taken as substitute for the transportation in the hold.

Tests 1 and 2 suggest that when the nodules are not mixed with water and freely and vigorously tumbled:

- they will exceed the -10 mm coarse threshold within an hour.
- it takes two hours of tumbling to exceed the -1 mm fine threshold (Figure 4-90, Figure 4-91).

These test results can be used to help constrain what might happen with dumping the nodules in a hold or hopper. It has been estimated that during the transportation process to the ore bulk freighter (i.e., after the nodules have reached the production vessel) the nodules will be dumped several times for a total of 35 metres which is roughly the equivalent of the tumbler turning 11.7 times (~40 seconds). Total time for dry transport including conveying has been modelled to only be 2.5 minutes (see section 4.8.4.3 below).

Therefore, if nodules were only transported dry, they very likely would remain “Group C like”.

The -10+1mm sized fraction nodules are prone to breaking more easily when dry than when mixed with water as the water cushions the nodules.

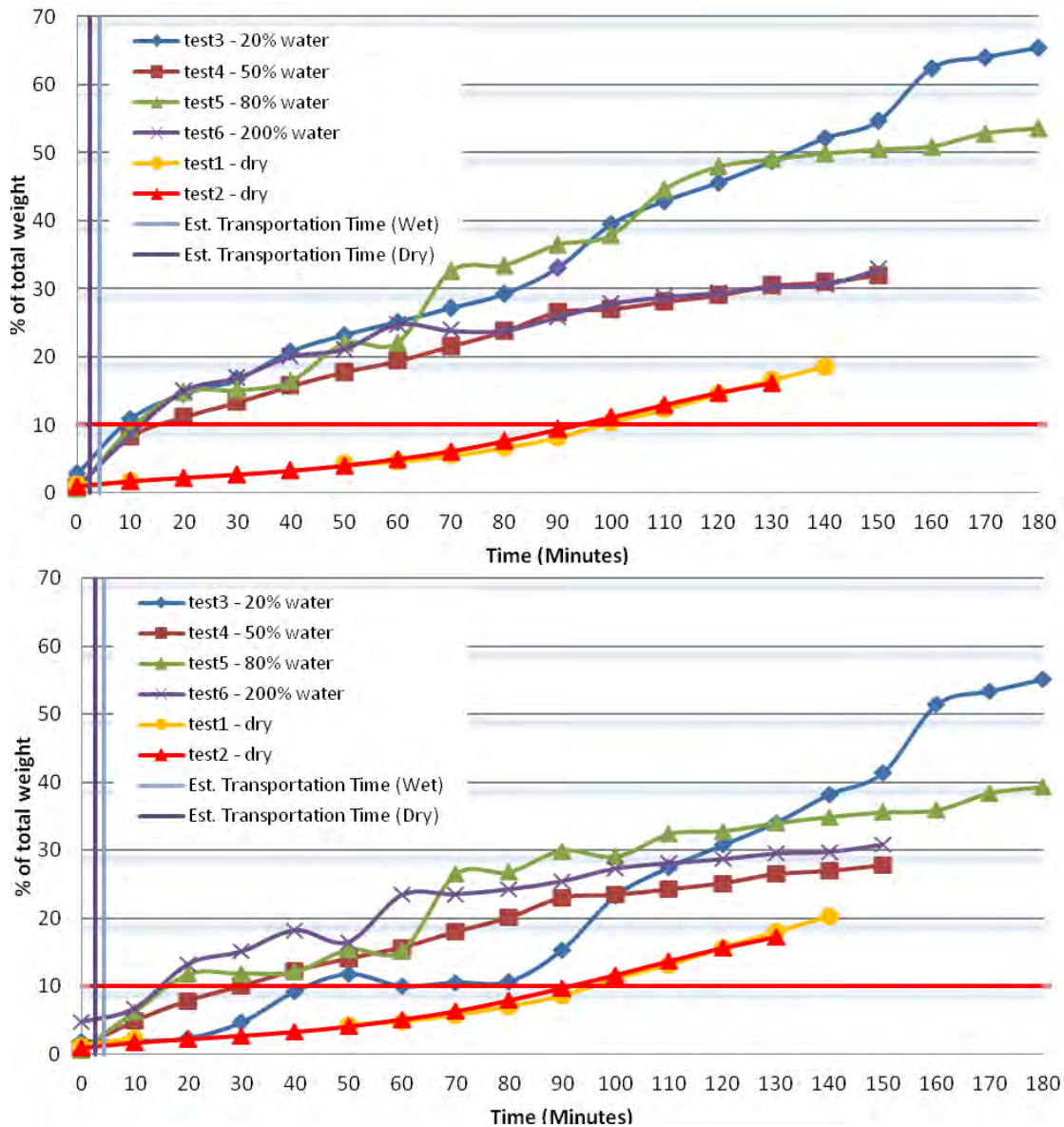


Figure 4-90: Results for all tests -1mm nodules, with average transportation time boundary (wet and dry). Upper chart includes losses in the -1 mm fraction.

4.8.4.2 Discrete wet transport

Wet transport is considered here to involve pumping and dumping. Tests 3,4 and 6 suggest that when the percentage of water added to the sample is increased (from 20% to 50% to 200%):

- the time taken -10 mm fines to exceed the coarse threshold increases from ~80 minutes to ~120 minutes (i.e. the 20% water test results are intermediate to the dry test results; Figure 4-91)
- the time taken for -1 mm sample to exceed the fine threshold remains at about 10 minutes but might extend to 20 to 40 minutes if losses are not considered as shown in Figure 4-90;

It has been estimated that wet pumping transit time between a production vessel and a transport vessel would be about 3.7 minutes (at 900% moisture at 5m/s for a total of 1,100 metres). Total transit including dumping into hoppers and holds and conveying on the vessel is 4.3 minutes (see section 4.8.4.3 below).

Therefore, if nodules were only transported wet under these estimated conditions, they very likely would remain “Group C like”.

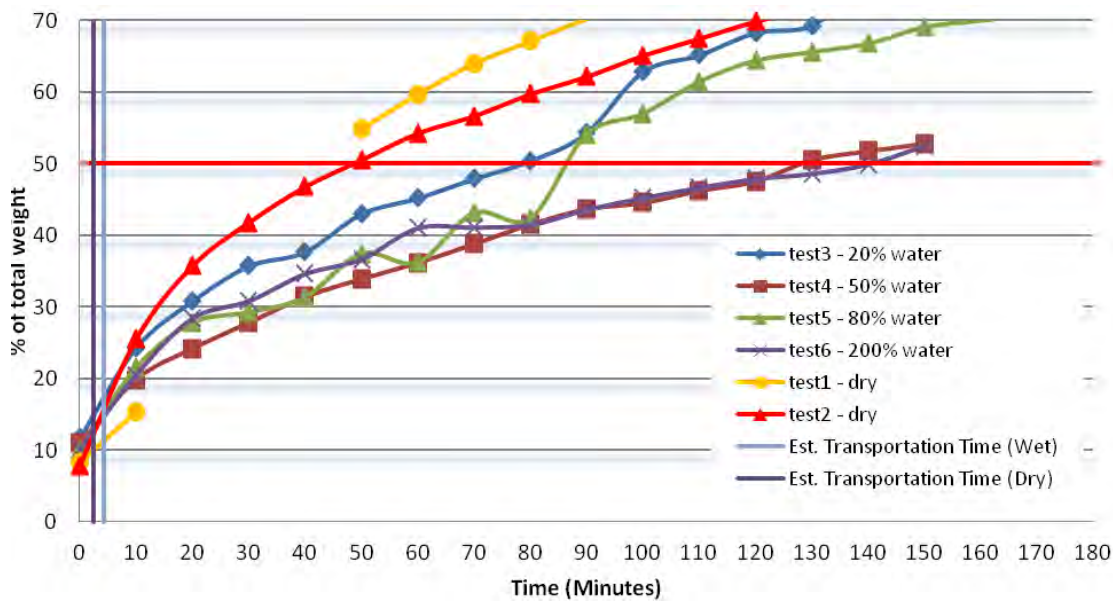


Figure 4-91: Results for all tests -10 mm nodules, with average transportation time boundary (wet and dry)

Although the test results discussed above are encouraging, two specific issues need to be considered further.

1. A combination of wet and dry transportation causes the nodules to exceed the +10mm and --1 mm boundaries at different points of the transportation chain.
2. Separation of fines from coarser material could lead to partial slumping of the cargo as part of the cargo would exceed both +10 mm and -1mm boundaries.

These issues are discussed briefly below which is all that is reasonable prior to specific design and testing of an ore transport system.

4.8.4.3 Transport modelling and combination of wet and dry transport

Three estimates of transport (and presumably attrition fines generation) times through a mining system are shown below in Figure 4-92. It was assumed that the sample as collected (dredged and hauled to the surface) was already through the process of seabed collection and lifting (via cable lift and skip). Thus, the modelled system is from the point of landing on the deck of the main mining vessel, transportation to holds, then lateral ship to ship transport to a bulk carrier before transport to the bulker holds. The three estimates are:

1. Dry only: some combination of belt conveyors, chutes and pneumatic pumping;
2. Wet only: use of hydraulic pump-conveying; and
3. Combination: with conveyors to the holds, and hydraulic pump-conveying between the vessels.

Dewatering was assumed to be done in the holds with bed drainage into sumps and bilges. There was no consideration of fines recovery and recycling.

Note that the time unit used is “attrition equivalent seconds” this is because as the exact timing of the process is unknown. In the case of vertical dumping the distance the material falls was equated to the distance it travelled in the trommel and the associated time. For horizontal belt conveying, pneumatic conveying and pumping transit speeds were assumed based on internet research and used to determine exposure times to attrition. The simple model in Figure 4-92 is included in Appendix 4G.

It is not known how representative the test work done here is of the attrition that would actually be experienced by a commercial scale nodule handling system, but in many cases, it seems likely that the attrition test work as described here would be more aggressive than what would be encountered in a commercial system (e.g. horizontal conveying should be relatively gentle, and hydraulic pumping would use a higher proportion of water (that would buffer the nodules more) than occurred in the wet trommel tests).

Assumed Model		Dry Transport	Wet Transport	Combination Transport
		2000 ft/min		
		610 m/min	5 m/s	
		1 m drop	1 m drop	
		1.14 secs	1.14 secs	
		seconds equivalent attrition	seconds equivalent attrition	seconds equivalent attrition
Dumped into hopper	5 m	5.7	5.7	5.7 (dry)
Conveyed to hold	100 m	9.8	20.0	9.8 (dry)
Dumped into hold	15 m	17.1	17.1	17.1 (dry)
Pumped to bulker transport	1000 m	98.4	200.0	200.0 (wet)
Dumped into bulker transport hold	15 m	17.1	17.1	17.1 (dry)
total equivalent attrition time (secs)		148.3	260.0	249.8
Total equivalent attrition time (mins)		2.5	4.3	4.2

*vertical dumping and horizontal conveying estimated via tumbling distance
pneumatic conveying and wet pumping time taken directly*

Figure 4-92: Modelled transportation time.
(after the ore has reached the production vessel)

Clearly the model expressed in Figure 4-92 is not especially sophisticated or precise but the modelled transportation times (wet, dry or combined) are all under 5 minutes (equivalent attrition) and could be as short as 2.5 minutes. These times are all much less than the shortest time it took for any wet sample to exceed the fine threshold and are an order of magnitude shorter than the time taken for any sample to exceed both fine and coarse thresholds and move from “Group C like” to “Group A like”.

4.8.4.4 Issue of separation of fines

Separation of fines from the coarse material could lead to a situation where part of the cargo moves from Group C like to Group A like and then slumps (Figure 4-93).

There are several explanations for granular convection, and the testing completed thus far does not indicate whether the nodules in the bulker would be prone to normal or reverse grading, but clearly it is an issue which needs to be explored further.

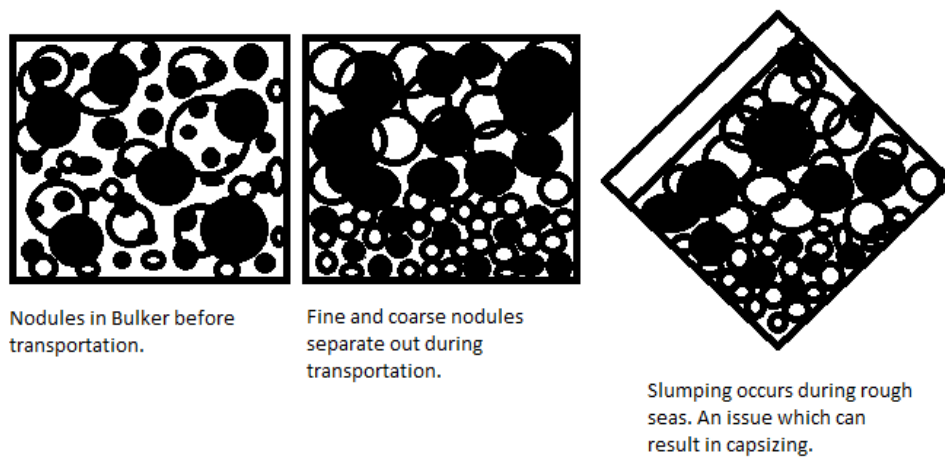


Figure 4-93: Illustration of the mechanism of separation of fines in a ship's hold leading to loss of stability

Picture drafted by B. Riada-Horn

4.8.4.5 Effect of more water in the nodule mass

The second objective of the test work was to better constrain how water content impacts on nodule attrition.

Figure 4-88 and Figure 4-89 suggest that moving from 0% to 20% to 50%+ water causes a change in nodule attrition with less damage to large pieces (interpreted as being due to some cushioning effect) but more damage in terms of producing fines (interpreted as being due to some degree of hydraulic erosion).

However, for >50% water there seems to be little further change (although the +80% water test had issues). This area needs further work especially at the circa 900% water content that pumped slurries are understood to contain. The testing would better be done in a pump circuit rather than in the sealed trommel used for this study.

4.8.5 Conclusions and Recommendations regarding the attrition fines testing

It is concluded that:

- The sample as received already had suffered attrition from the dredging lifting and transportation process to the lab. This amount of attrition is taken to represent what would occur during mining, and lifting, and although the sequence is different also what would occur during bulker transport from the PSV to market.
- The nodule samples as received before testing classify as Group C if they are considered as Iron Ore Fines per MGN 514 (M).
- After 100 minutes of relatively aggressive dry attrition two nodule samples moved from Group C like to Group A like.
- After 80 to 130 minutes of relatively aggressive wet attrition several nodule samples moved from Group C like to Group A like.

- Simple models of the attrition times nodules would endure during mining suggest that this would be an order of magnitude less than it would take them to move from Group C like to Group A like.
- The quickest threshold to be exceeded in terms of size distribution is the -1 mm fraction during wet attrition.

It is recommended that:

- In due course an expert group, under auspices of IMO, do a first principles study on safe transport of polymetallic nodules;
- Nodules be considered as Group C like for the purposes of ongoing mining concept studies (i.e., TML testing prior to loading is not required whether or not wet or dry transportation on the mining vessel and to the transport bulker is considered);
- That fines management during any wet transportation on the vessel be accommodated for in the design (i.e., fines measurement and fines separation);
- Future tests include higher proportions of water in a pump cycle as well as a test to see if fines and coarser nodules are likely to separate out during transportation in a hold.

4.9 Packing factor

Packing factor is the ratio of particles to void when the particles are stored in a container. Its inverse is called packing density, and both terms are routinely used in materials handling. While polymetallic nodules have a wet density of $\sim 2 \text{ g/cm}^3$ this is for the substance, i.e. an equivalent bulk density includes the voids and thus is usually a significantly lower figure. The bulk density of nodules will vary depending on whether the voids are filled with water (in a buffer or skip) or filled with air (in a ship's hold after draining of water from the voids), but the packing factor should not change if there is no change in particle sizes (say due to attrition).

Theoretical packing factors/packing densities, are available from literature (e.g. Table 4-20), but no nodule specific numbers are known to have been published.

Table 4-20: Example packing densities

Particle shape	Random close packing density
Spheres	0.60-0.64
Cubes	0.76
Parallelepiped (4.0 & L/D & 8.0)	0.51-0.67
Disks (L/D = 1)	0.63
Spheroids (0.6 & L/D & 1.3)	0.58-0.61
Rounded Aggregates	0.59-0.63
Crushed Aggregates	0.50-0.57
Fibres (L/D = 10)	0.48
Fibres (L/D = 167)	0.03

Source: (Chateau, 2012)

A short test program was developed to measure packing factor from TOML dredge samples.

4.9.1 Methods for estimating packing factor

- Two ~50 l punnets of dredge samples were selected: 1) smaller nodules from TOML Area A and 2) larger nodules from TOML sub-area F1 (Figure 4-94). A larger sample in a punnet would provide a more accurate estimate than a smaller bucket.
- As the dredge samples are likely to have dried somewhat, the punnets were filled with water and left overnight, then excess water removed, i.e. roughly 50% of the top layer of nodules just exposed and 50% just submerged (Figure 4-95).
- The entire punnet was weighed (tare 2.75 kg for an empty punnet), then drained and weighed again. The water was collected in buckets (tare 0.65 kg) and weighed separately.

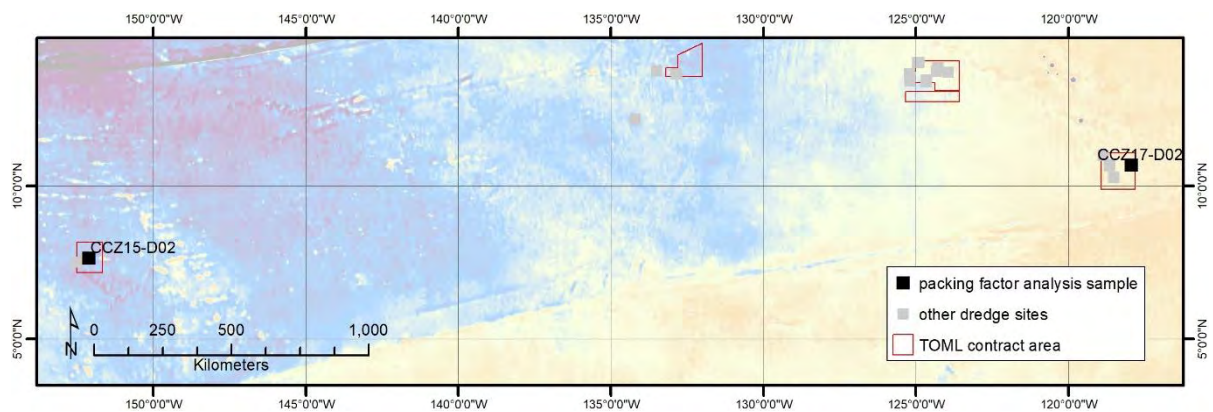


Figure 4-94: Packing factor test sample locations



Figure 4-95: Packing factor test samples

Left is the sample from TOML F1 it is I-RS type; Right is the sample from TOML A it is s-S type.

4.9.2 Result of packing factor measurements

Using the known density of nodules (refer section 4.6 above) packing factors are estimated per Table 4-21.

Table 4-21: Packing factor test results

TOML Area/Sub-Area	Sample Number	Dredge	Water weight (kg)	Nodule weight (kg)	Water Volume (1000 cm ³)	Nodule Material Volume (1000 cm ³)	Packing Density (volume)	Packing Factor (volume)
F1	26522	CCZ17-D02	22.7	70.95	22.7	36.385	0.616	1.624
A	28570	CCZ15-D02	20.4	80.05	20.4	41.051	0.668	1.497

Considering the samples have included a range of particle sizes, the results compare well with the packing density of other materials e.g. per Table 4-20. Clearly the smaller nodules pack significantly closer (~8%) than the larger more irregular nodules.

4.10 Conclusions and Recommendations arising from Chapter 4

In this chapter, some key physical and chemical properties of polymetallic nodules are presented that help constrain their character and formation at regional and local scales. These will assist future works and research including better evaluating their distribution and performance if commercial mining progresses. The work is based on samples of nodules from the TOML contract area and in places refers or compares to other nodules, including box-core samples of nodules from the NORI D and Marawa areas. The TOML nodules come from sites spanning up to 80% of the length of the CCZ, and much of its breadth.

After a summary of the current published dialog on the formation mechanism and mineralogy of CCZ type nodules, it is noted that nodule types across the CCZ vary more than local classification systems can handle. After review of a range of published systems the author added several size and textural qualifiers to the International Seabed Authority (2010a) classification, that was originally devised for this scale of application. Local scale classifications have merit when used locally, and the system used for NORI area D transfers well to adjacent TOML area F.

Strongly prolate nodules can often be found with their long axes in apparently random orientations. However, a case history from a photo-profile over a ridge in TOML B1, shows that prolate nodules can grow aligned along contour lines in situations where there is evidence for longitudinal currents (i.e., contourite sediment drifts). For future work, a more thorough study (that would require access to other photo profile datasets with prolate nodules) would be of benefit.

The small 'facies scale' of forms and size distribution of nodules are interpreted to relate to the influence of currents, and to a lesser extent other mechanisms, within the context of the stability of the host geochemically active layer. Most nodule forms can thus be explained by the simple interaction of thickness and stability of the geochemically active layer. After careful consideration of all apparent factors, biological activity is the most obvious explanation for why nodules remain at the seabed surface. An obvious avenue for future work is a self-consistent geometric-mass-energy balance model that can account for the above-mentioned factors. Micro-chemical analysis indicates that nodules only start to grow under sub-oxic conditions.

A final contribution from this section is a more complete documentation of the diagenetic crusts found in the CCZ (e.g., from TOML A and TOML D) but rarely documented. These crusts are a natural end member of the mechanisms of nodule formation, namely the cases where stability in the geochemically active layer (including bioturbation) is sufficient to allow ferro-manganese precipitates to amalgamate.

Following a synthesis of published work on nodule mineralogy, new electron microprobe and QEMSCAN results are presented and contextualized. This includes more unpublished data on the proportion Fe vs Mn rich phases (vernadite and buserite) that define the growth rings that typify these nodules, as well as observations regarding the disposition of key metals and various other phases, most notably interstitial smectite, and zeolite and an encapsulated remnant calcite-?barite phase. Future work could involve a more systematic study

Nodule chemistry is studied from a range of sources but focuses on new multielement chemistry from box-core data from the sub-areas TOML B, C, D, F, NORI D and Marawa 19,20. This work:

- places the CCZ nodules (including new box-core sample data), exactly as classified by past workers (mixed oxic and sub-oxic conditions of formation);
- shows that the TOML, NORI and Marawa samples have remarkably low variance in grade within areas and extending bulk (dredge) samples;
- indicates that there are six very clear main element groupings in terms of inter-correlation (in effect phyllo-manganate association; silicate association, barite association, apatite association, cobalt and similar, REE and other transition elements). This helps frame any discussion on geochemical characterization and genesis;
- recognises chemical variation at regional scales (between contract sub-areas sampled with box-cores) and at local scales (within given sub-areas).

While the regional variation in chemistry has been noted and studied prior (Mn, Ni, Cu, Co), the multi-element chemistry from the TOML/NORI/Marawa box-core samples is new. Specifically, the behaviour of elements like Ce, Ti, Ba, Ca, Al, Si, Sr and Th, alone and normalized to Fe show that Co grades trends in the CCZ are almost entirely decoupled from those for Ni, Cu, Mn and that for Fe. It is argued that CCZ mineralization is fed by variably blended contributions from calcite bio-productivity (e.g., foraminifera, coccoliths) and silicate bio-productivity (e.g., radiolarians, diatoms) with the silicate contributions being offset to the north of the calcite contributions (likely due to the circum-pacific North Pacific Current meeting the North Equatorial Current).

This is clearly an area that needs to be more rigorously tested on the basis of more systematic purpose collected data, perhaps incorporating mass-balance type calculations, with the very complex nature of silicate-ocean chemistry a challenge.

Chemical variations at the local scale can be distinct or more emphasized than the regional scale variations.

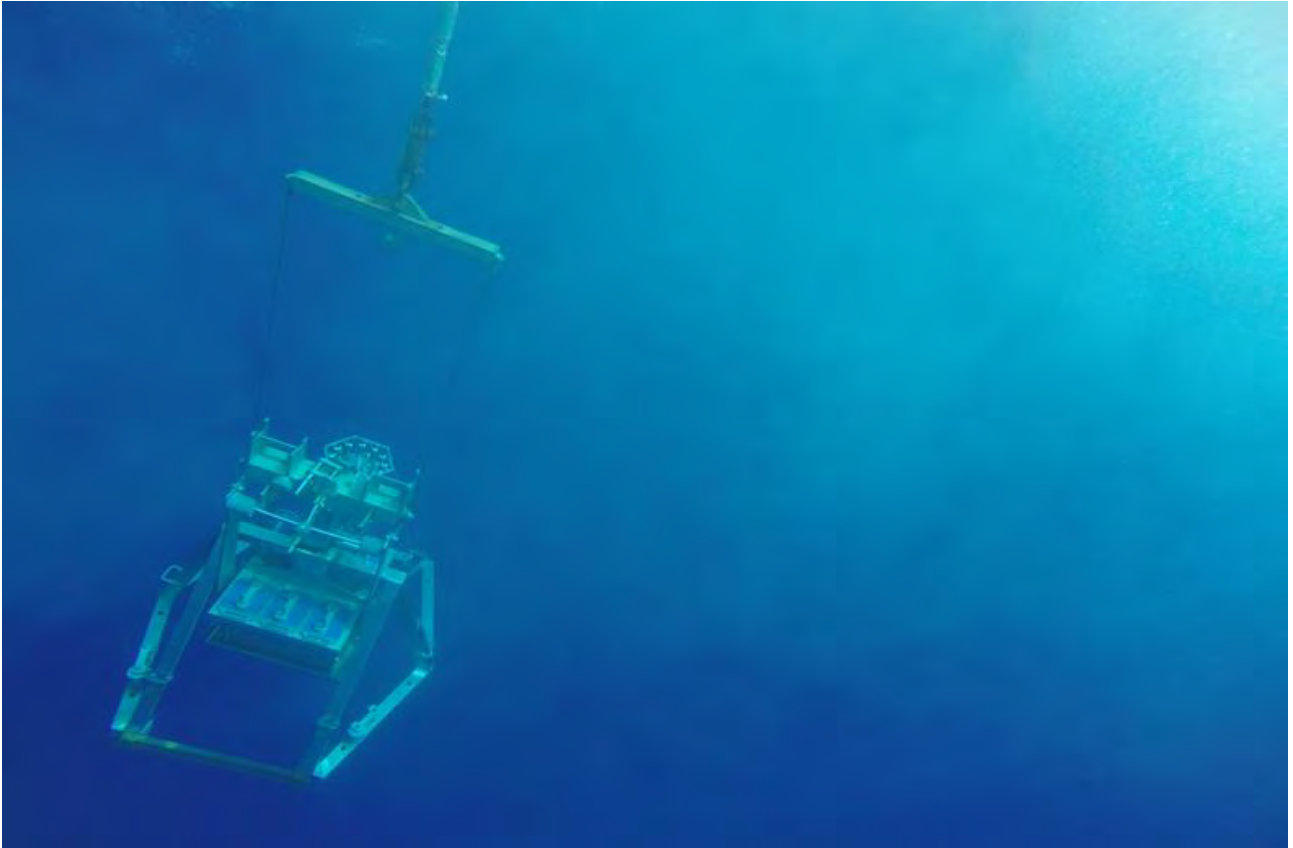
- Within the TOML-F/NORI-D areas there are south to north ($\pm 45^\circ$) changes in a range of elements, most notably Ca. This extends in some cases to sediment chemistry, which is available for some elements for part of the NORI D area. The likely cause is declining primary productivity with increasing latitude and seabed net export moving north from the equator and deeper north of Clipperton Fracture Zone. This variation matches a change in multibeam backscatter response mapped in Chapter 3. Local trends in Cu and Fe are weak but there is a clear correlation with nodule types in this area, with type 2 (RS) nodules having higher Cu and lower Fe reflecting varied hydrogenetic vs diagenetic formation.
- A somewhat enigmatic local scale trend in TOML B, is deduced to be possibly due to common inclusion of volcanic fragments in nodules coupled with regionally higher silicate bio-contributions.

- The chemistry of diagenetic crusts collected from TOML A and TOML D shows them to be quite distinct from each other, with the TOML A crusts (and some nodules) containing higher Ca, P (i.e. likely biogenic apatite) and Ti (exotic mineral component), while the TOML D crusts have higher Ba (origin unclear). Future work could include more detailed logging and analysis of the components in these dredge samples, perhaps extending to microprobe analysis.

The results of a series of physical tests on nodules comprises the next part of the chapter. While these vary widely in terms of detail and methodology, they combine to provide an essential first look at some of the nodule characteristics that would need to be considered by future nodule developers, and that do not appear to have been publicly addressed in detail to date. Some points:

- Within a tight range, nodules have a wet density of slightly under 2 g/cm³ with TOML B, C and D averaging 1.98 g/cm³ and TOML F 1.93 g/m³.
- Sediment densities (± 1.2 g/m³) follow a similar trend with TOML B and C sediments slightly denser and increasing more rapidly with depth than TOML D with a similar change again then to TOML F. Slightly less consolidation time and higher bioturbation in the southern and eastern areas are the interpreted reasons.
- Moisture content in nodules comprises around 28% free water and 16% water of crystallization;
- Air drying removes about 7 to 20% of total moisture, with most of this achieved within the first 200 hours and nodule type playing a key role in the differences (smooth type nodules losing less than rough-smooth type). Ambient humidity can vary results by at least 2 or so percent. After oven drying, up to 7% moisture can be reabsorbed in 18 hours for nodules and fragments, and as much as 10% for pulped samples.
- Nodules stored in water at the surface under-go some decompression (likely related to mineralogical and associated micro-fractures) and can absorb an additional 1 to 6% moisture.
- Drying nodules to 105° C prior to chemical analysis is an acceptable compromise with regards to industry standards, when mineral transformations and losses of different water types are considered.
- While starting off solid and stable, nodules have the propensity to crumble when tumbled under wet or dry conditions. This eventually can lead to a potential transport safety risk via slumping of cargo in the hold of bulk carriers due to a high proportion of fines. When handled dry, particles break more, and when handled wet, particles abrade more. Nodules can be considered per iron-ore fines guidance as they have more in common with iron-ore fines than other bulk commodities. Per this guidance dry only or wet only handling takes 1 to 2 hours to exceed tolerance thresholds. A combined wet and dry handling could however cause more rapid exceedance (1 hour or less), so the detail of handling needs to be considered in any future work, as does possible separation of finer and coarser particles in holds and any testing involving hydraulic risers.
- Nodules have packing densities of around 0.61-0.67 depending on nodule particle size distributions.

While by no means exhaustive, the key physical and chemical properties of polymetallic nodules presented here helps constrain their character and formation at regional and local scales, with clear future avenues for research. The properties are useful in the estimation of Mineral Resources (Chapter 5), and in conjunction with other modifying factors (e.g., Chapter 6), should assist in the estimation eventually of Mineral Reserves.



Box-corer sampler on recovery to the R/V Yuzhmorgeologiya, eastern CCZ, October 2015.

Photo credit: Rod Conroy.

5 Aspects of estimation and reporting of mineral resources of seabed polymetallic nodules: A contemporaneous case study

This chapter comprises a paper published in a special issue of the journal *Minerals*, titled *Exploration of Polymetallic Nodules*. The paper's background was the preparation of two Canadian National Instrument standard technical reports for the TOML contract areas. These reports included pioneering work, as they were the first mineral resources for polymetallic nodules estimated and reported to:

- a contemporary standard i.e. (Committee for Mineral Reserves International Reporting Standards, 2020); and
- to the highest level of confidence in estimation possible at this contemporary standard (i.e., Measured Mineral Resource).

Amongst other things, the author provided or led sampling and geological input into the two reports. Most of this input having been included in the subject matter covered in the earlier chapters of this thesis.

A good mineral resource estimate is one that is material, transparent and competent (as covered in the chapter/paper below). It is not complicated or overly precise, as this often works against transparency, with no material improvements in accuracy. Accuracy needs to be in the context of prospects for eventual economic extraction (should that occur), the precision of which is often considered in terms of months of production (i.e., hundreds of thousands of tonnes).

Mineral resource estimation in polymetallic nodules is a still evolving field e.g. (Ellefmo and Kuhn, 2020; Lipton et al., 2021; Yu and Parianos, 2021), and some of the latest developments are also covered in the paper. Ultimately the most significant contribution from the author involves helping establish what aspects of the geology were found to be truly material, in quantifying the remarkable mineral deposit that is the CCZ.

Article

Aspects of Estimation and Reporting of Mineral Resources of Seabed Polymetallic Nodules: A Contemporaneous Case Study

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Abstract: Exploration of seabed polymetallic nodules identifies the Clarion Clipperton Zone and the Indian Ocean Nodule Field to be of economic interest. Mineral resource estimation is important to the owner of the resource (all of mankind; and managed by the International Seabed Authority; ISA) and to developers (commercial and government groups holding contracts with the ISA). The Committee for Mineral Reserves International Reporting Standards was developed for the land-based minerals industry and adapted in 2015 for ISA-managed nodules. Nodules can be sampled in a meaningful manner using mechanical devices, albeit with minor issues of bias. Grade and moisture content are measured using the established methodology for land-based minerals. Tonnage of resource is determined via the abundance of nodules in kilograms per square metre of seabed. This can be estimated from physical samples and, in some cases, from photographs. Contemporary resource reporting for nodules classify the level of confidence in the estimate, by considering deposit geology, sample geostatistics, etc. The reporting of estimates also addresses reasonable prospects for eventual economic extraction, including factors such as mining technology, the marine environment, metallurgical processing, and metals markets. Other requirements are qualified persons responsible for estimation and reporting, site inspection, and sample chain of custody.

Keywords: polymetallic nodules; mineral resource estimation; mineral resource reporting; CRIRSCO; seabed geology; geostatistics

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1. Introduction

The estimation and reporting of mineral resources and their exploitable subsets, e.g., mineral/ore reserves, provide important information for the owners of the minerals, the owners of groups with development rights, and other stakeholders. We report here on aspects that we found important in producing some of the first contemporary mineral resource estimates for polymetallic nodules.

There are extensive deposits of high-grade polymetallic nodules resting on the seabed within the Clarion Clipperton Zone (CCZ) in the Pacific Ocean and the Indian Ocean Nodule Field (IONF) (Figure 1; International Seabed Authority [1], Mukhopadhyay et al. [2]). Recent interest in developing these resources has resulted in efforts to advance questions of mineral rights (e.g., Watzel et al. [3], Toro et al. [4], Hein et al. [5]).

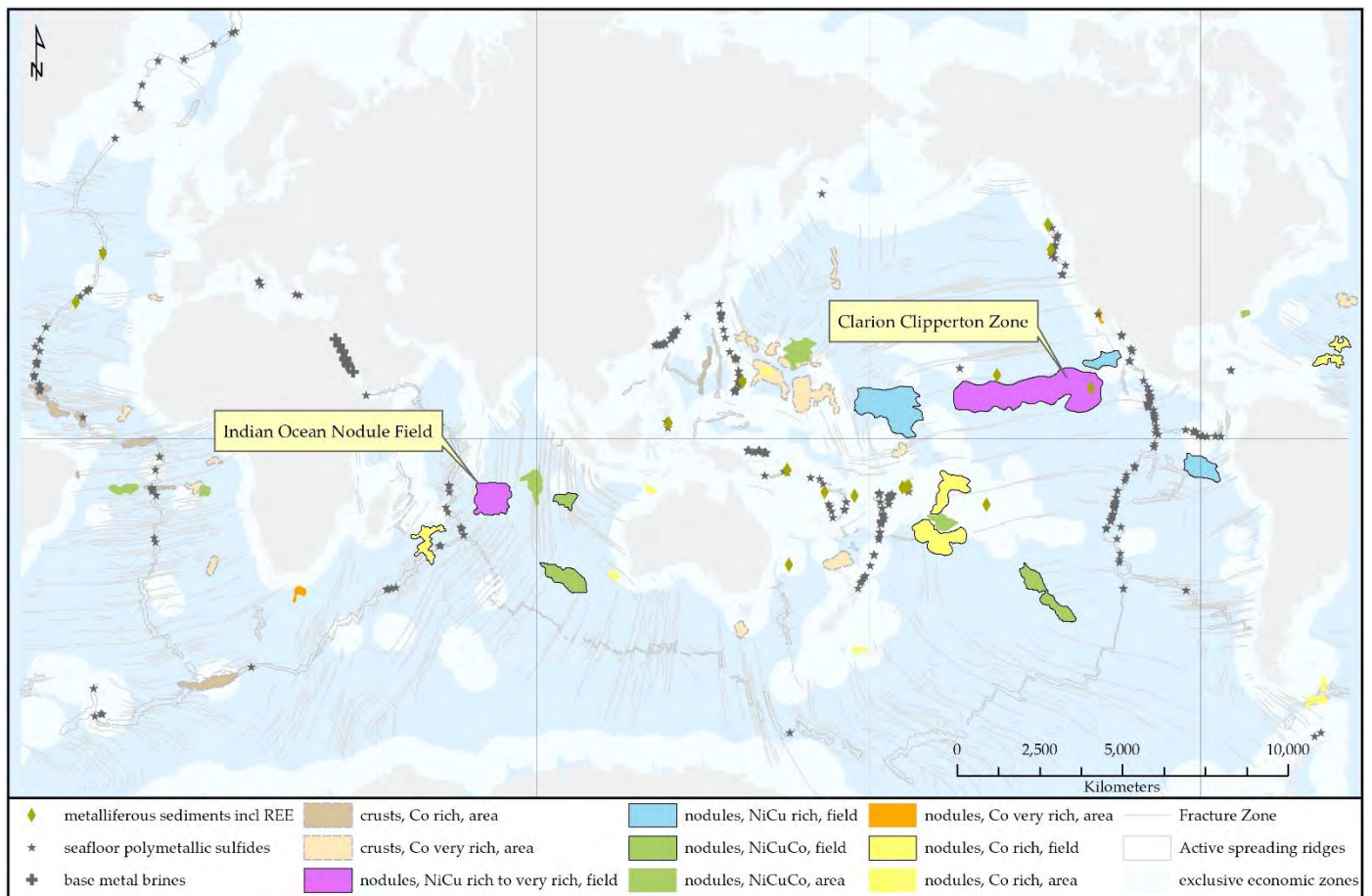


Figure 1. Locations of the Clarion Clipperton Zone and Indian Ocean Nodule Field. Adapted from Andreev et al. [6] and Matthews et al. [7]. Rich Co is generally $>0.4\%$, very rich Co is $>0.8\%$, NiCuCo is $0.7\text{--}1.7\%$ Ni + Cu, rich Ni-Cu is $>1.7\%$ Ni + Cu, and very rich Ni-Cu is $>2.5\%$ Ni + Cu; the fields are better constrained from sampling than the areas.

1.1. Mineral Owners

These deposits are located on the seabed within international waters, and ownership of the minerals cannot be directly attributed to any particular nation (as is typically the case on land). At the United Nations in 1972, ownership of these minerals was declared as “The Common Heritage of Mankind”, and a protracted process of defining international law to manage such minerals commenced [8]. The third United Nations Conference on the Law of the Sea (1973–1982) led to the United Nations Convention on the Law of the Sea (UNCLOS) of 1982 and the agreement adopted by the General Assembly of the United Nations in 1994 relating to the implementation of Part XI of UNCLOS. UNCLOS assigns the responsibility to organise and control activities in “the area” beyond national jurisdiction to the International Seabed Authority (ISA), especially regarding exploration and mining of the minerals; equitable distribution of the proceeds; adequate protection of the marine environment; protection of land-based industry (anti-dumping and anti-competition); and promoting development opportunities for citizens of developing states and marine scientific research [9]. State-owned or state-sponsored commercial enterprises can complete preliminary research on unclaimed seabed, and then apply for an exploration contract, with one condition being that they supply data for an area of equal quality that is then reserved for “Contractors” sponsored by developing states.

The ISA envisages that qualifying entities will convert part or all of their exploration contracts to exploitation contracts and will mine, process, and sell nodules and/or their derived metal products. These entities will pay fees, royalties, and taxes to the ISA and the nations in which they are located and who sponsor them. Remittances to the ISA will

then need to be suitably dispensed to the mineral owners. The reporting of mineral resources and, in due course, mineral/ore reserves to modern international standards has thus become topical and of increasing importance (Madureira et al. [10]).

It is worth noting that countries that have not signed and ratified UNCLOS do not recognise UNCLOS’s provisions. Most notably, the United States has issued its own seabed licenses for polymetallic nodules within the CCZ, albeit so far without any overlap with the ISA contracts or reserved areas (National Oceanic and Atmospheric Administration [11], Lipton et al. [12]).

1.2. Mineral Developers

At the time of writing, the ISA has issued 30 exploration contracts for deep-sea minerals (polymetallic nodules, polymetallic sulphides, and cobalt-rich ferromanganese crusts (ISA [13]), including 18 for polymetallic nodules, 16 in the CCZ, one in the IONF, and, most recently, one in the Prime Crust Zone (Figure 1). The contract holders are mostly national ministries or nationally owned entities, but in the case of CCZ polymetallic nodules, seven commercial entities are also included.

A recent revival of commercial interest in polymetallic nodules in the CCZ (Figure 2) has been driven by the improvement of metal prices in the 2000s, the expected increased demands for battery metals, the proposed release of exploitation regulations, and improvements in subsea technology (e.g., Sparenberg [14]). Any entity seeking or providing project financing will very likely need estimates of the mineral resources and mineral/ore reserves to be compiled and reported to modern international standards.

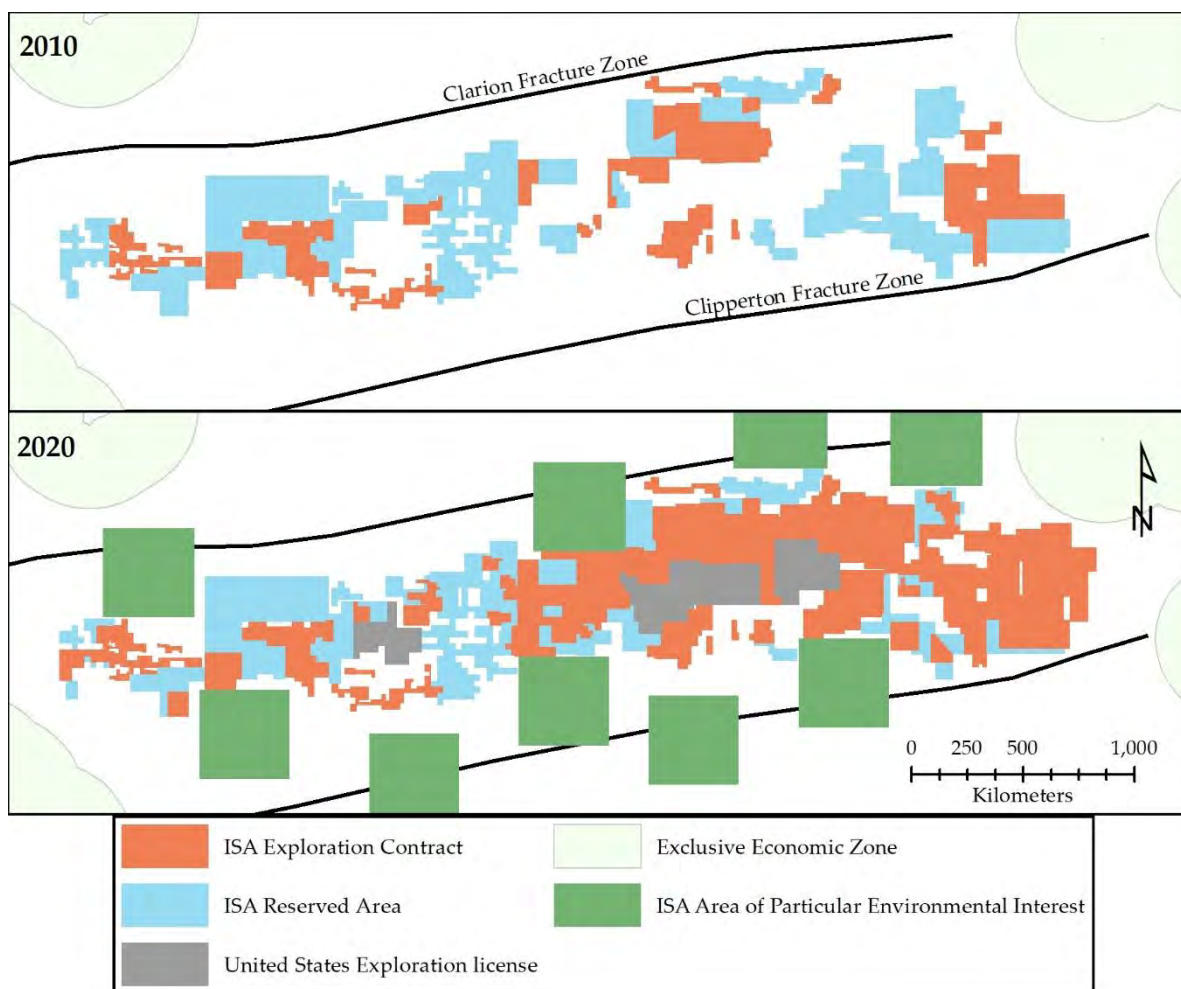


Figure 2. Growth in seabed claims in the CCZ. Sources: International Seabed Authority (ISA) [13], National Oceanic and Atmospheric Administration [11], and Marine Regions [15].

1.3. Reporting Rules

In many countries, the public reporting of mineral resources is regulated by formal codes or legislated instruments. The first formal code of this type among free-market economies was the Australasian Code for Reporting of Exploration Results, Mineral Resources, and Ore Reserves (the JORC Code), published in 1989 by the Joint Ore Reserves Committee of the Australasian Institute of Mining and Metallurgy and the Minerals Council of Australia (JORC). This code established several key criteria that should be addressed in public reports by companies listed on the Australian Securities Exchange (ASX). The code is explicitly guided by the principles of:

- Materiality;
- Transparency;
- Competence and responsibility.

The Committee for Mineral Reserves International Reporting Standards (CRIRSCO; [16]) was formed in 1994. CRIRSCO initially comprised an informal alliance of national reporting organisations such as JORC and has since evolved into a formally constituted committee with governing terms of reference. It has become the principal organisation coordinating the international mining industry on issues relating to the classification and reporting of mineral assets and is recognised by a range of global organisations, including the United Nations Economic Commission for Europe (UNECE) and the International Council on Mining and Metals (ICMM). There are currently 14 member regions and countries with mineral resource reporting codes within the CRIRSCO family (Figure 3).

Since 1989, the JORC Code has evolved, as have the other similar codes around the world (JORC [17]). In Canada, the Canadian Institute of Mining (CIM) publishes a guide to reporting on mineral resources and mineral reserves, which is updated periodically (CIM [18–20]). The other codes in the CRIRSCO family are very similar, and CRIRSCO draws on the various reporting standards to define an international reporting template (CRIRSCO [21]).



Figure 3. Map of member coders Committee for Mineral Reserves International Reporting Standards (as of August 2019). Source: Committee for Mineral Reserves International Reporting Standards [16].

The Canadian government, wishing to provide more clarity for investors, enacted National Instrument 43-101 (NI43-101), which sets strict rules for the reporting of mineral resources and mineral reserves and requires the CIM code to be followed for Canadian listed companies. Similar requirements exist in other countries or their stock exchanges.

A fundamental feature of the CRIRSCO family of codes is that they do not prescribe how a mineral resource should be sampled or estimated; instead, they set expectations as to what aspects of the data and estimation methods should be addressed in the mineral resource reports.

Estimating the sizes of seafloor polymetallic nodule deposits, especially at higher confidence levels (Figure 4), entails particular challenges because of their remote locations and inaccessibility for direct inspection due to the depth of seawater. There are also no terrestrial analogues to provide comparative data and precedents. Exploring and sampling deep-sea mineral resources is expensive, and the deposits are not amenable to the sampling methods typically used to define terrestrial deposits. To date, no commercial-scale mining operations have been attempted for the recovery of seafloor polymetallic nodules, although pilot-scale mining has been successfully completed. Consequently, satisfying the requirements of international mineral reporting codes, based on the relevant experience of the competent person or qualified person (QP) and the reasonable prospects of economic extraction, cannot rely on direct precedents.

This paper summarises some of the key issues related to determining mineral resource estimates of polymetallic nodules and reporting them to the CRIRSCO standard. This study necessarily focuses on the CCZ, as this is the first area for which Mineral Resource estimates have been compiled and reported publicly. It discusses the public reporting requirements under the Canadian National Instrument 43-101 (NI43-101) and how these requirements were addressed by the QPs. For a more detailed presentation of the sampling data and estimation methods, the reader is referred to the published mineral resource estimates, such as those by Nimmo et al. [22], Lipton et al. [12], DeWolfe and Ling [23], Lipton et al. [24,25].

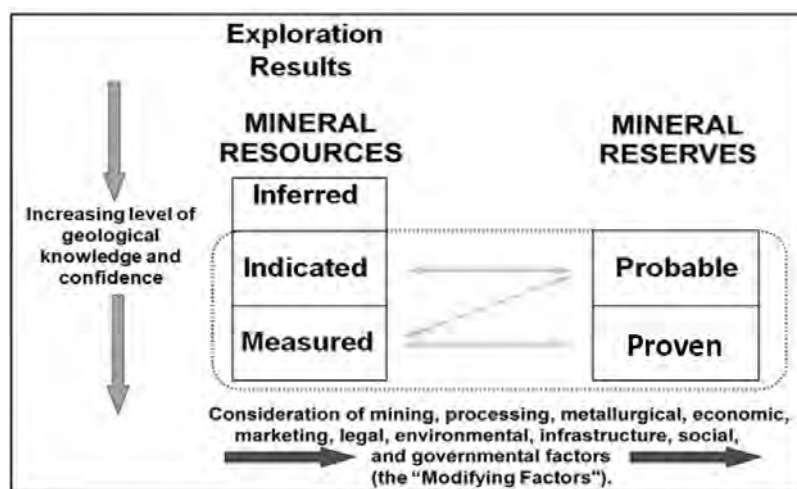


Figure 4. Levels of confidence and relationships for NI43-101 mineral resources and mineral reserves. Source: Canadian Institute of Mining Metallurgy and Petroleum [19].

2. History of Evaluation of Polymetallic Nodule Deposits

The occurrence of seabed nodules has been known since the mid-1800s (Murray and Renard [26]), and perhaps the first realisation that nodules in the region of the CCZ might be of economic interest was published in 1958 (Menard and Shipek, [27]). However, the first known published estimate of the size of the CCZ deposit was by Mero [28], who estimated 1656 Bt for the entire Pacific from a set of 29 photographs, 10 dredges, and 62 box cores (Mero did not specify the wet or dry weights; instead, wet tonnes were commonly quoted in early work, as wet sample mass is more easily measured at sea). Mero was clear on the sparsity of his dataset and provided ranges of nodule abundance.

Mero's work helped to spark a boom in the exploration of nodules through the late 1960s and 1970s [12]. There are no known published mineral resource estimates from this

era. Explorers quickly focused on the Clarion Clipperton Zone (CCZ) and Indian Ocean Nodule Field (IONF) due to their higher abundances and higher metal grades, as indicated by initial sampling.

In 1982, the United Nations Ocean Economics and Technology Branch issued an assessment of manganese nodule resources [29] that included a systematic discussion on the available data types and estimation methodologies. This assessment included short summaries of global and CCZ-focused estimates of mineral resources, including those of Pasho and McIntosh, Bastien-Thiry et al., McKelvey et al., and Lenoble [30–33].

Pasho and McIntosh's [30] assessment of the recovery of polymetallic nodules involved Monte-Carlo simulations. These analyses were driven by a then-proposed mining methodology, whereby a towed collector is towed repeatedly at different headings in a given area with very limited seafloor steering control (T. Brockett 2016 pers comm). The simulation aimed to predict when recovered nodule volumes would become uneconomic due to a high proportion of the collector re-covering his or her old tracks with few—if any—remaining nodules.

Lenoble ([33]) presented a careful consideration of modifying factors to convert a mineral resource into a mineral reserve (albeit not to any current code).

In 2002, Kotlinski and Zadornov [34] published the average grades and abundances for the contract area held by the Interoceanmetal Joint Organization (sponsored by Bulgaria, Cuba, Czech Republic, Poland, Russian Federation, and Slovakia) and described variation by latitude.

In 2003, the ISA convened a special workshop for Contractors and other experts (e.g., [35–37]) who pooled their data (>10,000 data points) and expertise, enabling the mineral resources for the entire CCZ to be estimated by the ISA. This estimate was updated in 2010 [38]. Using different approaches (based on sample statistics and considering a biochemical model), an Inferred Resource of between 21.1 and 30.7 Bt was estimated for the entire CCZ. None of the ISA estimates were reported using an internationally recognised code.

For the Federal Institute for Geosciences and Natural Resources of Germany (BGR), Ruhleman et al. [39] reported a table of “basic values... including averaged bulk nodule metal contents”, including 795 Mt (dry) @ 1.3% Ni, 1.1% Cu, 0.17% Co, 7.0% Fe, and 29.2% Mn within 58,000 km² for their E1 area.

The first mineral resource estimate for deep-sea polymetallic nodules reported in compliance with a CRIRSCO code was published in 2013 for Nautilus Minerals by Nimmo et al. [22]. The authors issued an NI 43-101 Technical Report documenting an inferred mineral resource of 410 Mt (wet) @ 1.2% Ni, 1.1% Cu, 0.24% Co, and 26.9% Mn. This was within an area of 51,891 km² held under contract by Nautilus subsidiary, Tonga Offshore Mining Limited (TOML). This estimate was followed up in 2016 by Lipton et al. [12] under the same codes with mineral resource estimates to inferred, indicated, and measured levels of confidence. Much of this work forms the basis of the present paper.

In late 2014, the ISA convened a workshop with subject matter experts and existing mineral rights holders (called Contractors; see Table 1) to better understand the status of the polymetallic nodule mineral resources and establish a standard for reporting within the area [40,41]. The standard could then be used by Contractors in complying with their obligations to annually report their exploration activities. This workshop led to the ISA adopting the CRIRSCO guidelines as their reporting standard and specific guidelines being published for the estimation of mineral resources for polymetallic nodule deposits.

Table 1. Summary of CCZ mineral resource estimates from the ISA 2014 workshop.

Contractor	Tonnage	Abundance	Grades	Comments
State Scientific Center Yuzhmorgeologia [42]	448 Mt (dry)	Not provided	1.39% Ni 1.1% Cu 0.23% Co 29.3% Mn	Used classification of State Commission on Mineral Reserves of the Russian Federal Government Agency
Korea Institute of Ocean Science and Technology [43]	188.4 Mt (?dry)	10.4 kg/m ² (?dry)		Relates to a Priority Mining Area (PMA) with an area of 18,113 km ² and an estimate that 60% is mineable
Deep Ocean Resources Development Co Ltd. [44]	643Mt (wet)	8.57 kg/m ²	1.35% Ni, 1.06% Cu, 0.23% Co and 27.85% Mn, 29.02% total moisture	Global estimate for their entire 75,000-km ² contract area, referenced the JORC code but did not mention the role of competent persons
Interoceanmetal Joint Organization [45]	48.1 Mt (wet)	Not provided	1.31% Ni, 1.29% Cu, 0.16% Co, 32.6% Mn	H11 sub-area
Tonga Offshore Mining Limited [46]	410 Mt (wet)	9.4 kg/m ²	1.2% Ni 1.1% Cu 0.24% Co, 26.9% Mn	Abundance cut-off of 6 kg/m ² . To NI 43-101 standard, from Nimmo et al. [22]

DeepGreen Metals Inc. released a NI 43-101 Technical Report documenting mineral resource estimates for the entire contract area held by its subsidiary, Nauru Ocean Resources Inc. (NORI), in 2018 [23] and for the NORI Area D in 2019 [24].

In 2018, Global Sea Mineral Resources, a member of the DEME Group and an ISA contract holder, referred to a mineral resource estimation process related to a test area within their B4 sub-block [47]. This included the use of autonomous underwater vehicle images (nodule coverage) and the application of factors for nodule size and sediment cover. Some grade data were presented, but the report did not provide all of the information required by the CRIRSCO code.

3. Reporting Standards and the International Seabed Authority

The reporting of a mineral resource estimate is usually done to a standard or code required by the users of the estimate—for example, the regulatory body for the financial capital market being used for project funding or the nation in which the deposit resides. In some cases, a company is required to report under more than one code, even though this can lead to inconsistencies in the reporting and even in the estimates.

For the ISA, the existing structure of CRIRSCO works well to meet the requirements of regulators and Contractors alike, especially as the Contractors developing mineral resources in the area come from over a dozen different countries. To this end, the ISA updated its reporting requirement for Contractors to include reporting to a standard, as outlined in Annex V of the ISA ([48] replicated on the CRIRSCO site [48]). This standard is largely based on the JORC Code (one of the CRIRSCO member codes) but is notably different as it does not include the need for a qualified or competent person. The ISA standard does note that reporting under other regulatory requirements needs to be considered and that, in many cases, the more conservative of the two codes will need to be followed.

As the ISA is an associated body of the United Nations, CRIRSCO has also produced a bridging document ([49]) to try and relate the member codes to the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC; [50]).

4. Methods for the Evaluation of Polymetallic Nodule Deposits

4.1. Contrasting Estimation of Terrestrial Mineral Resources and Polymetallic Nodule Mineral Resources

Metalliferous mineral deposits occurring on land were commonly formed deep in ancient oceanic or continental crust or covered after deposition by younger rocks. The majority of these deposits are buried or only partially exposed on the modern land surface. Evaluation of these mineral resources is, therefore, a three-dimensional task, requiring estimation of the volume of the mineralised body, its density, and the grades and spatial distribution of the elements or minerals of interest. The CRIRSCO family of codes requires that the volume of waste removed to access the mineral resource be considered as part of an assessment of the reasonable prospects of eventual economic extraction.

Because the nodules of economic interest are all located on the surface of the seafloor, the third dimension (vertical depth) has no impact on their economic assessment. The process of mineral resource estimation is, therefore, essentially two-dimensional.

The seafloor polymetallic nodule deposits that are currently recognised have no overburden (Figure 5). Furthermore, the proposed nodule mining systems (including those piloted in the late 1970s (Figure 6)) all separate and reject, in the very first step of mining, almost all of the unconsolidated seabed sediment upon which the polymetallic nodules rest (e.g., Brockett et al. [51]). Thus, the volume, mass, and grade of the sediment are not material to the economic value of the mineral resource, even if they have considerable significance in terms of the marine environment and the geotechnical aspects of subsea mine engineering.

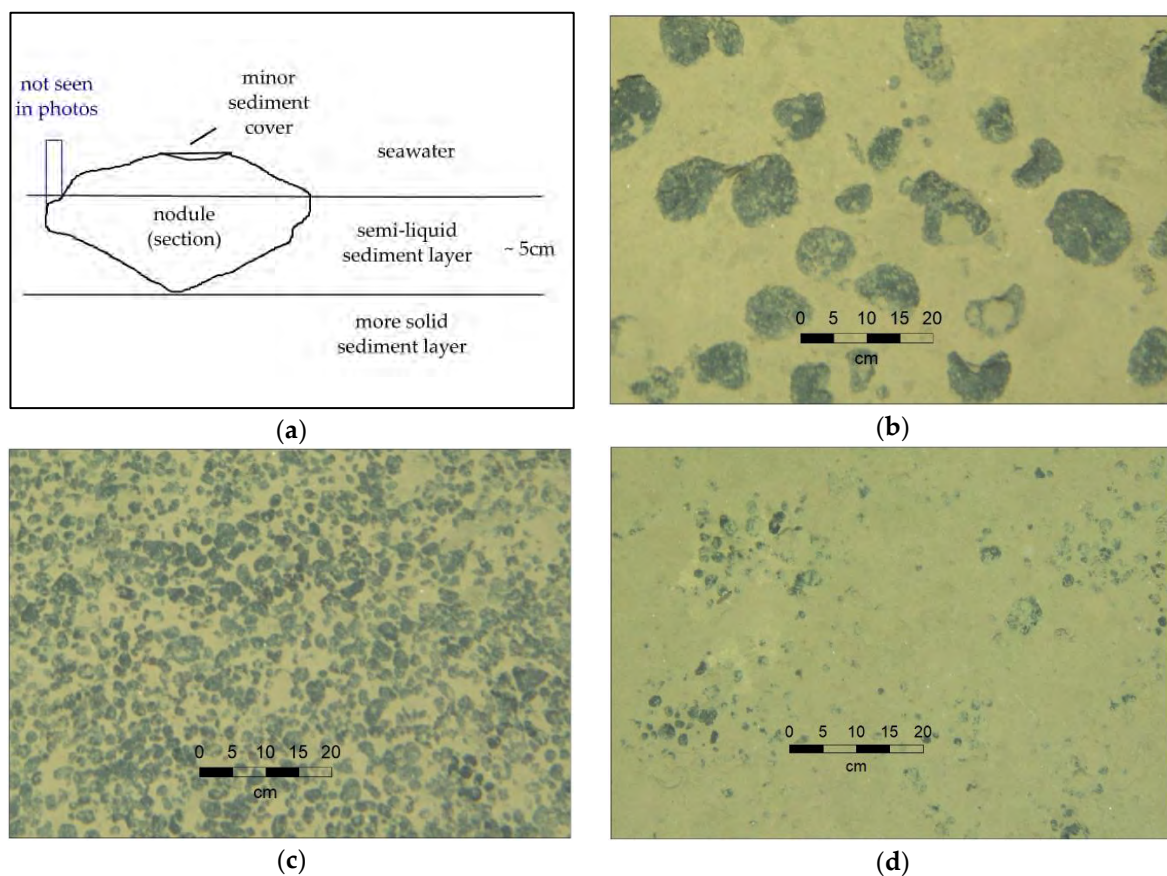


Figure 5. Polymetallic nodules on the seabed. (a) Schematic cross-section of nodules on the seabed; (b) example of large nodules (source: Tonga Offshore Mining Limited (TOML) image 2015_08_17_044250); (c) example of small nodules (source: TOML image 2015_08_17_105534); (d) example of covered nodules (source: TOML image 2015_09_16_183847).

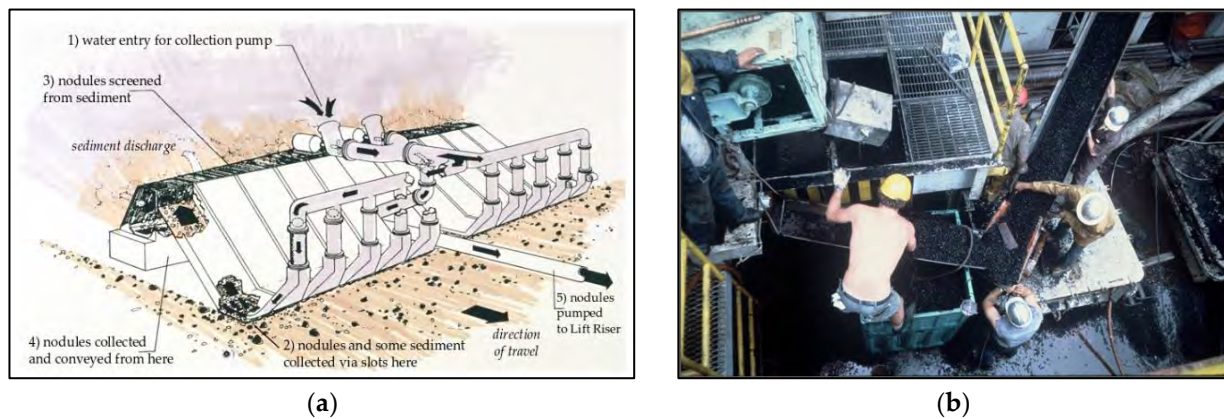


Figure 6. Polymetallic nodule pilot mining by Ocean Management Inc. of Seattle, United States in 1978. (a) Pilot nodule collector schematic; (b) reception of nodules at the surface vessel. Sourced and adapted from Brockett et al. [51].

By convention, polymetallic nodules are estimated and reported in terms of their abundance, in wet kg/m^2 , on the seabed (e.g., [12,25,37,52]). What constitutes the seabed, however, is not consistently defined. The majority of nodules are found at the surface or within the top 5 cm of clay-ooze (e.g., Figures 5 and 7), but sampling in the CCZ has revealed that, locally, there can be up to 25% more nodules buried at depths of 5–40 cm ([12,45]). Buried nodules were not considered important for, or included in, the mineral resource estimates by Lipton et al. [12] because of the lack of data on the extent of their occurrence.

Nodule abundance is typically reported in wet kg/m^2 because the water content is relevant to the behaviour and cost of the nodules during collection from the seafloor and transportation to processing facilities. Water content also has a direct impact on the cost of processing the nodules to extract the metals of economic interest. This convention is akin to the reporting of coal resources on an “air-dried” basis.

Despite its scale, the CCZ is effectively a single mineral deposit [22]. The nodules in the CCZ all formed via broadly similar processes in a single (prolonged) event. Land-based and shallow marine deposits have similar distributions (albeit at a smaller scale), with a single deposit comprising several lenses, shoots, or gravel beds.

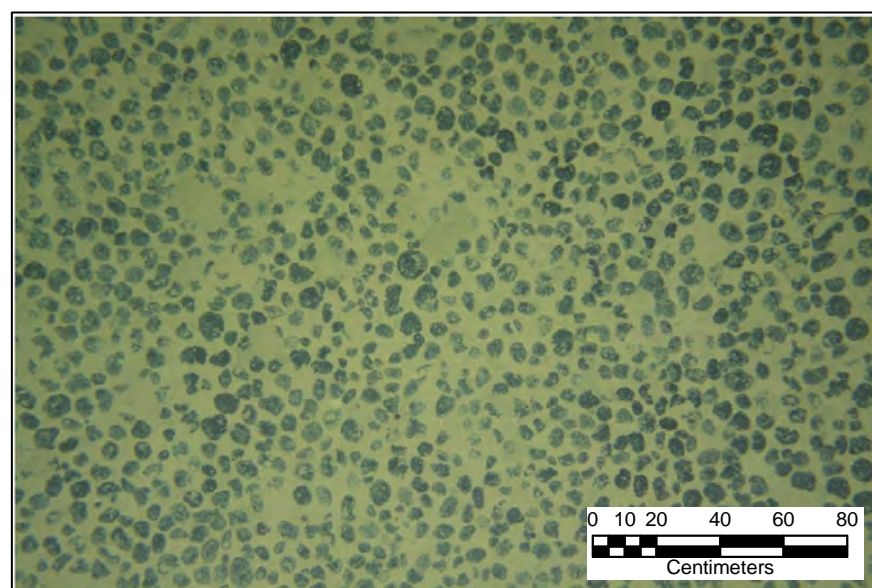


Figure 7. Example of an area with a high abundance of nodules. Source: TOML image 2015_08_10_155723.

4.2. Geology of Polymetallic Nodule Deposits

Consideration of the geology and the spatial distribution of mineralised material is essential for a reliable estimation of mineral resources. Although the areal extent of polymetallic nodules is enormous, nodules are not equally developed or preserved on all parts of the seafloor. At the scale of the estimation, discrete domains can be defined (geologically mapped) to more accurately constrain the mineral resource estimate.

The bulk of the seafloor is geomorphologically classified as abyssal hills (gently crenulated ridges; Figures 8–10). Cooling and structural reorganisation, following seafloor spreading, are believed to have given rise to this seafloor form, which is the most common geomorphological form on Earth (Kennish [53]). Within the CCZ, the ridges are typically oriented NNW–SSE, with an amplitude of 50 to 300 m and a wavelength of 2 to 10 km.

The basaltic basement of the abyssal hills is covered by sediments, and within the CCZ, there is a stratigraphic sequence of carbonate chalks and overlying siliceous clay-oozes (Figure 10). Seabed currents can move the clay-oozes into thicker drifts, which typically host few, if any, nodules (Figures 8 and 11).

Superimposed onto the abyssal hills are more recent volcanic units, including mappable seamounts and knolls (Figures 8 and 12), sheet flows, and fissure lavas/dykes. There are also numerous narrow, and often rocky, fault escarpments (Figures 10 and 13) that can expose the chalk layer or basement volcanic rocks. All of these units are less prospective for nodules (Fouquet et al. [54], COMRA, [55]).

Ship-based 12-kHz multibeam echosounder survey (MBES) can be used to measure (a) the distance to the seabed (bathymetric depth or seafloor topography) and (b) the reflectance (backscatter) of the seabed. Analysis of the two responses, especially backscatter, allows for some interpretations of seabed geology. Hard substrates, nodule fields, and nodule-free areas are often distinguishable qualitatively in the backscatter data, especially if supported by towed camera survey and/or higher resolution sidescan and sub-bottom profiler acoustic surveys (e.g., Figures 8 and 9). Use of the backscatter response is effective in helping explorers to find and delineate larger nodules, and larger nodules may also be associated with higher abundances (e.g., Ruhlemann et al. [39]).

The wide swath of MBES means that its potential use in geological interpretation and mineral resource estimation is attractive. COMRA ([38]) used acoustic response in their Multi-Frequency Exploration System (MFES), which was refined by Tao et al. [56]. Knobloch et al. [57] included MBES response in their combined artificial neural network and geostatistical mineral resource estimation, and Wong et al. [58] observed >85% average accuracy for their study area, using a combination of bathymetry and backscatter processed through an artificial neural network. Gaziz et al. [59] applied machine learning to AUV (autonomous underwater vehicle) MBES and photographic data for predictive modelling at a smaller scale (i.e., pre-mining scale). However, Lipton et al. [12] illustrated that the sediment type also affects the response, with near-surface chalk absorbing more sound than siliceous clay-ooze, so care may be needed in new areas.

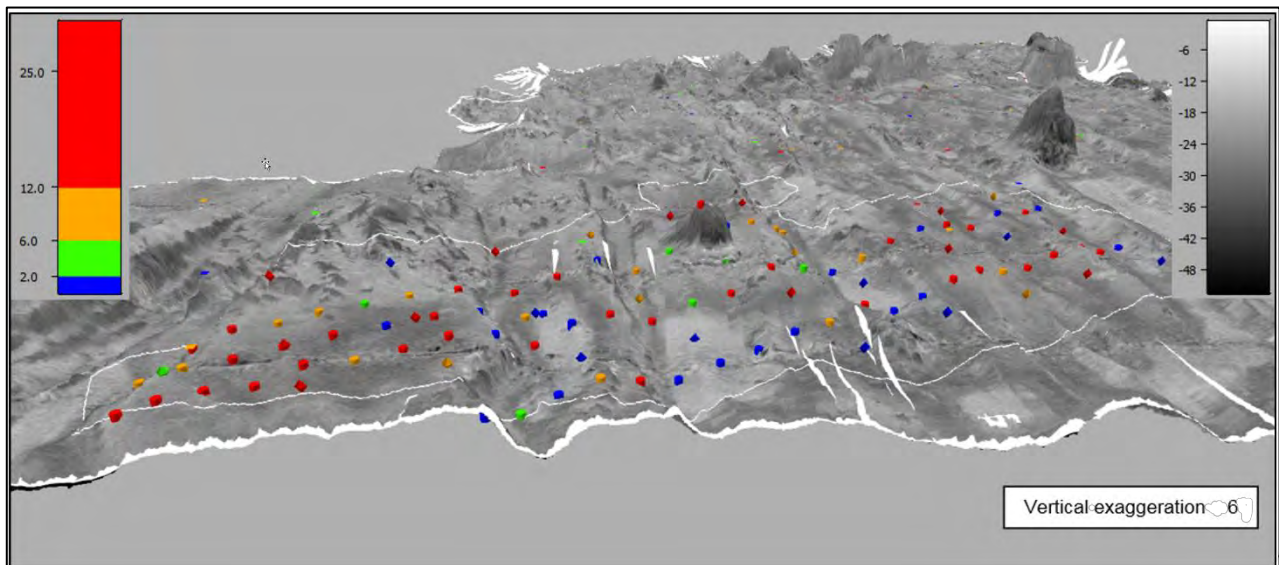


Figure 8. Nodule-rich and nodule-poor areas on a typical area of seafloor in the CCZ. The scheme shows 12-kz multibeam echosounder (MBES) backscatter based on bathymetry and sample data. For scale, the sample symbols are typically 3-km apart (refer also to Figure 9). Abundance (coloured) is given in wet kg/m²; the acoustic absorption (backscatter; grey scale) is in dB. Very dark areas generally relate to exposed volcanics (no nodules to speak of and not sampled), very light areas generally relate to sediment drifts (some sampled), and intermediate grey areas are nodule-bearing sediments. Within the white outline is the area that was estimated to an indicated and measured level of confidence, while outside, it was estimated to an inferred level.

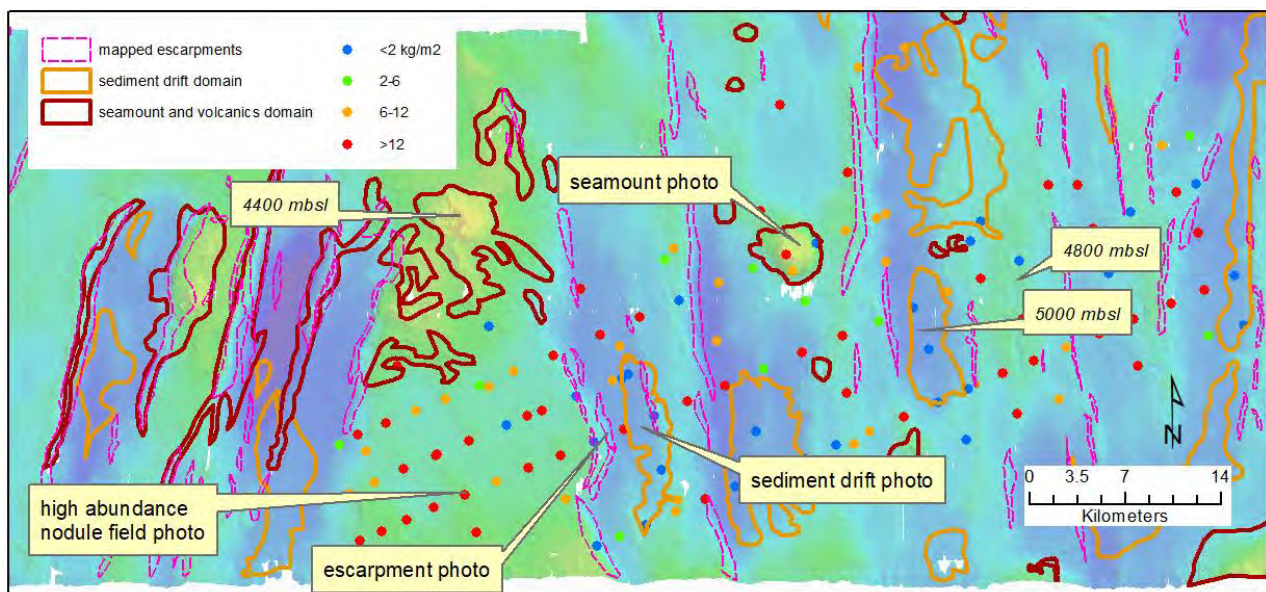


Figure 9. Resource domains in one part of the CCZ nodule deposit. The colour scale represents the seabed bathymetry with example depths for scale. The area is the fore and mid-ground of Figure 8. Photo sites are for Figures 7 and 11–13.

Lipton et al. [12] used MBES data to help define domains with low potential for nodule abundance that were excluded from the mineral resource estimate. These included volcanic areas and soft sediment drifts, where seabed photos and box core samples both confirmed that there were few, if any, nodules present.

Figures 8 and 9 show how changes in host and basement geology can relate to nodule abundance and thus help to define such domains for mineral resource estimation.

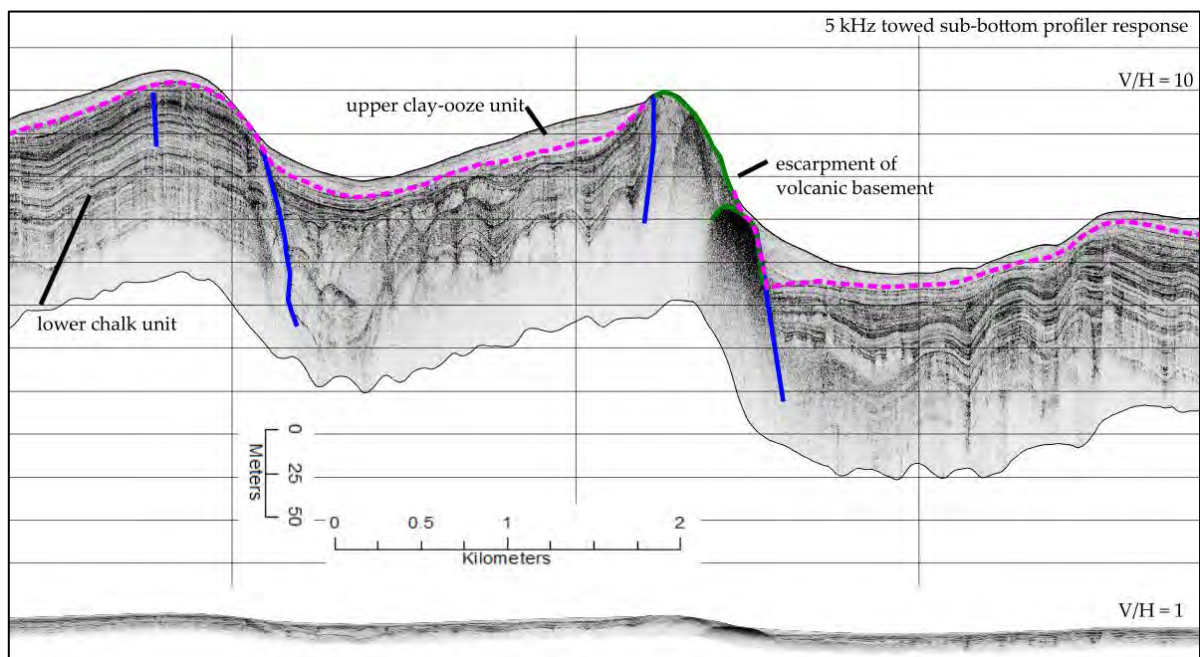


Figure 10. Example sub-bottom profiler image of the host/basement for the nodule deposit.

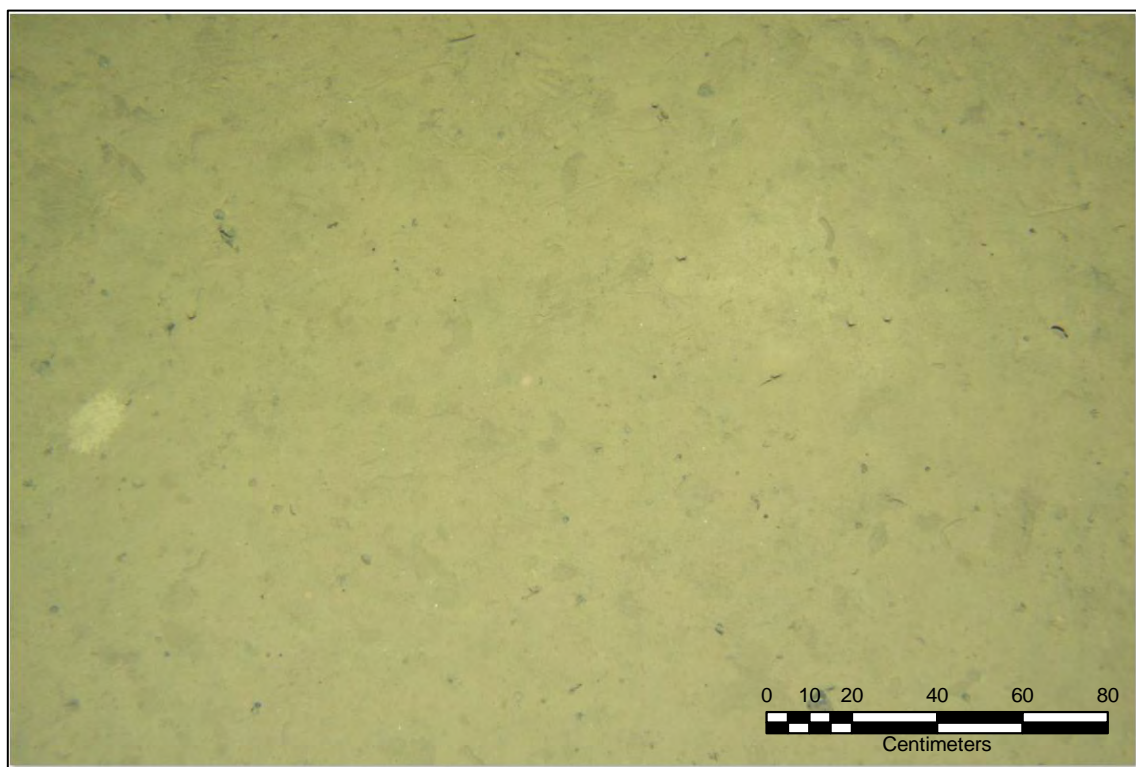


Figure 11. Sediment drift example photo. Source: TOML image 2015_08_10_225306.

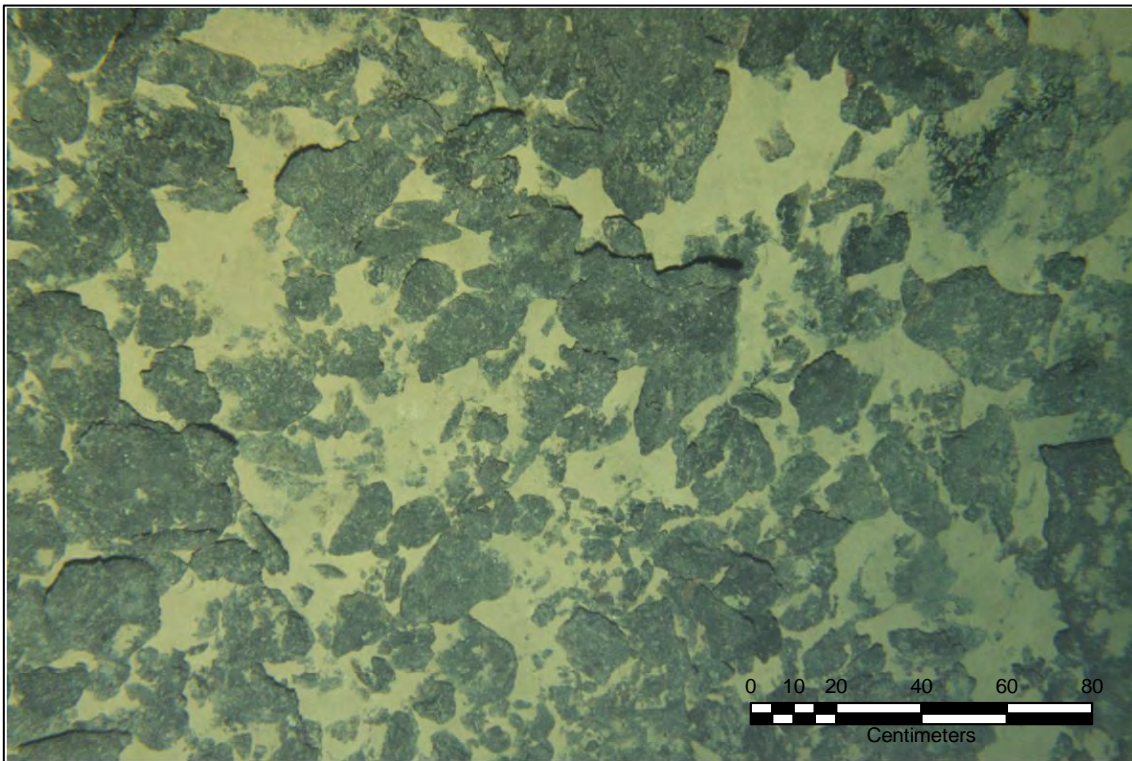


Figure 12. Volcanic knoll crest example photo. Source: TOML image 2015_08_17_094309.

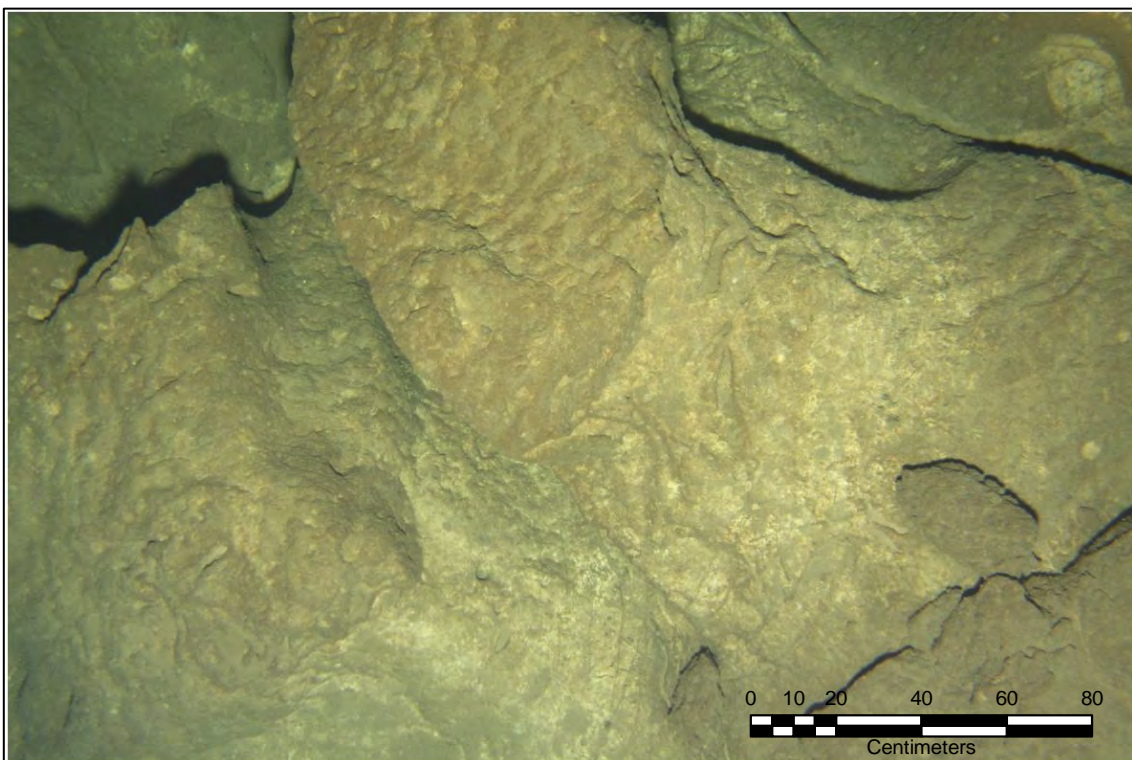


Figure 13. Chalk escarpment example photo. Source: TOML image 2015_08_10_205331.

4.3. Sampling

4.3.1. Physical Sampling

There are two main types of samplers used for the physical sampling of polymetallic nodules: free-fall grabs (FFGs) and box corers (BCs). FFG samplers are dropped over the sides of expedition ships and sink to the seafloor without any cable link to the boat (which then proceeds to drop more FFGs in nearby locations). The FFG contacts the seafloor (Figure 14) with a spring-loaded pair of clamshell net bags. This seafloor contact triggers the ejection of ballast, making the sampler buoyant, and the clamshell net bags close as the sampler starts to ascend, capturing the nodules. After it reaches the sea-surface, the FFG sampler is recovered by the boat.

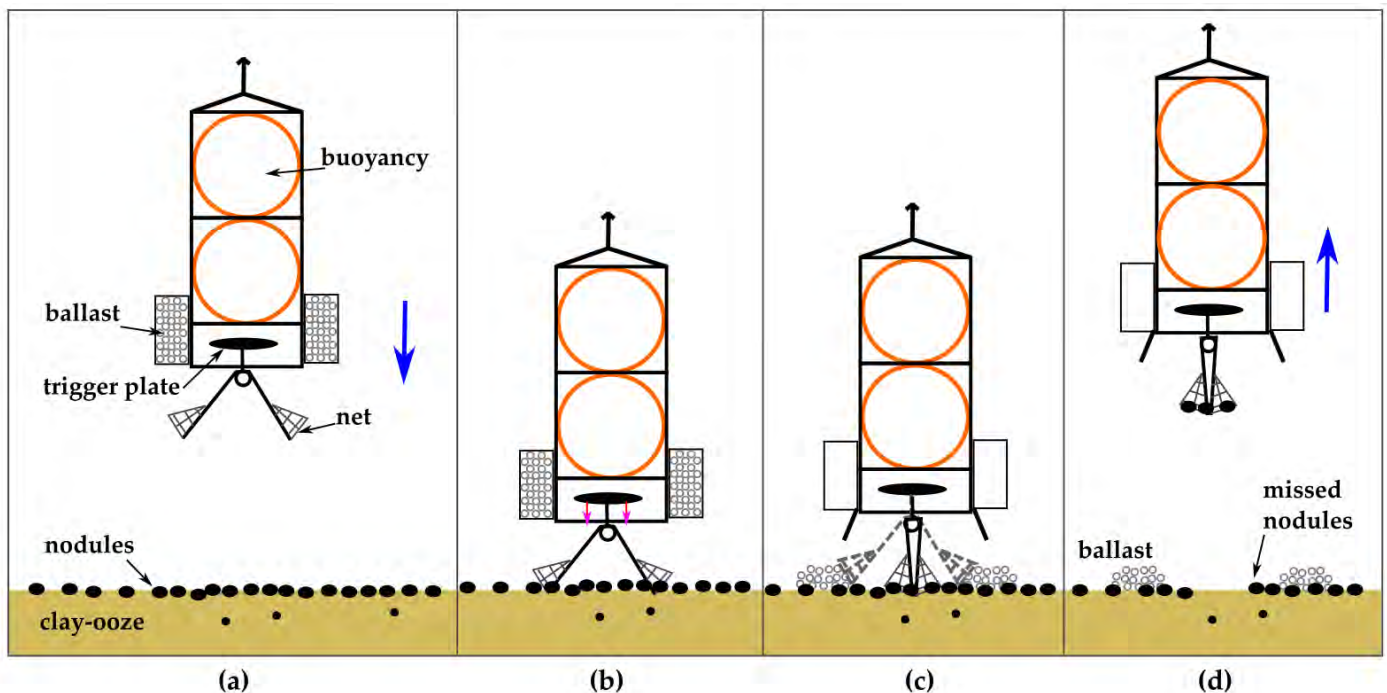


Figure 14. Schematic of the sampling process of nodules using free-fall grab (FFG). (a) Free-fall descent; (b) landing and trigger; (c) ballast dump and closing of grab with start of ascent; (d) free ascent. Modified from Lee et al. [60].

A BC sampler consists of an open rectangular steel box with a convex, steel base plate on a rotating arm (Figure 15). The BC is lowered down to the seafloor on a cable, with the base plate retracted. On a soft substrate, the box is typically driven up to 50 cm into the seafloor. As the BC sampler begins to be winched upwards, the base plate rotates into a position under the box, capturing the material within the box in a relatively undisturbed state.

As BC samplers are lowered to the seafloor on a cable, only one can be deployed at a time. At CCZ water depths, it takes around 4 to 6 h to deploy and then recover a BC. BC samples are thus more expensive to collect than FFG samples but generally have a much lower risk of sampling bias. A few nodules near the edge of the box may be pushed into or out of the box or may be pushed below the surface layer in the box core. Thus, a larger area-section box corer should have less primary sampling error, especially in areas of a few large nodules. A low level of disturbance is also favourable for geotechnical tests and biological sampling (Figure 16).

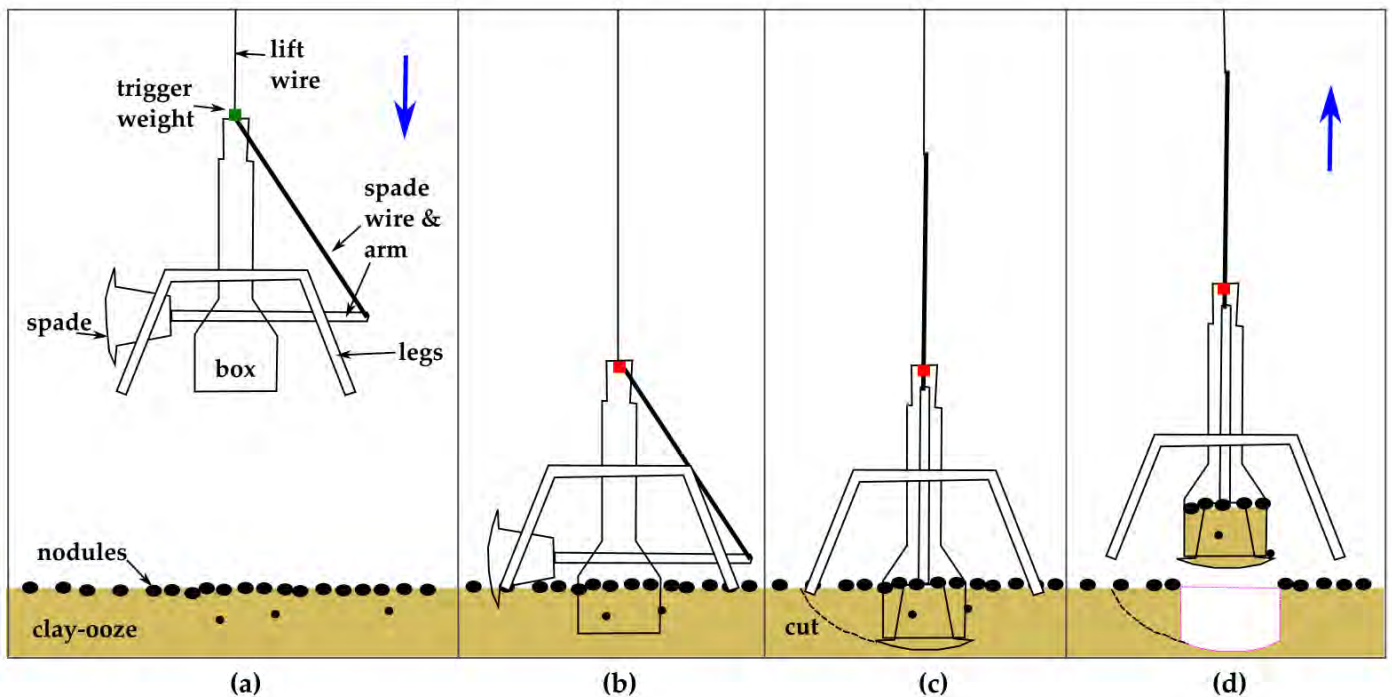


Figure 15. Schematic of the sampling process of nodules using a box corer (BC). (a) Descent on wire; (b) landing and trigger; (c) spade pulled to base of box by the lift and spade wire at the start of ascent; (d) lifted ascent. Modified from Lee et al. [60].



Figure 16. Nodules and mud in a box corer (SYMPAS). Source: Museum National d'Histoire Naturelle [61].

FFG samplers are quicker to deploy than BC samplers and are, therefore, cheaper to operate, but they tend to leave some nodules behind during collection and thus underestimate the true abundance of nodules at the sample location (Hennigar et al. [62]; Lee et al. [60]). Data collected only with FFGs have been used to estimate mineral resources at an inferred level of confidence (e.g., [22]).

Lee et al. [60] compared FFG and BC data in some detail. They found a wide range of differences between FFG and BC measurements of abundance, but with a consistent bias, with FFG under-reporting the abundance relative to BC (Figure 17) measurements. The authors attributed the biases to mechanical effectiveness. FFG samplers have been

demonstrated to underestimate the actual abundance, as smaller nodules may escape some grabs during ascent, and larger nodules around the edge of the sampler may be knocked out or fall out during the sampling process. A related key issue is the size of the FFG or BC (area covered) versus the nodule diameter.

Lee et al. [60] suggested an overall correction factor of 1.4 to convert an FFG abundance to a BC abundance. However, the authors acknowledged that any simple factor lacks precision. Many workers (e.g., [12,24]) do not use any correction factors and accept that estimates of nodule abundance based on FFG samples are likely to be conservative.

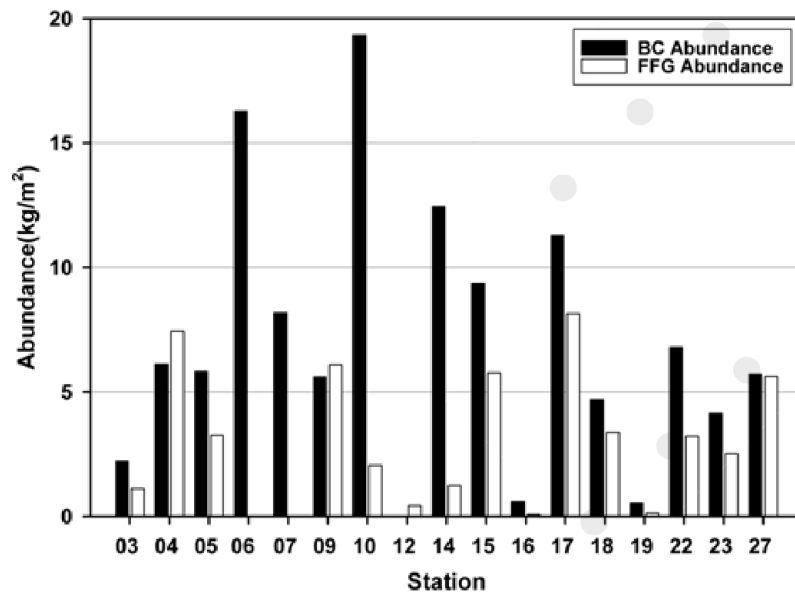


Figure 17. Comparison of returned abundances from BC and FFG at test stations within the KORDI exploration area. Source: Lee et al. [60].

As with terrestrial deposits, sampling on a reasonably regular sample grid is preferable for mineral resource estimation. Due to the high cost of FFG and BC deployment, it is desirable to optimise sampling patterns by identifying areas likely to be poorer in nodules from multibeam back scatter data and excluding (domaining out) such areas from sampling and from the mineral resource estimate. These areas include volcanic knolls and other recent volcanic rocks.

Evaluating polymetallic nodule deposits with BC samplers, or even FFG samplers, at spacings close enough to achieve a high level of confidence is a slow and expensive process. TOML achieved only slightly more than an average of four BC samples per day [12]. Consequently, alternative, lower-cost methods for measuring nodule abundance have been used to supplement physical samples.

4.3.2. Seafloor Photographs and Long-Axis Estimates of Abundance

Attempts to use simple nodule coverage to predict abundance have so far been shown to be ineffective (e.g., Sharma [63], Park et al. [64], Ellefmo and Kuhn [65]). A strong relationship between the length along the long or major axes of nodules (LA) and their weights was demonstrated in the 1970s by commercial explorers, such as Kennecott Exploration and Ocean Mining Associates (Felix [66]; Kaufman and Siapno [67]). Thus, if the nodules are mostly clear of surficial sediment, as is often the case in the CCZ, an estimate of abundance can be derived from photographs of the seafloor. The benefits of photographs over physical sampling, especially for short-range estimates, are that photographs are quicker and cheaper to capture than box-core sampling and measure a larger area.

Lipton et al. [12] successfully used such a technique. Photographs of the seafloor were taken using a camera mounted on the box core immediately before landing the box corer

(Figure 18). Upon retrieval, the long-axis lengths and masses of the nodules were physically measured. The long axis of each nodule on the seabed was also measured digitally from the photograph.

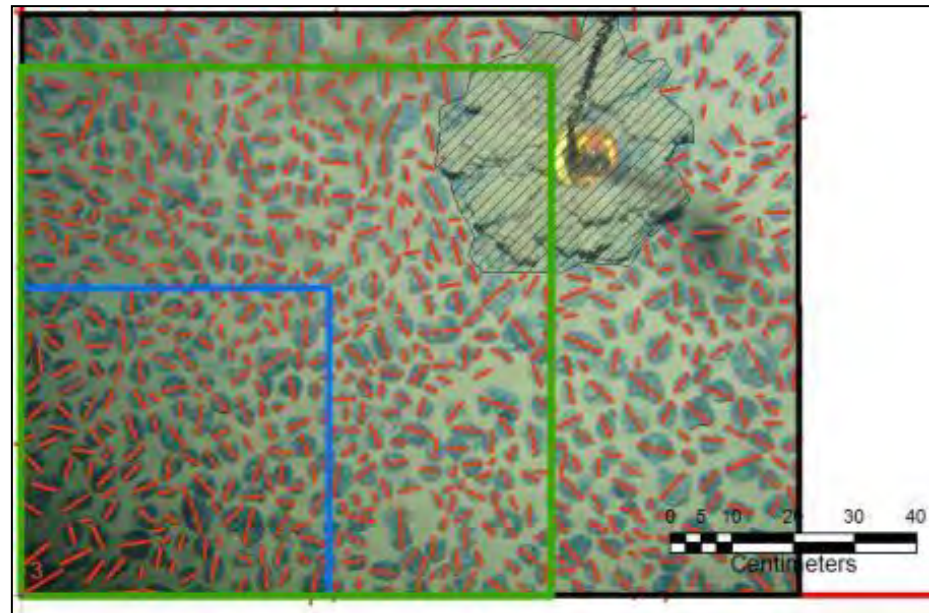


Figure 18. Example of long-axis estimate (LAE) measurements from a photograph taken from box-core-mounted camera. Source: Lipton et al. [12]. The blue frame is an example of an area that would be collected by a 0.25-m² box corer, and the green frame is an area that would be sampled by a 0.75-m² box corer.

Felix [65] proposed an empirically derived formula for nodules within an unspecified part of the CCZ held by Kennecott Exploration as follows in Equation (1):

$$\log_{10} W = 2.71 \log_{10} LA - 0.18 \quad (1)$$

where W is the wet mass of the nodule in grams, and LA is the long or major axis of that nodule in centimetres. Thus, the log form used in Equation (1) effectively provides a linear fit between those two characteristics.

The measurements of [12] (Figure 19) indicate small variations in the empirical regression relationship between areas:

$$\text{TOML area B1: } \log_{10} W = 2.81 \log_{10} LA - 0.18 \quad (2)$$

$$\text{TOML area C1: } \log_{10} W = 2.71 \log_{10} LA - 0.27. \quad (3)$$

These small variations likely relate to slight differences in the relative growth rates of nodules along their three Cartesian axes or to their bulk densities.

These formulae were then applied to LA measurements digitised from photographs of the seafloor from a towed camera system. The photographs were scaled using either parallel laser pointers or physical scales (e.g., scale annotated on camera trigger weights; Figure 18). As the measurements were done manually, which is an onerous process (including QA/QC), only every 100th photo was measured. This still enabled the estimation of weights of more than 90,000 photographed nodules. The calculated weight of the measured nodules in a given photograph was divided by the area of that photograph to derive a measure of abundance at that location.

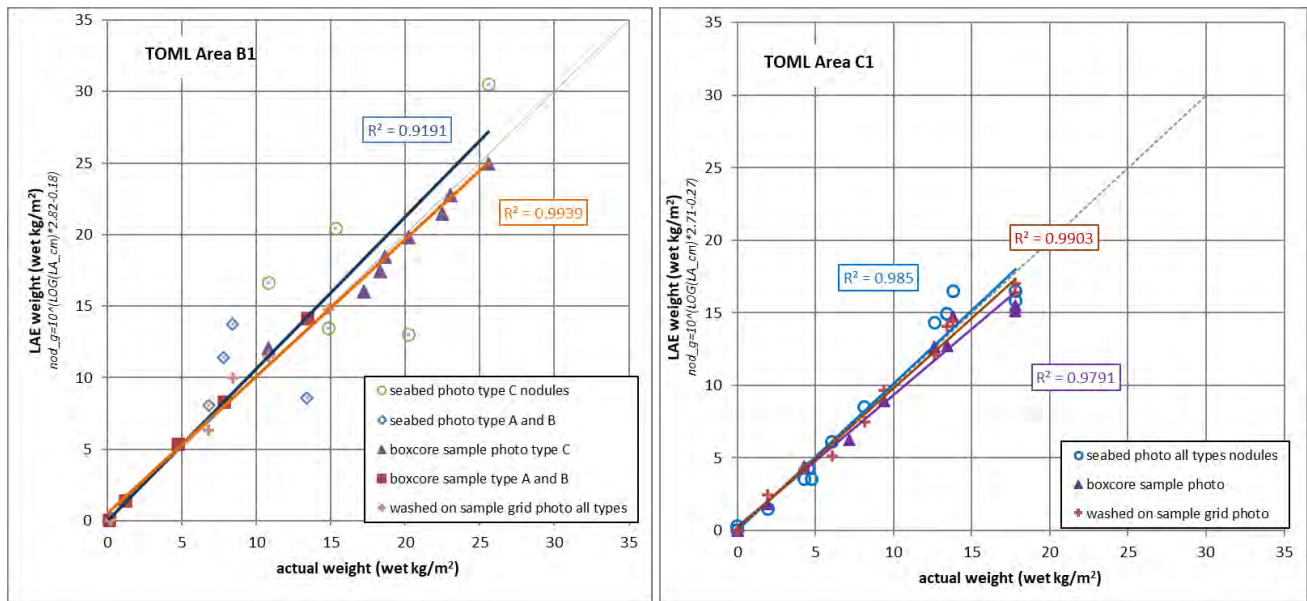


Figure 19. Correlations between total long-axis lengths and nodule sample weights, TOML areas B1 and C1. Source: Lipton et al. [12]; total sample weights and measurements were used for reasons of accuracy. Seabed photographs were taken from the box-core sampler immediately prior to landing; box-core sample photographs were taken of the undisturbed samples after landing the sampler back on the expedition vessel. Grid photo measurements are from nodules on a sample display grid after collection from the box core and washing and weighing. For TOML Area B1, the samples were also classified using a local nodule facies system to see if there was a discernible difference in the relationship. A type nodules are mostly small nodules, B type nodules are of mixed sizes, and C type nodules are mostly large nodules.

As Figure 20 shows, the system can be imprecise in some cases but is generally unbiased and sufficiently accurate for the purpose of estimating overall abundances for a mineral resource. Likely sources of imprecision include:

- Site-scale variations in the local regression relationships (mostly likely due to site-based variations in the thickness of the geochemically active layer and thus the thickness of the nodules);
- Varying scales in the towed photo images (e.g., a slightly oblique perspective when taking the photograph due to flaring of the towed systems resulting from vessel heave);
- Partial sediment cloaking or covering of the edges of nodules (Figure 5);
- Imprecision in the manual digitising process.

One issue identified by [65] may relate to bimodal or variant populations of nodules. Within the NORI D area (adjacent to the BGR eastern area considered by [65]), two distinct facies (or populations) were able to be handled separately in LAE-based estimates by [24,25]. It also remains to be demonstrated that a more accurate relationship between nodule size and weight could be determined through image analysis and even shape fitting to nodules (e.g., Schoning et al [68]). Using a single axis is simpler and may prove less error-prone than trying to use multiple geometries.

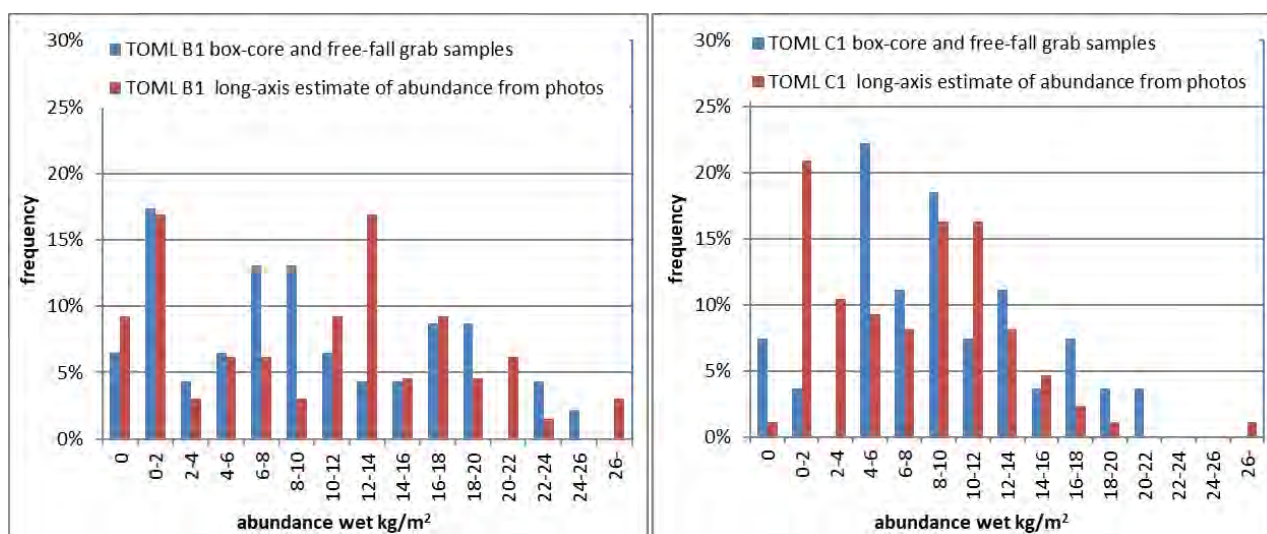


Figure 20. Histograms of abundances measured by physical sampling and the photograph-based long-axis estimate across TOML areas B1 and C1.

Ultimately, high degrees of sediment cover are a key limitation in applying photo-based abundance estimations in some areas (e.g., Figure 21; after Felix [66]), as elaborated by Mucha and Wasilewska-Blaszyk [69,70]. Lipton et al. [12] found this to be a problem in two out of the five TOML areas that they estimated to an indicated level of confidence (namely, TOML area D1 and D2), so they relied only on box-core samples in these areas.

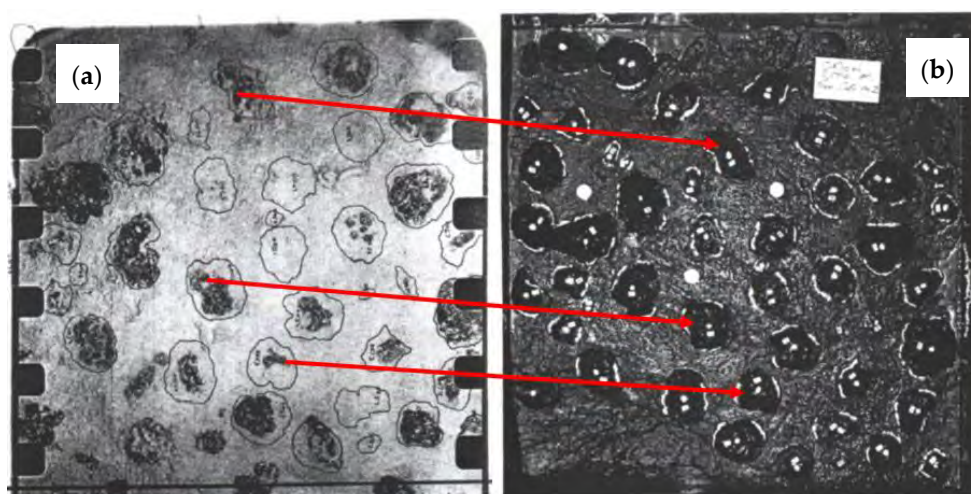


Figure 21. Seabed (a) and box-core (b) photograph pair in an area with a high degree of sediment cover. After Felix [66].

The TOML nodule mineral resource estimate in [12] was the first to include mineral resources at a measured level of confidence, and LA estimates were a key short-range abundance data source crucial to reaching this level of confidence.

Lipton et al. [12] also trialed an automated image processing technique on photographs taken at approximately 25-m intervals along three lines in the TOML areas (prototype software by Gideon Steyl of GeoSquare Consulting). This trial demonstrated the strong continuity of nodule abundance, supported the physical measurements from box-core samples, and demonstrated the accuracy of the automated method (Figure 22). Automated image processing may be useful for the detailed mapping of nodule abundance ahead of the deployment of seafloor production systems.

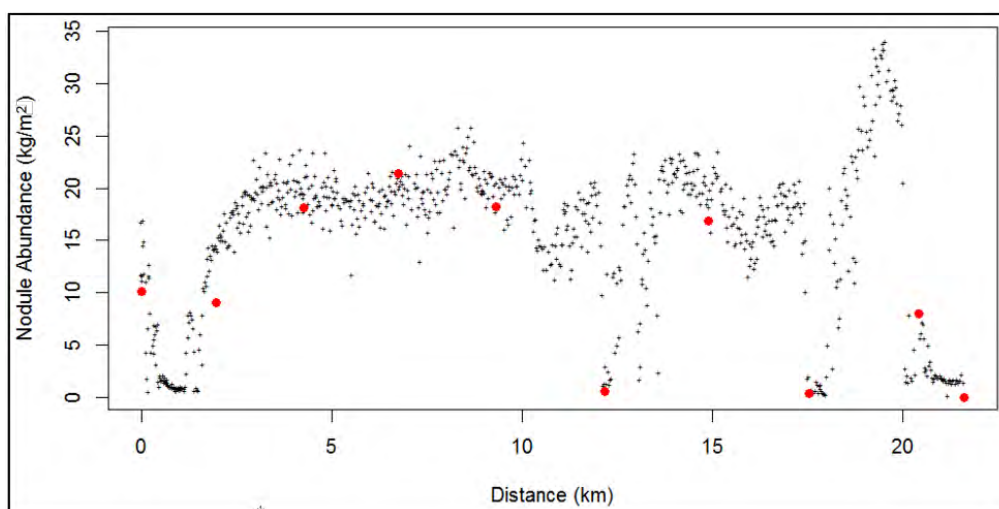


Figure 22. Nodule abundance photo-profile line CCZ15-F04 that crosses sub-area B1 for measured mineral resources. Source: [12]. Red dots—nodule coverage for seafloor photos that were used in the manual estimate of abundance using the long-axis estimation method and in the measured mineral resource estimate. Black dots—nodule abundance for all other seafloor photos derived by automated processing.

The approach of using photographs to estimate abundance has been developed further by Lipton et al. [24], who use a multiple linear regression approach that combines LA estimate and percentage nodule coverage. This approach was demonstrated to be accurate for a calibration set of samples for one particularly important facies of nodules in their estimate. As this facies has closely packed nodules, LAE alone is very difficult to do in an accurate, consistent manner.

4.3.3. Assaying

The measurement of nodule grades is carried out using the same principles and methods used for terrestrial deposits [12,23,25]. The general procedure used in [12] was as follows:

- Split the nodules into representative aliquots;
- Dry the nodules and then crush and pulverise them, reducing the sample size between each step with splitters;
- Analyse a wide range of elements using a mixture of X-ray fluorescence (XRF) and inductively coupled plasma spectrometric (ICP) methods. Measure loss on ignition using a thermogravimetric analysis furnace;
- Use blanks, duplicates, and certified reference materials not known to the laboratory to confirm the precision and accuracy of the analyses.

Polymetallic nodules are hygroscopic ([12]), which means that unless special care is taken, sample aliquots can gain weight after drying, leading to an underestimation of the grade in the analysis step.

Selection of the drying temperature is important. Two main types of water are present:

- Water of crystallisation included within the manganese and iron oxide minerals. This was determined in TOML test work to consistently be around 16% by wet weight (including the likely trace levels of other volatiles) [12]. A very small amount of water from crystallisation likely starts to be removed at temperatures as low as 50–70 °C through a transformation of the manganese mineral busserite into birnessite, but most manganese and iron oxide minerals are stable until reaching higher temperatures (115 °C and greater; Novikov and Bogdanova [71]);
- Free water included within pores and other cavities within the nodules, including water adsorbed onto mineral surfaces—this is estimated to be around 28% by wet

weight depending on the micro and macro void space in the nodules. Air-drying may remove approximately 16% (absolute) of this, with the rest removed by oven drying (up to 105 °C).

In this regard, nodules are similar to some tropical laterites which commonly have 25–30% free water and 15% water of crystallisation (Lagendijk and Jones [72]).

Estimating the water content is then complicated further because the nodules have very high porosity ([73]) and are hygroscopic. After drying to 105 °C, pulped nodules may absorb 7% of moisture by mass, or more, within a day if exposed to ambient air [12].

Lipton et al. [12] also reported experiments to understand the drying behaviour of nodules. Nodules were air-dried at ambient temperatures for extended periods and then oven-dried for several hours in increasing temperature steps. The combined drying curve is summarised in Figure 23. The tests suggest that some of the oxy-hydroxide minerals are only meta-stable and that some decomposition occurs across a continuous range of relatively low temperatures. Ultimately, the authors in [12] concluded that the industry standard drying temperature of 105 °C for rock samples provides a reasonable baseline for geochemical analysis.

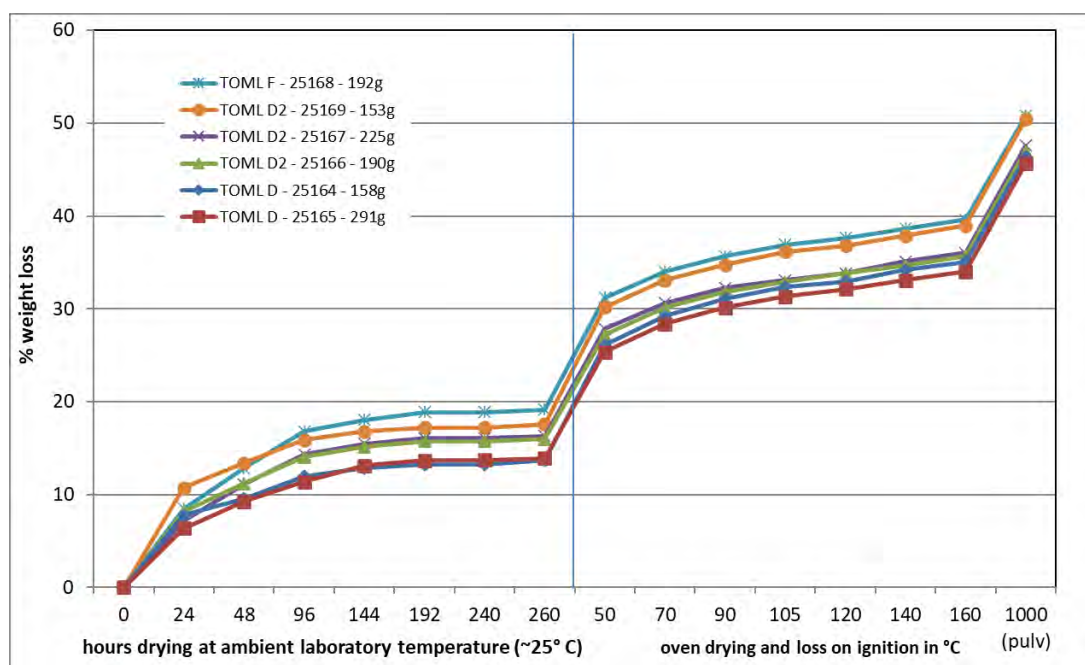


Figure 23. Three-stage drying curve for polymetallic nodule samples. Source: Lipton et al. [12].

While nodule grades are quoted on a dried basis, abundances and tonnages are usually quoted on a wet basis. This is a commonly accepted practice for similar bulk commodities containing significant amounts of free water (e.g., iron ore or nickel laterite), as the wet weight is often simpler to measure and more significant in terms of any future mining and shipping operation.

4.3.4. Historical Samples

The CRIRSCO codes require that details of sampling and assaying be included in mineral resource reports. Specifically, this involves the sampling method, sample size, assaying methods, assay quality assurance/quality control (QA/QC) data, and chain of custody of the samples. This requirement is problematic for the historical samples collected in the CCZ in the 1970s and 1980s by various groups and supplied to some Contractors by the ISA, as the required information is usually missing [22]. The historical sample results are relevant, however, to contemporary resource estimates, and they have been used previously by ISA [38] in the estimation of the inventory of the entire CCZ deposit.

Due to the very high cost of resampling, it is preferable to establish an acceptable level of confidence in the historic data rather than to simply reject it. In preparing the first CCZ mineral resource under NI 43-101, Nimmo et al. [22] carried out several statistical comparisons and were able to:

- Corroborate the ISA-supplied historical results by comparing the data between different original collection organisations and with other published data (non-ISA) from the CCZ nodule deposit. This was possible due to the large size of the CCZ deposit and the relative homogeneity of the grades across vast areas.
- Demonstrate a level of quality control by directly requesting information on sample collection and analysis from the original groups, also noting that the ISA, as an independent and accountable organisation, would need to check the data they received, as these data were used to define retained and released mineral rights under the groups' administration.
- Retain the services of an independent qualified person with direct experience in sample collection from the CCZ.

Nimmo et al. [22] concluded that historical nodule sample data are suitable for the purpose of estimating mineral resources to an inferred level of confidence. The likelihood that the historic data included free-fall grab samples that may underestimate nodule abundance was recognised but not considered to compromise the estimation of inferred resources. Subsequent authors of published mineral resource estimates (e.g., [12,23]) have reached the same conclusions.

5. Estimation Case Study—Tonga Offshore Mining Limited Contract Area

The authors were intimately involved in the first nodule mineral resource estimates completed to a CRIRSCO standard, as frequently referred to above, and as documented in publicly available technical reports (e.g., Nimmo et al. [22] and Lipton et al. [12]). The estimates pertained to a single contract area issued by the ISA to TOML. This case study serves as a synopsis of many of the above-mentioned principles with the results of the estimation exercises.

5.1. Samples and Related Data

The estimate in Nimmo et al. [22] for TOML Areas A to F was based entirely on the historical FFG and BC data in Table 2 and was thus restricted to an inferred level of confidence. The more closely spaced historical data in TOML Area B (Figure 24) did not improve the level of confidence, as QA/QC information was sparse.

The estimate in Lipton et al. [12] used data collected from two marine expeditions conducted after the estimate in Nimmo et al. [22]. These included multibeam mapping of much of the area, carefully collected and more closely spaced BC samples, and long-axis abundance estimates from a towed seafloor photo survey (Table 2, Figure 24). This additional work confirmed and extended the area that could be estimated; in some areas, this work enabled the estimation of resources to an indicated level of confidence, and in one area, it enabled estimation of a resources to a measured level of confidence (Figure 4).

The criteria for classification were assessed by the qualified person responsible for mineral resource estimations in accordance with the CIM definitions.

Table 2. Data matrix for the Tonga Offshore Mining Limited mineral resource estimates.

Data Type	2013 Inferred Estimate	2016 Inferred Estimate	2016 Indicated Estimate	2016 Measured Estimate
Historical samples from FFG and BC	Critical for grades and abundance estimates	Critical for grades and abundance estimates	Support for grades and abundance estimates	Not needed
Multibeam bathymetry and backscatter	Not available	Used in some areas for model domaining	Needed for model domaining	Needed for model domaining
BC physical samples with full QA/QC and chain of custody	Not available	Used in TOML Area F for grades and abundance estimates	Critical for grades and abundance estimates	Critical for grades and abundance estimates
Long-axis estimates of nodule abundance	Not available	Not available	Support for estimates in some areas	Critical for estimates
Higher-resolution sidescan sonar seafloor mapping	Not available	Not available	Not needed	Support for model domains

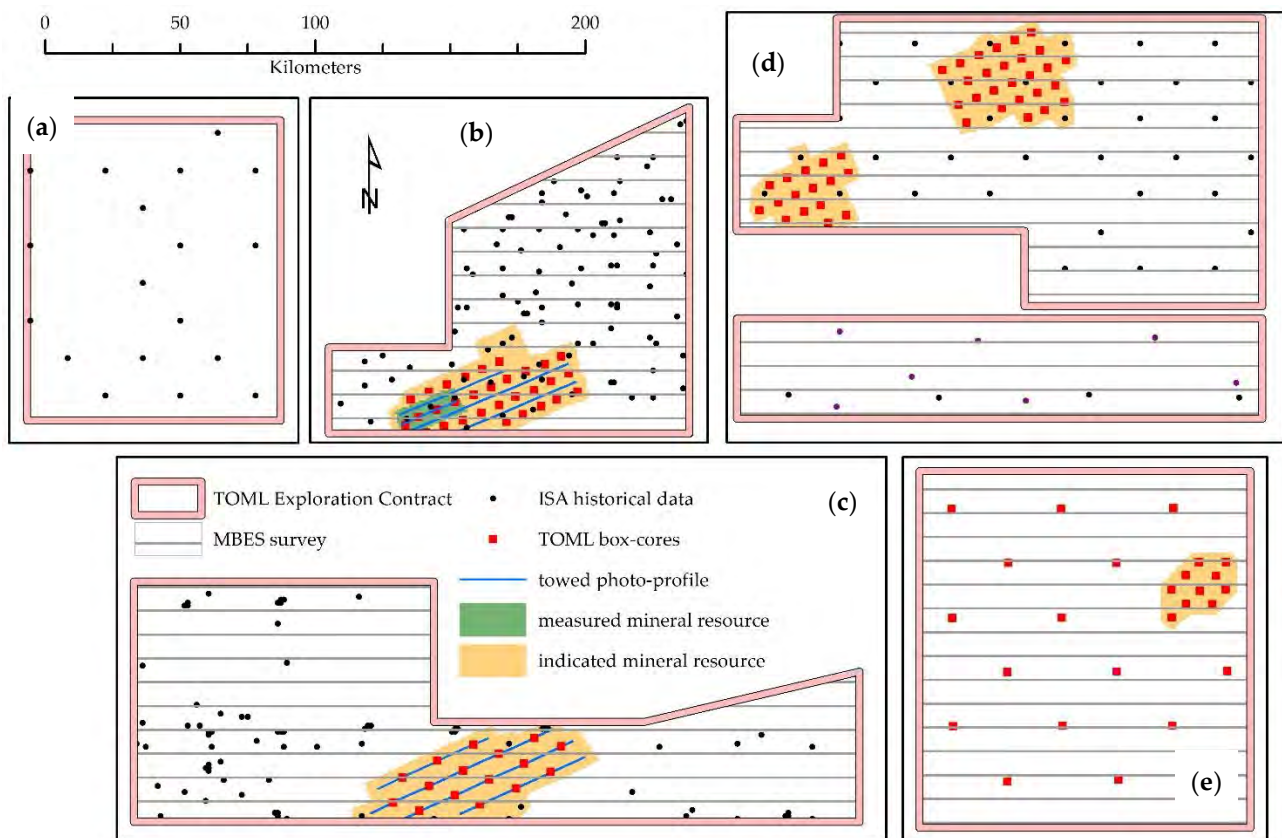


Figure 24. Key data behind the TOML mineral resource estimates. (a) TOML Area A, (b) TOML Area B, (c) TOML Area C, (d) TOML Areas D and E, (e) TOML Area F.

5.2. Domains and Model

The process for estimating the TOML nodule mineral resource followed a typical workflow for terrestrial deposits, with the significant difference that the estimate model was a two-dimensional grid (block model).

Geological interpretation of the seafloor defined two domains: a nodule-bearing domain (called NOD in Figure 25) and a nodule-free domain (NON).

The nodule-bearing domain featured clay-ooze-covered abyssal hills (e.g., Figure 8), typically with sampling indicating that high-grade polymetallic nodules were present with some level of supporting backscatter response. The abyssal hill escarpments were not excised as their areal extent was judged to be non-significant at the block scale used for the inferred and indicated resources (see below). There were no escarpments within

the area estimated to a measured level of confidence. TOML Area A was not mapped or sampled beyond the historical data, so it was assumed to be entirely covered with the NOD domain and confidence in the estimate retained at an inferred level.

The nodule-free domain was a combination of sediment drifts and volcanic areas. These are both accurately mappable from multibeam surveys and known from photographs and box-core samples to usually have few, if any, nodules. Nodule values within this domain were set to null, and the boundaries with the nodule-bearing domain were “hard” (values were not shared across the boundaries).

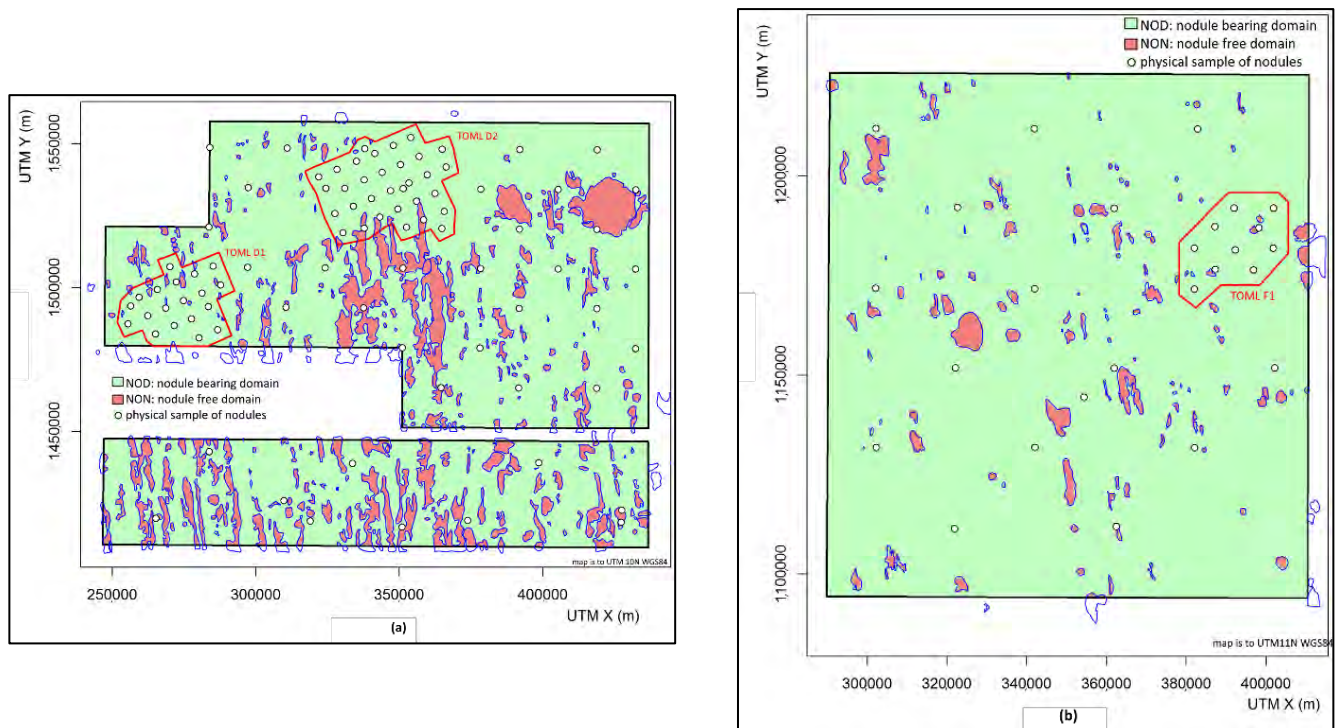


Figure 25. Example domains in TOML mineral resource estimates. (a) TOML D and E (b) TOML F. Red outlines are areas estimated to an indicated level of confidence; otherwise, these areas were estimated to an inferred level.

Six block models were constructed, one for each TOML exploration sub-area (Figure 24). Each model was blocked and based on the data spacing in Table 3.

Table 3. Data matrix and confidence for the TOML mineral resource estimates in [12].

critierium	TOML B5338	TOML B1	TOML C1	TOML D1, D2	TOML F1	TOML F	Other areas
Level of confidence	measured	indicated	indicated	indicated	indicated	inferred	inferred
Block size	1.75 × 1.75 km	3.5 × 3.5 km	3.5 × 3.5 km	3.5 × 3.5 km	3.5 × 3.5 km	7 × 7 km	7 × 7 km
Historic sampling	referred to	included	included	included	included	referred to	generally, < 20 × 20 km
Box-core spacing	~7 × 7 km	~7 × 7 km	~15 × 15 km off-set	~7 × 7 km	~7 × 7 km	~20 × 20 km offset	not needed
Photo-profile (abundance only)	relied at ~3 km × 3.5 km, (verified at ~30 m × 3.5 km)	included at ~3 km × 7 km	relied at ~3 km × 7 km	not used (clay-ooze cover)	not used (operational reasons)	not needed	not needed

Sub-cells with dimensions of 0.875 × 0.875 km were used to accurately represent the boundaries of the TOML exploration areas, the areas interpreted to contain no nodules, and the boundaries between measured and indicated levels.

Grades were then estimated into the blocks using ordinary kriging once the key statistical parameters were established.

5.3. Geostatistics and Model Estimation

Mineral resources for polymetallic nodules were estimated from measurements of nodule abundance and nodule grades at identified locations. Preparation of the data included declustering and exploratory data analysis [12]. In most of the TOML areas, the variability of nodule abundance is significantly higher than that of the metal grades (Table 4). Estimation of abundance is, therefore, the key variable of uncertainty for mineral resources.

Table 4. Declustered statistics of all polymetallic nodule samples within the TOML exploration area.

Variable	Samples	Minimum	Mean	Median	Maximum	Var	CV
Abundance (kg/m ²)	527	0	10.20	9.16	30.77	39.35	0.61
Mn (%)	338	6.54	28.09	28.71	33.79	10.414	0.11
Ni (%)	338	0.33	1.26	1.31	1.55	0.03	0.14
Cu (%)	338	0.22	1.11	1.16	1.51	0.045	0.19
Co (%)	338	0.02	0.22	0.22	0.35	0.003	0.24

Var = variance; CV = coefficient of variation. Source: [12].

Geostatistics provides a range of methods for modelling the spatial continuity of regionalised variables such as abundance and grades. The primary tool for modelling the spatial continuity of such variables is the semi-variogram (commonly abbreviated as the “variogram”). The variogram is a graph of the variance between data points as a function of distance. Variograms are typically constructed either in multiple orientations to test for spatial anisotropy, or all vectors may be considered in an omni-directional variogram. Experimental variograms are calculated for the data points and then fitted with an appropriate model selected from a range of valid mathematical functions.

Variograms were generated using the box core sample data and two-structure spherical models fitted to them (Table 5). As the variables of interest (nickel, cobalt, copper, and manganese) are unlikely to be entirely independent, the variogram models for each variable were selected with consistent parameters, where this process was determined to be reasonable. This was done to ensure that the element relationships or correlations evident between samples were respected implicitly during estimation and reflected in the resource estimate.

Manganese and nickel variograms showed greater continuity in the 150° direction (e.g., Figure 26), and cobalt showed greater continuity in the 060° direction (Figure 27). The 060° direction is roughly parallel to the broad regional trend of the CCZ, and the 150° direction is parallel to the abyssal hills. Copper showed no anisotropy.

Table 5. Model grade variogram models.

Variable	Nugget		Spherical Structure 1		Spherical Structure 2		Anisotropy Ratio	
	C0	C1	Range H1		Range H2			
			060° (km)	150° (km)	C1	060° (km)	150° (km)	
Mn	0.21	0.37	5	10	0.42	15	30	0.5
Ni	0.21	0.37	5	10	0.42	15	30	0.5
Cu	0.21	0.37	22	22	0.42	70	70	1.0
Co	0.21	0.37	22	16	0.42	70	50	0.714

Source: [12].

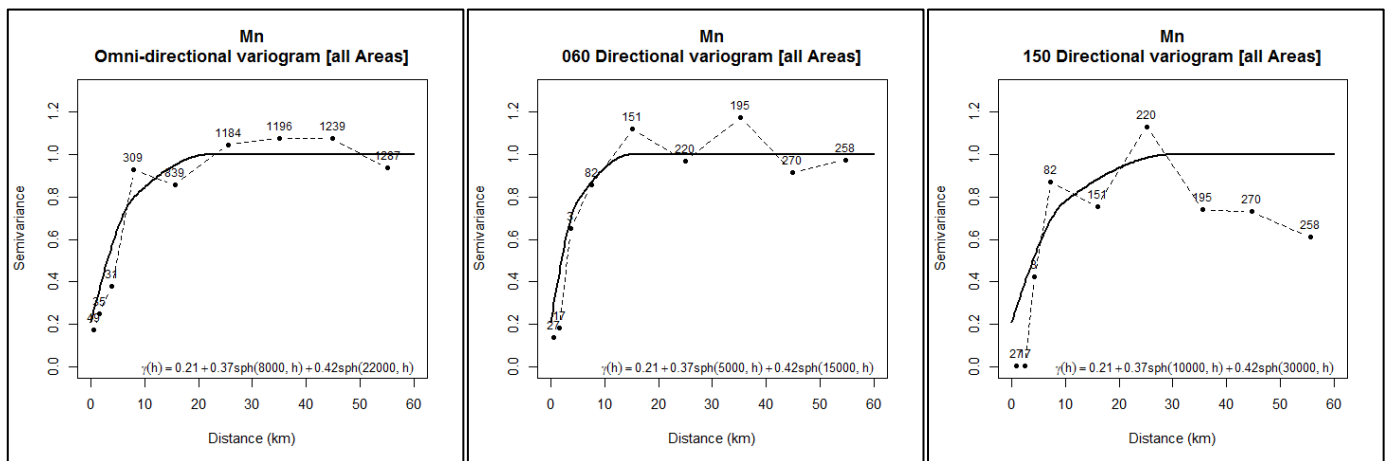


Figure 26. Mn omni-directional, 060° and 150° directional variograms. Source: [12].

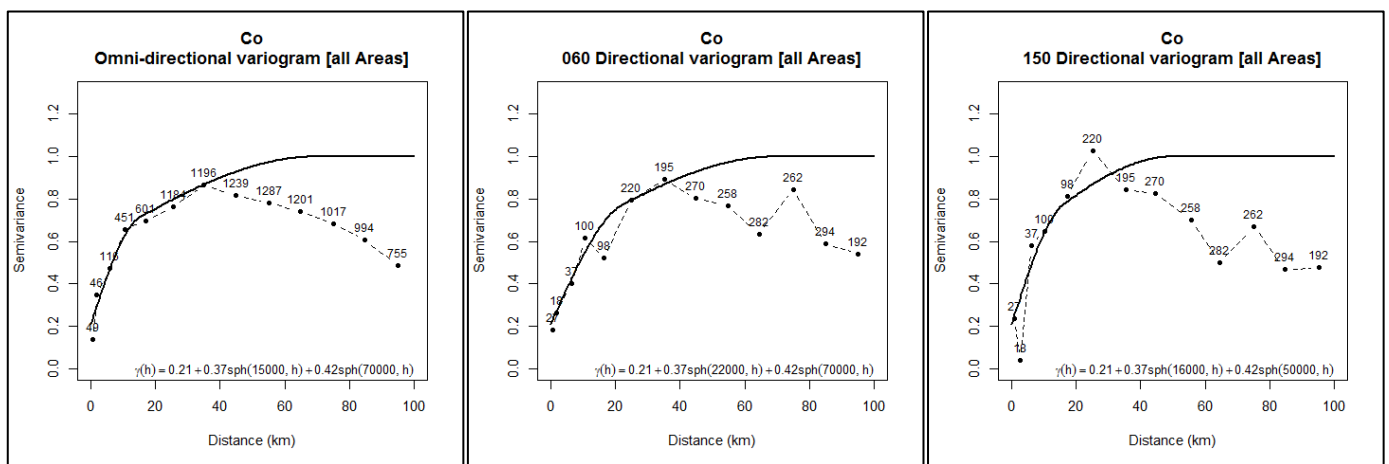


Figure 27. Co omni-directional, 060° and 150° directional variograms. Source: [12].

The variogram models for abundance generated from the box-core data were compared with variograms generated from the LAE abundance values. The variogram structures were similar. The experimental variograms combining both physical samples and LAE in [12] showed ranges of around 5 km for abundance (Table 6, Figure 28) versus 5 to 22 km for grade (e.g., Figure 26). It is noted that variograms in [25] have a range of around 3 km for abundance from the NORI D Area.

Table 6. Model abundance variogram models.

Variable	Nugget		Spherical Structure 1		Spherical Structure 2		Anisotropy Ratio
	C0	C1	Range H1		Range H2		
			060° (km)	150° (km)	C1	060° (km)	
Abundance	0.40	0.60	5	5	–	–	1.0

Source: [12]. “–” means not defined

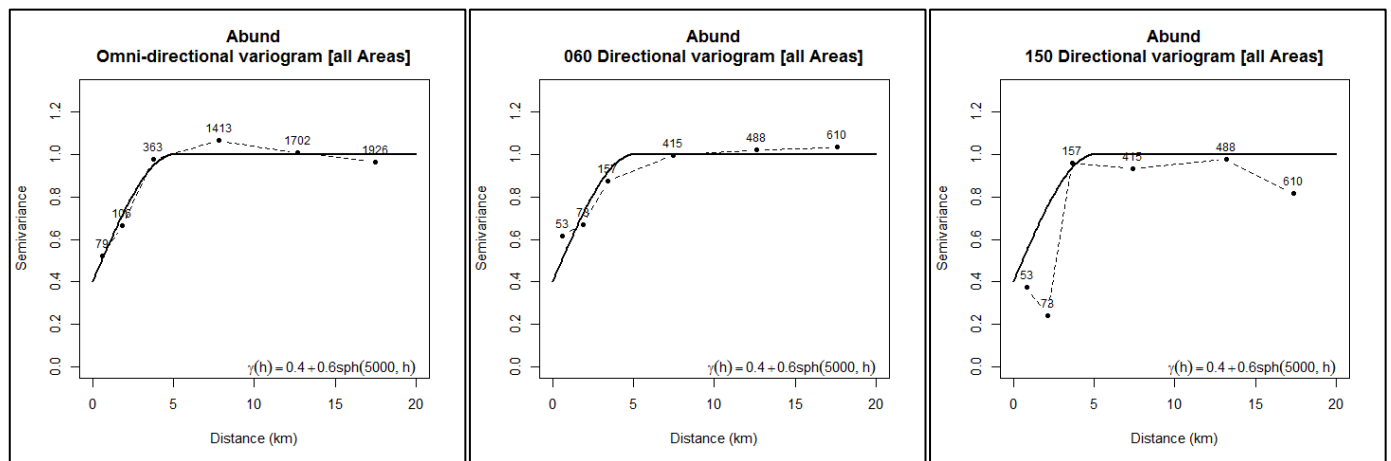


Figure 28. Omni-directional and 060° and 150° directional variograms for abundance. Source [12].

Also interesting is the periodic effect (hole effect) evident in the variogram at ranges of approximately 7.5 and 15 km (Figure 29). This may be related to the periodicity of the spacing between the abyssal hills.

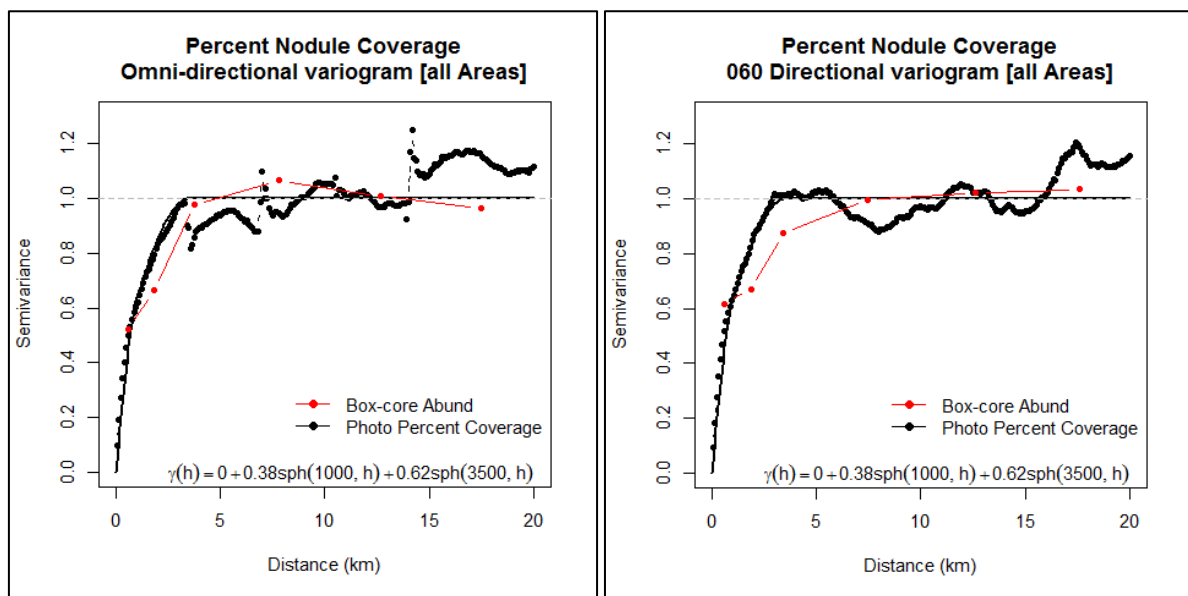


Figure 29. Omni-directional and 060° directional variograms for percent nodule coverage estimated from seafloor photos. Source: [12].

Ordinary kriging was used to estimate the nodule abundance, along with manganese, nickel, copper, and cobalt, for every cell in the block model. Panel support (volume) was approximated by estimating the values on a three by three (nine points) grid equally spaced within each block, with the point estimates averaged to give the block estimate. For each estimate, a circular neighbourhood with a radius of 30 km was used to find the closest samples (a minimum of one and maximum of 32). If no samples were found within the first 30 km, then the search radius was increased to 60 km and then 90 km to ensure that every block was estimated. The relatively large number of samples used for estimating a value for a block was chosen to ensure that the block estimates were smoothed to reflect the confidence in the estimate. Estimate checks were done using the nearest neighbour and inverse distance weighting interpolation techniques [12].

6. Discussion

6.1. Reasonable Prospects of Eventual Economic Extraction

The CRIRSCO family of codes requires that a mineral resource must have reasonable prospects of eventual economic extraction. The qualified persons in Lipton et al. [12] considered that there were reasonable prospects that:

- In the foreseeable future, mining of polymetallic nodules from the seafloor would be technically feasible.
- Processing of polymetallic nodules to extract nickel copper, cobalt, and manganese products would likely be feasible using a combination of existing extractive technologies (e.g., Haynes et al. [74]).
- The metal products would have a market because there is anticipated to be increasing demand for these metals for traditional purposes supported by increased demand for electrochemical cells (batteries).
- The entire process, from seafloor collection to the delivery of metalliferous products, could be achieved in an economically viable manner.

The mining aspects are the most uncertain because the conditions on the seafloor are unlike any on land. Lipton et al. [12] considered that the assumption of reasonable prospects for economic mining was supported by:

- Success in the pilot mining of polymetallic nodules in the CCZ by two groups in the late 1970s (e.g., Brockett et al. [51]).
- Successful sub-sea operations at similar or greater water depths, including tasks such as the installation of oil and gas production facilities at circa 2500 m; the spudding of drill holes at circa 3000 m; cable laying and retrieval at circa 5000 m; and the collection of samples at circa 11,000 m.
- Demonstration of various lift systems from water depths such as the CCZ, including cable, pumping, and airlift solutions.
- Demonstration of operating offshore production vessels including the transfer of product.
- The similarities of some proposed metallurgical processing routes to existing facilities for terrestrial ore sources.
- Higher grades than some terrestrial ore sources and upsides in terms of recoverable metals.
- Lack of overburden and no need to cut rock, at least in part, compensating for working at a depth. Reduced mine infrastructure outside of the production system.
- Transport distances for product comparable with those of other seaborne bulk commodities.
- Benefits of homogenous mineralogy in metallurgical optimisation and cost reduction.

Confidence in the prospects for the eventual economic extraction of polymetallic nodules is growing, as reflected by the increase in applications for exploration contracts in the CCZ, including many by commercial entities (Figure 2). The Contractors are also considering in detail the scale that nodule mining is likely to operate at, i.e., within the marine topography and general environment (e.g., Volkmann and Lehnen [75]).

6.2. Marine Environment

The marine environment of the region falls under the Regional Environmental Management Plan (REMP) for the CCZ established by the ISA ([76]), which includes the definition of the Areas of Particular Environmental Interest (APEIs; Figure 2). Any mineral-resource-specific Environmental Impact Statement needs to consider the REMP.

Under NI 43-101, environment studies, permitting, and social or community impact are important subjects (i.e., modifying factors) for the qualified persons to consider (CIM

[19]). This applies to all mineral deposit technical reports reported to this standard, irrespective of whether the relevant work is a marine project or not.

Therefore, consideration of the marine environment is an implied aspect of reasonable prospects of eventual economic extraction. In feasibility study level NI 43-101 reporting, consideration of the marine environment relies on compliance thresholds in addition to general commentary around environmental protection, mitigations, monitoring, and adaptive management.

Consideration of the impacts on the marine environment may ultimately result in the application of modifying factors to convert the mineral resource to a mineral reserve. For example, the ISA requires the establishment of Preservation Reference Zone(s) (PRZ(s)) within a contract area to preserve ecosystem functions and be representative of the communities and ecology of the mined area. It falls upon the Contractor to define these limits through the EIA process. There are currently no firm regulatory thresholds in this regard, but stakeholder expectations, emerging industry best practices, precedents, boundary conditions, and the appreciation of different shapes and sizes of contract areas will also come into consideration.

Ultimately, the qualified persons behind any future reserve estimate will need to determine the materiality of environmental modifying factors in a mineral reserve estimate just as they will need to do for other types of modifying factors.

6.3. Qualified Persons, Independence, and Transparency

The role of the qualified person (QP) or competent person (CP) is well-explained in the NI 43-101 and JORC member codes to CRIRSCO. Individuals with relevant skills and experience who have supervised the writing of the technical report and estimation of the mineral resources must sign off on the results and need to be prepared to defend their work to their peers. Under NI 43-101, QPs are required to provide written consent to the public reporting of their work. The CRIRSCO family of codes requires QPs to have a minimum five years' relevant experience in the matters for which they take responsibility.

It is unlikely that a single person will have all the skills and experience required to complete a mineral resource report under NI43-101, so several QPs are often required. A report is thus usually compiled under a lead QP, with other QPs contributing to key sections. The QPs may be supported in specific aspects, such as marine engineering, oceanography, and marine ecology, by "other experts" who are named but do not sign off on the report or resource estimate.

As mineral resource estimates are published and often used to raise finances for mining ventures, the independence of at least some QPs is often a requirement. Similarly, transparency in the data collection and mineral resource estimation process is strongly preferred to assist in the explanation of the results (and of any future changes to the estimate).

6.4. Property Inspection and Chain Of Custody

The CRIRSCO family of codes requires that QPs engage in a physical inspection of the deposit or explain why this inspection is not possible. This inspection is intended to provide an opportunity for independent verification of the geological features of the deposit visible in the outcrop or mine faces. For deep-sea nodule deposits, the water depth effectively precludes a physical visit, and the long (2 to 3 month) duration of exploration cruises makes short-term visits by many QPs impractical.

To address this problem, Lipton et al. [12] relied on:

- the inclusion of a QP who had actually spent 3 months working in the CCZ;
- a documented chain of custody around the collection of box core samples and sea-floor images; and
- the fact that numerous other independent organisations had explored the deposit in the past and reported essentially similar results.

Demonstration of the chain of custody is also required for photographs used for abundance estimation under NI 43-101. Thus, for Lipton et al. [12], data were sent directly to the mineral resource QP from the expedition ship.

7. Conclusions

The application of established, and mostly land-based, mineral resource reporting guidelines to seabed polymetallic nodules in the CCZ has proven to be relatively straightforward. The long history of exploration and development on the deposit helps to provide important context.

The geology of polymetallic nodule deposits appears to be relatively well understood, and multiple lines of evidence, such as physical samples, seabed photographs, and multibeam echosounder survey, have led to a common view of the deposit's characteristics. The sampling methods and scales of mineralisation are unique to this type of deposit but are not an impediment to the estimation or reporting of mineral resources.

The deep-sea location of the deposits presents some challenges for mineral resource estimation, but, conversely, the extremely low variance of nodule abundance and grades form a stark and beneficial contrast with most terrestrial metalliferous deposits.

The commercial mining of polymetallic nodules has not yet been achieved; therefore, there are no precedents to draw upon for the estimation of mineral (ore) reserves. Nevertheless, successful pilot mining of polymetallic nodules in the CCZ in the late 1970s, a long history of deep-water oil and gas operations, and the apparent amenability of polymetallic nodules to various proven metallurgical processing methods, all indicate that there are reasonable prospects for defining mineral reserves and developing viable production systems on the deep seafloor.

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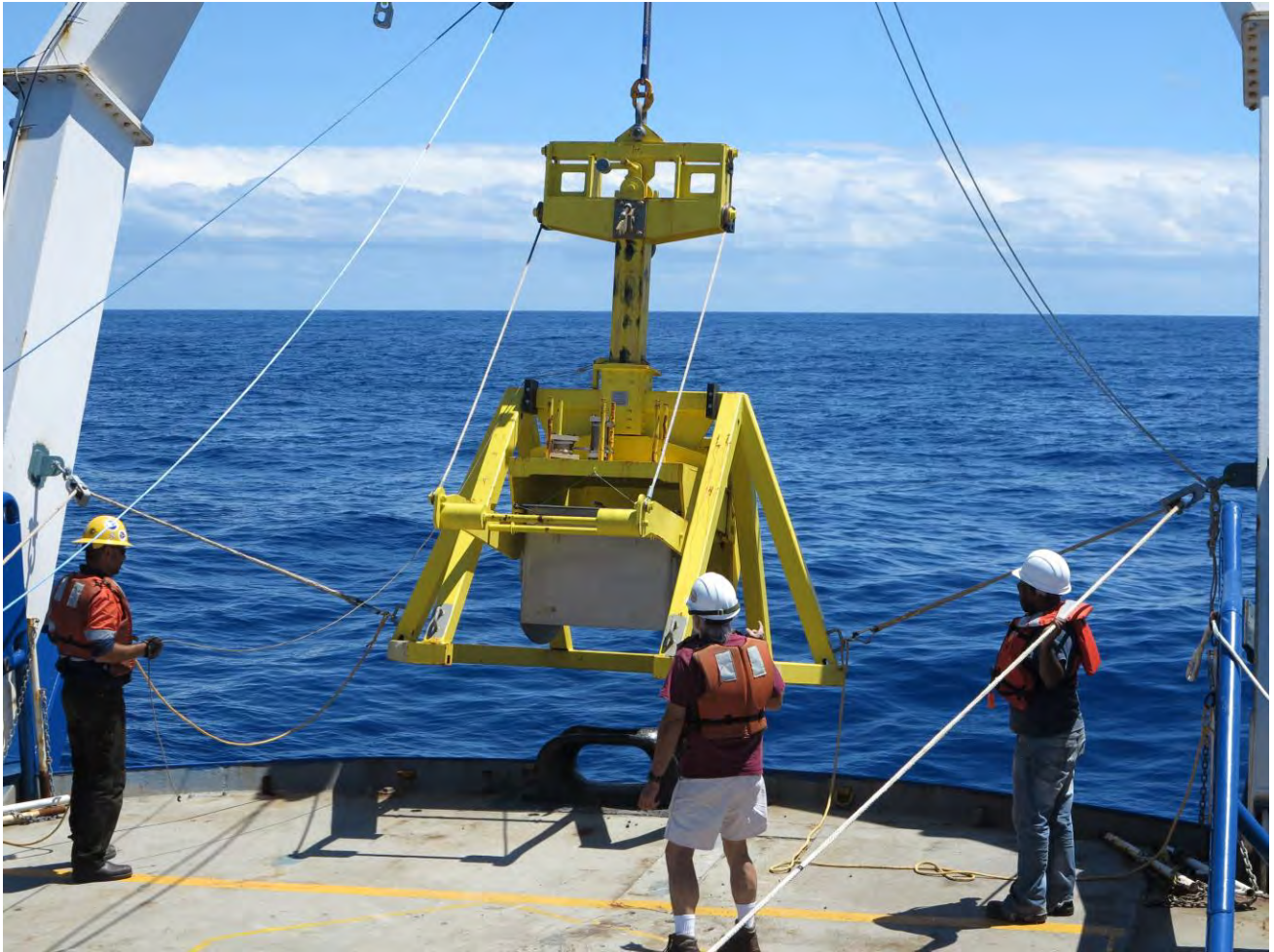
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First and final deployment of a prototype large area box-corer sampler on the R/V Mt Mitchell, central CCZ, September 2013.

Photo credit: Ashton Flinders.

6 Towards Modifying Factors

This chapter presents some of the published contributions made by the author in a few of the study areas that should be addressed before commercial exploitation of polymetallic nodules can be responsibly considered. The published documents comprise section 9.23 Appendix 6A: Other Publications, and their essentially original abstracts/summaries comprise this chapters along with some example figures. While from disparate fields, they contribute to Modifying Factors (per Figure 4 in Chapter 5) as it is this type of multidisciplinary approach that is required to:

- i. Accurately understand the costs and benefits of allowing a project such as deep seabed mining to proceed; and
- ii. Effectively and efficiently manage the project development to the point of sustained operations.

It is also worth noting that most of the publications presented here are based on physical or photographic samples collected from, or enroute to, the TOML contract areas, during the CCZ13, CCZ15 and CCZ17 expeditions. For the few that do not rely on those samples, measurements of other geological or related properties, such of those in Chapters 3 and 4, are still key.

A mineral resource is converted to a mineral (or ore) reserve through the application of modifying factors. Selection of key modifying factors (the potential list is almost limitless) is usually made by the project lead (or lead Qualified Person) on consideration of the factors' influence on project economics and project risk. For example, in the mining industry, metals or ore sales prices often have the largest single impact on a projects valuation, so forecasts/assumptions need to be included. Ecosystem impact, say relating to extinction of an endangered species, could stop the project from being permitted, so specific baseline, mitigation, management and monitoring also needs to be included.

Project management and project valuation go hand-in-hand, as repeated feedback between them is normally needed, especially if development options or material changes are involved. Some aspects of this approach exist even at the exploration and mineral resource definition stages, i.e. in the assessment regarding reasonable prospects for eventual economic extraction and in the selection of mineral resource cut-off parameters (Chapter 5). Nonetheless the mineral resource estimate and its underlying geological understanding are expected to remain relatively immutable. Projects that fail due to "issues" with the mineral resource need to be contextualised into those that fail because the mineral resource was wrongly estimated and those that fail because the mineral resource was misunderstood or misrepresented.

There is no prescriptive method for either project management or project valuation, it is up to the developer to choose what approach (and how much risk) they wish to take. However, there is considerable literature available regarding "best practice" in both fields e.g. (Australasian Institute of Mining and Metallurgy, 2013; McCarthy, 2015; McCluskey and Barros, 2016) and reporting codes such as NI 43-101 (CIM Mineral Resource & Mineral Reserve Committee, 2019) and JORC (Joint Ore Reserves Committee, 2012) lay out some expectations in what should be presented to prospective and existing investors of publicly listed companies.

6.1 Mineral abundance modelling methods

As discussed in section 4.3.2, nodule size distributions are interpreted to reflect their growth history in the geochemically active layer, at the 'facies scale', over long periods of time. Based on fundamental and validated hypotheses, the more sophisticated methods described in the paper below have potential

application not just in mineral resource (abundance) estimation, but in short term mine planning and mining system optimisation. This is because understanding the distribution of the sizes of nodules in a field or selective mining unit allows you to estimate their abundance by simply counting them, or in some cases by simply measuring their proportion of seabed coverage. This can include estimating the proportions of larger and smaller particles that the mining system would need to process (in conjunction with processing rates e.g. collector speed).

6.1.1 Empirical application of Generalized Rayleigh Distribution on resource prediction of seabed polymetallic nodules. (Yu and Parianos, 2021).

In this paper, an effective empirical statistical method is developed to improve the process of mineral resource estimation of seabed polymetallic nodules and is applied to analyse the abundance of seabed polymetallic nodules in the Clarion Clipperton Zone (CCZ). The newly proposed method is based on three hypotheses as the foundation for a model of “Idealized Nodules”, which was validated by analysing nodule samples collected from the seabed within the Tonga Offshore Mining Limited (TOML) exploration contract (Figure 6-1). Once validated, the “Idealized Nodule” model was used to deduce a set of empirical formulae for predicting the nodule resources, in terms of percentage coverage and abundance. The formulae were then applied to analysing a total of 188 sets of nodule samples collected across the TOML areas, comprising box-core samples and towed camera images; collected by one of the authors and detailed in (Lipton *et al.*, 2016) as well as Chapters 3 and 4 of this thesis. The analysis also relies upon detailed box-core sample measurements from other areas reported by Schoening and Gazis (2019). Numerical results for resource prediction were compared with field measurements, and reasonable agreement has been achieved. The new methods have the potential to achieve more accurate mineral resource estimation with reduced sample numbers and sizes. They may also have application in improving the efficiency of design and configuration of mining equipment.

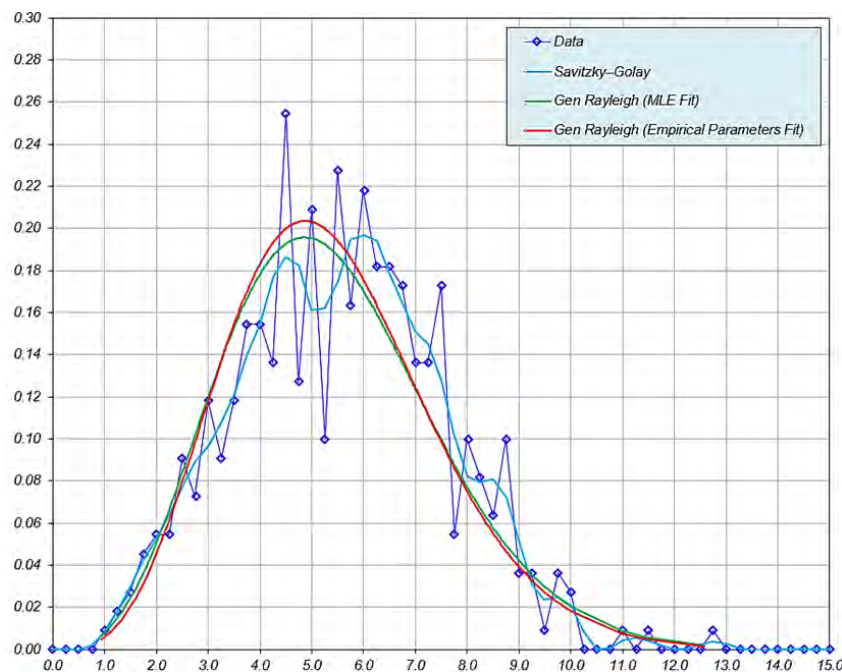


Figure 6-1: Probability Density Functions of an example towed seabed photograph (CCZ15-F05 2015_08_29_131349)

6.2 Protection of the marine environment

The marine expeditions led by the author in section 9.1 and 9.2 as much as possible integrated environmental sampling into the workflows for geology and geotechnical work. This included oceanographic measurements, sampling for micro, meio and macro fauna, and habitat mapping. Additional details on this sampling is included in Item 9 of Lipton *et al.*, (2016), for which the author served as Qualified Person and relying on Adrian Flynn of Fathom Pacific as an Other Expert.

A wide range of environmental research including baseline environmental surveys is required to inform contractors and regulators on if polymetallic nodule mining can be conducted without serious harm to the marine environment. This is required by UNCLOS (International Seabed Authority, 2001) and, as in other industries, expected to be summarised through an Environmental Impact Statement (EIS). Approval processes aside, this research is also often critical for contractors (with oversight from regulators) to support the monitoring and management of impacts during mining, as typically summarised through an Environmental Management and Monitoring Plan.

The CCZ15 towed photo-profiles, as well as photo profiles collected within the territorial waters of Kiribati enroute to the CCZ, were exhaustively logged by TOML staff (over 400,000 observations) under direction of the author and Christina Mele Pomee-Fatu. This was done in collaboration with Adrian Flynn of Fathom Pacific, Melbourne, Australia and researchers Erik Simon Lledo and Daniel Jones at National Oceanography Centre, Southampton United Kingdom. The data from Kiribati (Central Pacific Basin and Line Islands Rise per Chapter 2) is of special environmental value as it provides comparative data from outside the CCZ. This collaborative work resulted in two papers as follows:

6.2.1 Multi-scale variations in invertebrate and fish megafauna in the mid-eastern Clarion Clipperton Zone (Simon-Lledó *et al.*, 2020).

The abyssal seafloor of the Clarion Clipperton Zone (CCZ) in the central Pacific has the largest known deposits of polymetallic nodules and associated benthic faunal communities with high biodiversity. The environmental factors that structure these communities, both at regional and local scales, are not well understood. In this study, seabed image surveys (towed photo-profiles in TOML B1, C1, and D per Chapter 3) were used to assess distribution patterns in invertebrate and fish megafauna (>1 cm) at multiple scales in relation to key environmental factors: food supply to the seabed varying at the regional scale (hundreds of km), seabed geomorphological variations varying at the broad local scale (tens of km), and seabed nodule cover varying at the fine local scale (tens of metres). We found significant differences in megafaunal density and community composition between all study areas (e.g., Figure 6-2). Variations in faunal density did not appear to match with regional productivity gradients, although faunal density generally decreased with increasing water depth (from E to W). In contrast, geomorphology and particularly nodule cover appeared to exert strong control on local faunal abundance and community composition, but not in species richness. Local variations in faunal density and beta-diversity, particularly those driven by nodule presence (within study areas), were of comparable magnitude to those observed at a regional level (between study areas). However, regional comparisons of megabenthic assemblages showed clear shifts in dominance between taxonomic groups (perceivable even at Phylum levels) across the mid-eastern CCZ seabed, suggesting a higher regional heterogeneity than was previously thought.

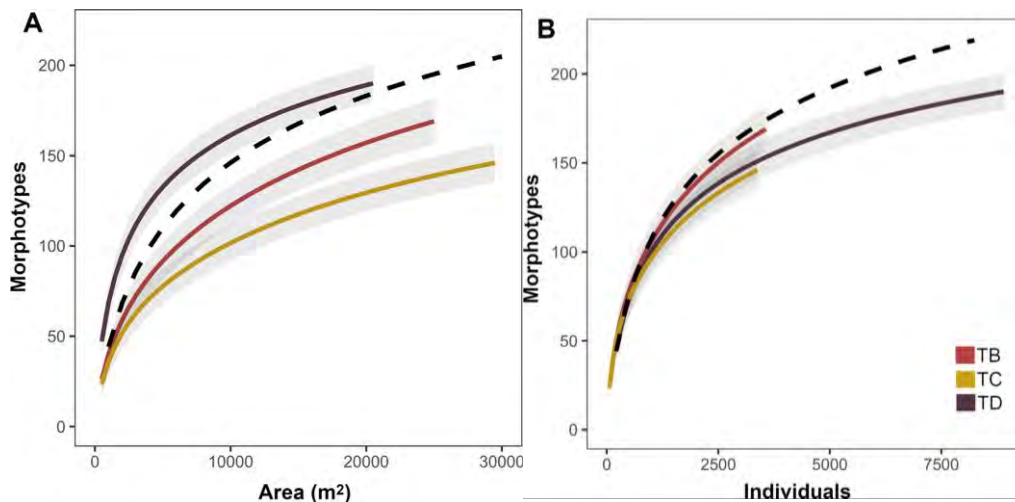


Figure 6-2: Invertebrate morphotype accumulation curves for each study area.

Dashed line represents combined data. Lines represent mean values across the 100 randomizations performed at each sample unit size increase, for each study area. Shadowing representing 95% confidence intervals. Dashed line represents mean values of curve calculated using whole-study combined data. (A) Curves calculated as a function of the seabed area sampled. Slope coefficients at line end: 0.0022x (TB); 0.0015x (TC); 0.0020x (TD), 0.0007x (Combined). (B) Curves calculated as a function of the number of the individuals sampled. Slope coefficients at line end: 0.0156x (TB); 0.0131x (TC); 0.0046x (TD), 0.0032x (Combined).

6.2.2 Preliminary Observations of the Abyssal Megafauna of Kiribati. (Simon-Lledó et al., 2019a)

We report on preliminary observations of the abyssal megafauna communities in the exclusive economic zone of Kiribati, a huge abyssal area with few previous studies. These observations also provide useful context for marine minerals exploration within the exclusive economic zone (EEZ) and for the neighbouring Clarion Clipperton Zone (CCZ), where deep-sea mining operations are planned. Seafloor images collected during seabed mining exploration (section 9.2) were used to characterize megafaunal communities (fauna > 1 cm) in three abyssal plain areas in the eastern Kiribati EEZ (study area extending from 1 to 5°N and 173 to 156°W). Additionally, hydrographic features in each of the survey locations were inferred by reference to near-seabed current flows modelled using open-sourced oceanographic data. The images showed a dominance of foraminiferal organisms. Metazoan communities were high in morphospecies richness (e.g., Figure 6-3) but had low density. These general patterns were comparable to abyssal megabenthic communities in the CCZ. There was evidence of spatial variation between the assemblages in Kiribati, but there was a relatively large pool of shared morphospecies across the entire study area. Low metazoan density limited detailed assessment of spatial variation and diversity at local scales. This finding is instructive of the levels of sampling effort required to determine spatial patterns in low density abyssal communities. The results of this study are preliminary observations that will be useful to guide future biological survey design and marine spatial planning strategies.

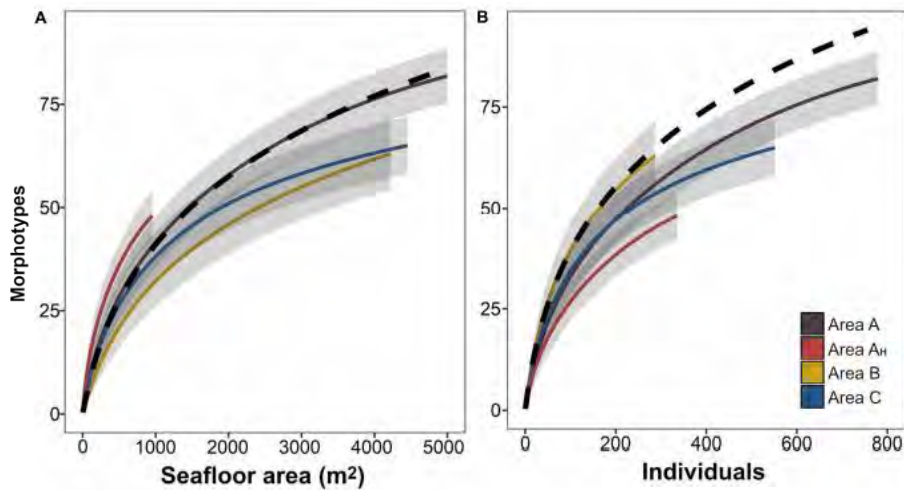


Figure 6-3: Metazoan morphospecies accumulation curves for each survey area.

Curves were calculated as a function of the seabed area (A) or the number of individuals encompassed by the sample unit size (B). Lines represent mean values across the 100 randomizations performed at each sample unit size increase, for each study area. Shadowing representing 95% confidence intervals. Dashed line represents mean values of curve calculated using whole-study collated data.

The data (and analysis) above resulted in four of the 23 datasets compared at a 2019 ISA biodiversity workshop (Jones et al., 2019) and the bulk of those in Figure 6-4.

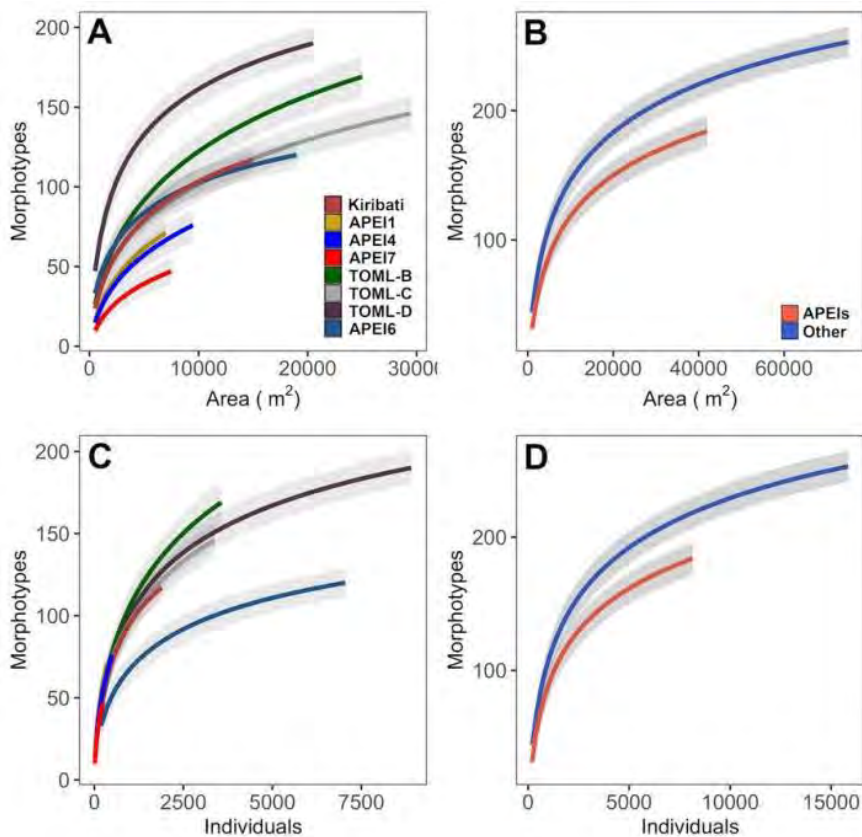


Figure 6-4: Rarefied morphotypes accumulation curves calculated across and combining Std-datasets.

Reproduced from (Jones et al., 2019). Curves were calculated as a function of the seabed area (A-B) or the number of individuals encompassed (C-D) in image-based sampling. Lines represent mean values across the 100 randomizations performed at each sample unit size increase, for each separate Std-dataset location (A and C) and combined for all APEIs and rest of locations within the CCZ (B and D) and hence excluding the Kiribati EEZ dataset. Shadowing representing 95% confidence intervals.

6.3 Mining and lifting

The author has led or co-led three interrelated patents and three published reports related to a novel concept for the mining of polymetallic nodules, namely:

6.3.1 EP3146154A1 Decoupled seafloor mining system. (Parianos *et al.*, 2014a)

Concerns a multi-stage seafloor mining system that has at least concentration stage (500 in Figure 6-5), a reclamation stage (300), and a haulage stage (200). The system includes a concentrating system that processes seafloor materials, a reclaimer machine that collects the processed seafloor materials, and a mechanical haulage system that receives the processed seafloor materials collected by the reclaimer machine and conveys discrete parcels of the processed seafloor materials to a surface vessel (100).

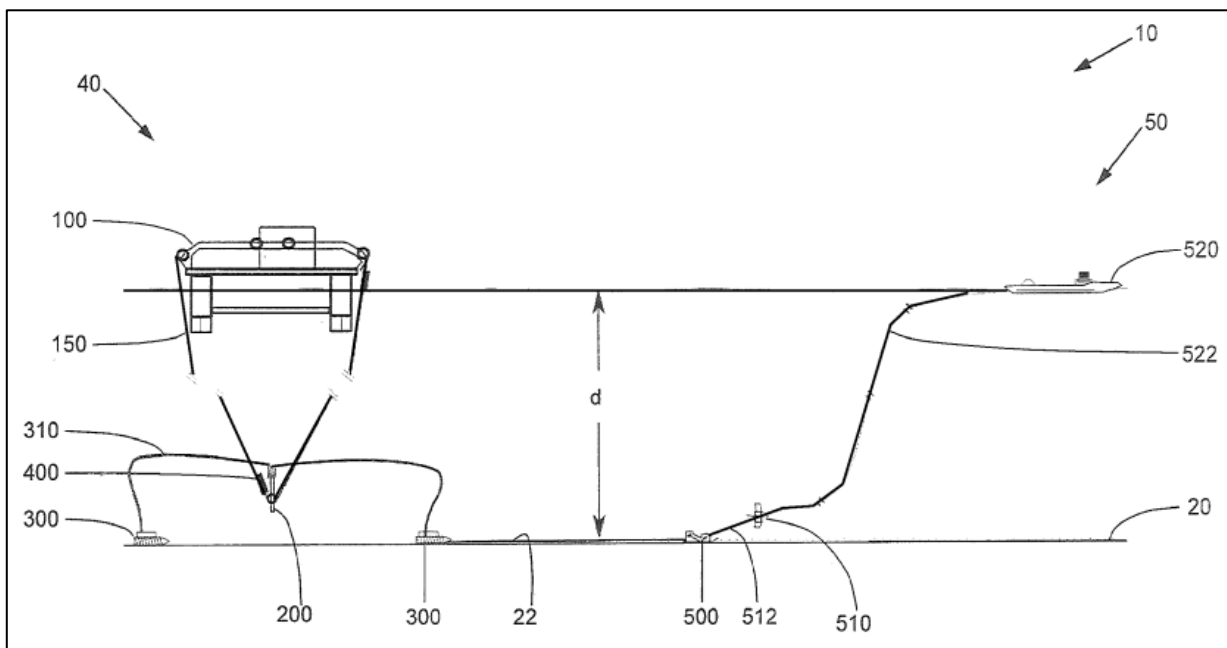


Figure 6-5: Decoupled seafloor mining system invention

6.3.2 EP2956590B1 A seafloor nodule concentrating system and method. (Parianos *et al.*, 2014b)

Concerns in more detail the concentration stage in the first patent. A seafloor nodule concentrating system is provided. The seafloor nodule concentrating system has a surface vessel (110 in Figure 6-6) and an undersea steering vehicle (120) secured to the surface vessel. The undersea steering vehicle is adapted to be towed by the surface vessel. The seafloor nodule concentrating system also has a nodule collecting apparatus (130) connected to the undersea steering vehicle. The nodule collecting apparatus is located on the seafloor. The seafloor nodule concentrating system also has a position determination device (140) adapted to determine the position of the nodule collecting apparatus and communicate position information of the nodule collecting apparatus to the undersea steering vehicle and surface vessel.

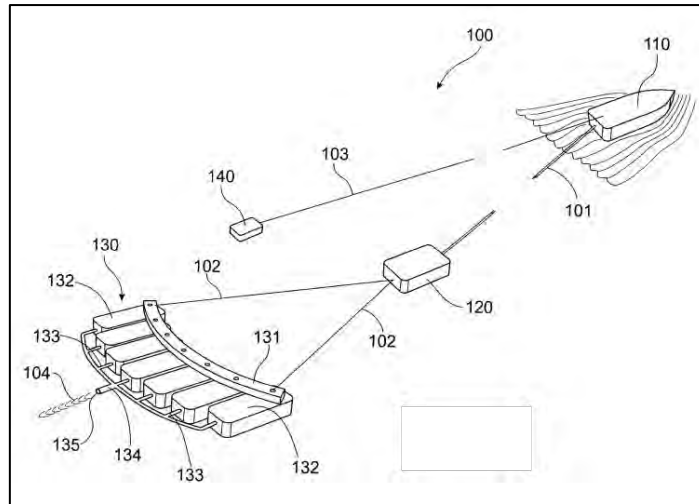


Figure 6-6: Seafloor nodule concentrating system and method invention

6.3.3 US10883252B2 Seafloor haulage system. (Berndt *et al.*, 2014)

Concerns in more detail the mechanical haulage system in the first patent (EP3146154A1). A seafloor haulage system (10 in Figure 6-7), for lifting seafloor materials from the seafloor to the surface, that has a line member (150), preferably synthetic rope, that extends at least partially between the seafloor (via a buffer; 200) and the surface (with winches; 110a, 110b, 112) and a container, preferably a plurality of containers (400 a,b), capable of carrying a load connected to the line member. The containers have a steerable element, such as a rudder, that enables the container to manoeuvre as it is propelled, typically towed by the line member, through the water.

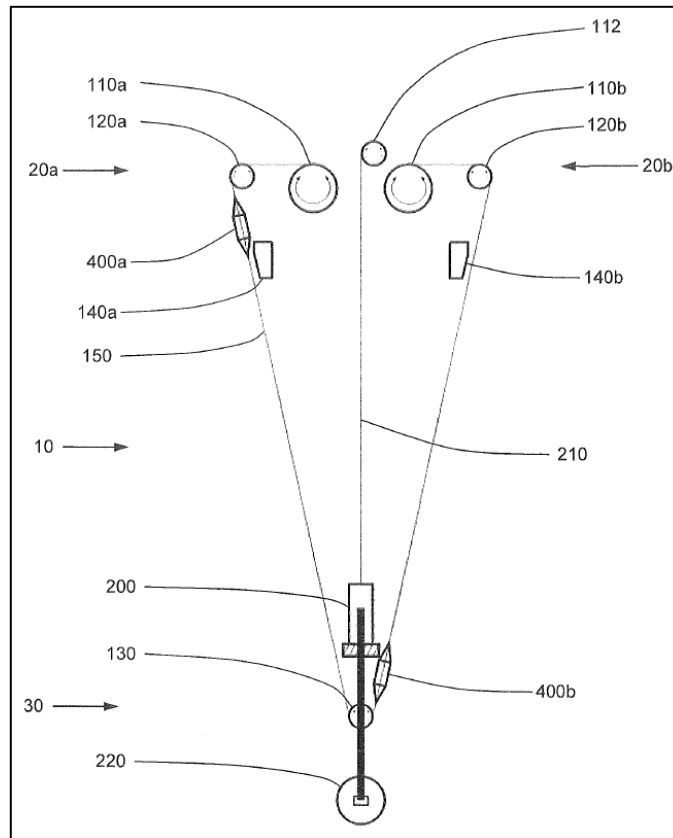


Figure 6-7: Seafloor haulage system invention

Note that a fourth patent (US20160311620A1 A Seafloor Vertical Hoisting System and Method) was abandoned when additional study found that it was not competitive with neither cable lift nor hydraulic risers.

Ongoing design and testing for the above-mentioned mining concept included full scale testing of the lateral conveying subsystem. This system within the concentrator array delivers nodules to a central point, where they are to be stacked in a windrow. The subsea lateral conveyor uses water to push nodules along a gently sloping tube (i.e., they are not suspended) so use less power and likely causes less attrition fine generation than a traditional hydraulic riser. Two technical reports were published on the lateral conveying subsystem as follows:

6.3.4 Nodule Lateral Conveyor -A Full-Scale Test (Manocchio *et al.*, 2020)

Nautilus' Decoupled Underwater Collection System design currently consists in part of a Concentrator Array (CA), led by a Concentrator Steering Unit (CSU), in turn towed from a surface vessel via towing umbilical. While this concept has survived critical review to date and is largely based on proven technology, it has not yet been fully tested at pilot scale. The collector sub-component in the CA was pilot tested in 1978 using collection widths of 2 and 3 m. The Nautilus full scale Concentrator Array (CA) design involves coupling up to 7 several such modules for an effective collection width of 21m. In our design, once the nodules are collected, they are deposited into a concentrated windrow on the seafloor for later reclamation.

To achieve this, nodules collected along the length of the CA need to be conveyed to the centre for windrow at a sufficient rate to meet the volumes required for full production. Nodules along the width of the CA, but particularly from the outer extremities, need to be moved at relatively high speeds to prevent accumulation. Given that this type of conveying is not known to have ever been done before at these rates and velocities, we set about doing a numerical simulation (reported below in Yu *et al.*, (2020)). This numerical simulation has identified critical velocities capable of conveying particles to satisfy the required production rate. However, the numerical results needed to be validated by real world data. We decided we could do a full-scale test to both prove the concept in a test environment but also substantiate the model for future design.

A full-scale test program was developed and undertaken 31st Jan – 3rd Mar 2020, in a purpose-built water filled test tank at Nautilus Minerals/TOML warehouse in East Brisbane, Australia. Some 55 tests were conducted involving:

Setup and calibration runs

- 1st set of tests with 6 m long array over 0° incline
- 2nd set of tests with 6 m long array over 3° incline
- 3rd set of test with 9 m long array over 0° incline

The authors were primarily responsible for the development of the test equipment, performing the testing, processing and validating the data with the numerical simulation.

The testing achieved the primary objective of demonstrating that nodules can be transferred at the velocities required to meet full production. The key findings are as follows:

1. The test program has shown the concept of a lateral conveyor is effective in conveying nodules at the desired production rates. In all test program cases, with a Flow Velocity over 2 m/s, all nodule particles can

be transported through the full-scale Conveyor Tube with a length up to 9 m (300 mm diameter), given a nodule feeding rate of 6 kg/s or higher.

2. The recommended flow velocity for is 4 m/s. However, extensive tests were carried out using flow velocity of 3 m/s for a 6-m Tube and this proved to be sufficient. For a design tube length of 9 metres, the numerical simulation, which has been validated by the testing, shows a flow velocity of 4 m/s will ensure a low nodule volume concentration throughout the Tube (<15%) to avoid a potential “backlog” of the Conveyor Tube.

3. With a recommended flow velocity of 4 m/s, *Shaft Power P1* required to generate the flow rate is estimated to be 11.88 kW and the required *Pump Power P2* is 14.25 kW. A high-flow and low-head impeller is recommended for this operation, similar to those commonly used in axial flow pumps.

4. This testing has played an important role in validating the numerical work detailed in (Yu et al., 2020). A Drag Coefficient of 0.4 is used throughout the numerical simulation, as commonly recommended in the literature.

A full-scale lateral conveyor is planned to be incorporated into the future pilot testing in the CCZ with actual nodules to test the “steady-state” conveying, which is impractical to achieve in a test environment.

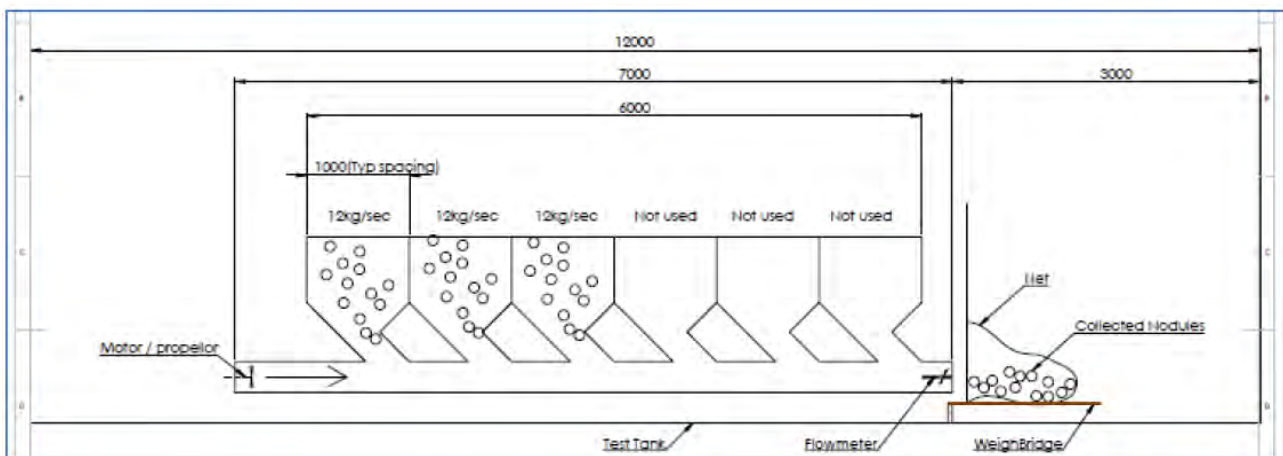


Figure 6-8: Schematic of test conveyor 6 m (1 side only)

6.3.5 Nodule Concentrator: Lateral Conveyor -Numerical Simulation (Yu et al., 2020)

The Lateral Conveyor is a key element of the Concentrator Array (CA), which carries the nodules picked up by each Concentrator module from the seafloor to the centre of the Concentrator Array to form a windrow. A new conveying concept was devised, which uses water flow in a conveyor tube, generated by an impeller at one end. The tube is fed from overhead feeders spaced equally along the tube.

A numerical model was developed to simulate the operation of such a Lateral Conveyor. The movements of nodule particles in the conveyor tube were modelled using a “section-wise” approximation, which assumes flow parameters remain the same in the section between two feeders and a flow steady state has been reached (i.e. the flow parameters are no longer varying with time). The numerical procedure consists of:

1. Firstly, the flow velocity loss along the tube is estimated by applying the principal of “conservation of energy” to the transferring of kinematic energy from the flow to the nodule particles.
2. Secondly, various differential equations governing modes of particle movements in a uniform flow are derived and solved.

3. Finally, the nodule particles movements are simulated, section by section along the tube, using the previously solved equations of particle movements (solved in 2 above), with the reduced “section-wise” flow velocity (estimated in 1 above) as boundary conditions.

The numerical results were calibrated and compared with the results of a full-scale lab test program (reported above in Manocchio *et al.*, (2020)), which was carried out in conjunction. The calibrated numerical method was then used to analyse the nodule conveying process, which is impractical to test in a lab environment. The results of the analyses are hoped to provide design parameters for a future project.

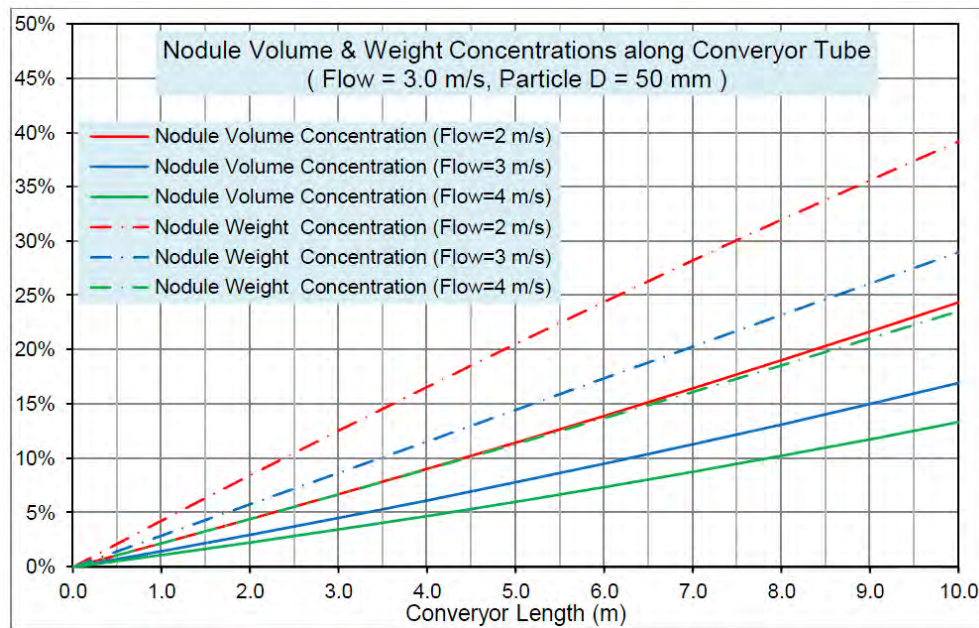


Figure 6-9: Nodule weight and volume concentrations along length of conveyor tube at different flow velocities

Development of the haulage concept, under direction of the author, was done by TOML’s then owner Nautilus Minerals between 2012 and 2020. Most of the work is unpublished and proprietary, but a collaboration with Institute of Deep-Sea Science and Engineering (IDSSE) in Sanya China, led to the following publication.

6.3.6 Model Test of Skip Lifting System for Deep-sea Mining. (Xiao *et al.*, 2019)

Skip lifting is a new concept of mechanical lifting system for deep-sea mining. It is expected that skip lifting is capital cost effective and energy efficient compared to hydraulic pump lifting system. Furthermore, the lesser by-products of seawater and sediment is very attractive in the aspect of minimising environmental impacts. This paper presents fundamental results of scaled model test (Figure 6-10) conducted for the purpose of technological study on skip-lifting system. Main measurement factors are system configuration, angular response and horizontal acceleration of buffer station. Study results reported here will provide reference data for the pilot test and the commercial realization. The hydrodynamic resistance of skips obtained from our single skip test help explore further the key parameter of water resistance.



Figure 6-10: Skip lifting model test setup

Water tank (left), carriage and topside of skip-lifting model (centre), conceptual diagram and components (right)

6.4 Process Metallurgy

As mentioned at the start of Chapter 4, polymetallic nodules are a bulk commodity. This means their processing is much like iron-ore, bauxite and nickel laterite (McQueen, 2005), in that the entire rock needs intensive processing (smelting or leaching) from the outset and unlike some other types of ores (e.g. seafloor massive sulphides) that can have the ore minerals cheaply concentrated prior to the more intensive processing steps. Past research, e.g. (Haynes *et al.*, 1985) has identified that CCZ polymetallic nodules can very likely be processed using existing technology, albeit with some level of adaption. The high intrinsic value in polymetallic nodule mineral resources also means that in due course purpose built metallurgical plants may make economic sense. Development of metallurgical processing options for polymetallic nodules, under direction of the author, was done by TOML between 2012 and 2020. Most of the work is unpublished and proprietary, but a collaboration with the University of Queensland, Brisbane Australia, has led to two papers as follows below. The dredge sample used in the testing for these papers is from CCZ17-D01 in TOML C1 per Figure 6-11.

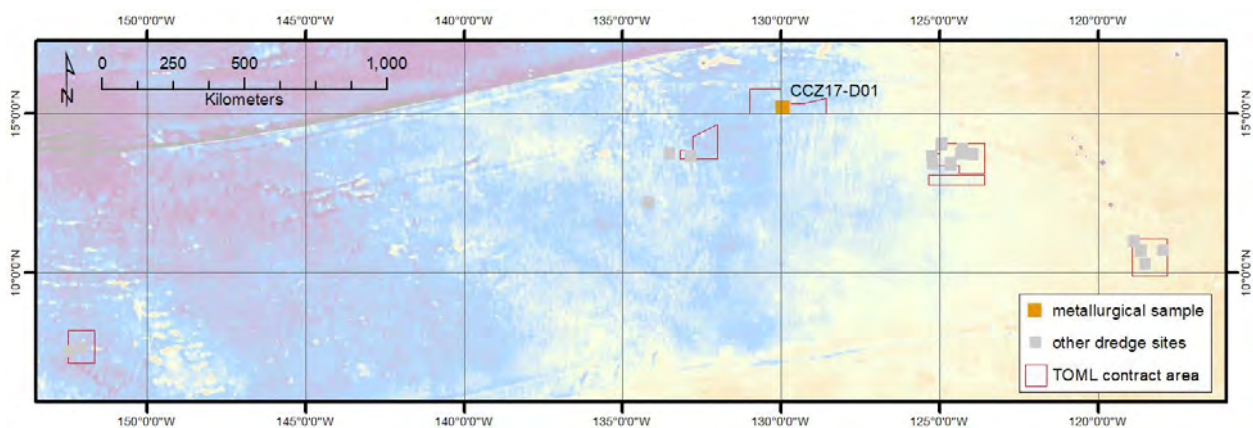


Figure 6-11: Location of the metallurgical sample

The first paper re-looks at role of flux and reductant in an attempt to reduce the temperature of smelting separation of Ni, Cu and Co, to as as low as possible (this opens the possibility to use a wider range of potentially more efficient furnace designs). The second looks at the generation of metal-matte (sulphide)

which is a much more useful intermediate product than alloy in refine further, albeit harder to create initially.

6.4.1 Thermodynamic and Experimental Study on Efficient Extraction of Valuable Metals from Polymetallic Nodules. (Su et al., 2020a)

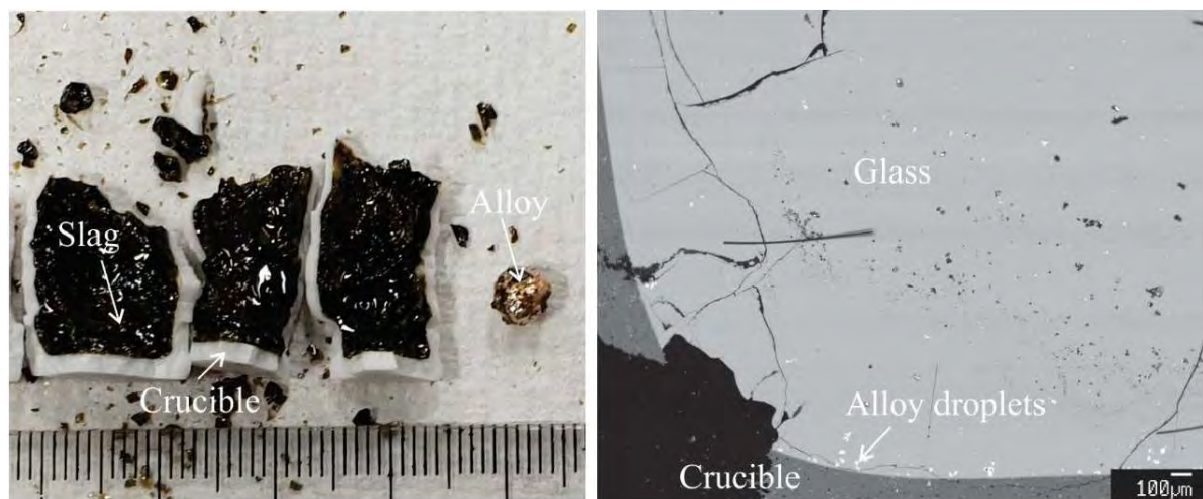


Figure 6-12: Quenched polymetallic nodule sample after smelting at 1,350 °C with 4 wt% carbon addition. Sample ND9.

Polymetallic nodules are promising resources for the extraction of valuable metals such as copper, nickel, and cobalt, as well as manganese alloys. To achieve efficient extraction of useful metals from the emerging resource, high-temperature carbothermic reduction of nodules was investigated by optimizing the reductant addition, slag and alloy systems. Thermochemical software FactSage was used to predict the liquidus temperature of the slag system, which is not sensitive to FeO, CaO and Al₂O₃, but decreases significantly with decreasing MnO/SiO₂ mass ratio. The experiments were designed to reduce the oxides of Cu, Co and Ni completely, and reduce FeOx partially depending on the amount of graphite addition while leaving the residual slag for further processing into ferromanganese and/or silicomanganese alloys. Co, Cu and Ni concentrations in the alloy decreased with increasing graphite addition. The optimal reduction condition was reached by adding 4 wt% graphite at the MnO/SiO₂ mass ratio of 1.6 in slag. The most effective metal-slag separation was achieved at 1,350° C, which enables the smelting reduction to be carried out in various types of furnaces.

6.4.2 Alternative Resources for Producing Nickel Matte -Laterite Ores and Polymetallic Nodules (Su et al., 2021).

Polymetallic nodules and nickel laterite ores are composed of various valuable metals and have similar nickel concentration, which makes them ideal alternatives for industries seeking to meet the increasing demand for nickel resources. The extraction process of polymetallic nodules can utilize the well-established nickel laterite treatment process without the need for developing new processes and thus, save capital costs.

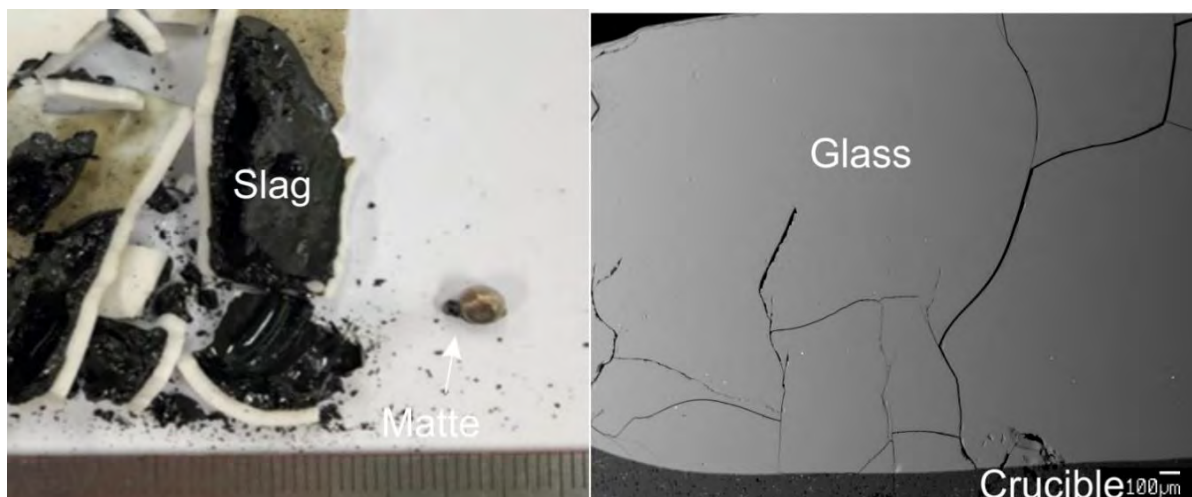


Figure 6-13: Quenched polymetallic nodule sample after smelting with sulfide at 1350 °C, with 4 wt% carbon, 5 wt% FeS addition. Sample NM3

Herein, to efficiently extract nickel from these resources, high-temperature carbothermic reduction and sulfurization were investigated by optimizing the slag and matte systems. FactSage, a thermodynamic software was used to predict the slag system's liquidus temperature and the formation of nickel matte. It was found that nickel matte formation was not dependent to CaSO_4 addition whereas the nickel concentration in matte decreased with an increasing amount of the sulfiding agent FeS. Furthermore, the addition of a reductant significantly affected the concentration of nickel in the matte. A nickel concentration of ≥ 30 wt% and iron concentration of ≤ 40 wt% in matte were achieved by adding 0.5 wt% and 3 wt% carbon to nickel laterite ores and polymetallic nodules, respectively. Furthermore, replacing the sulfiding agent FeS with CaSO_4 during the smelting of polymetallic nodules decreased the iron concentration in matte ≤ 15 wt% and increased the nickel concentration ≥ 50 wt%. Thus, this study confirmed the possibility of matte formation with high nickel concentration and low iron content by utilizing alternative nickel resources at 1,350 – 1,450 °C.



Clipperton Atoll

Source: Google Earth (Copernicus). Image date is November 2007

7 Conclusions, short synthesis and way forward

There are no references in this chapter, as these often require prolonged contextual explanation and/or qualification, which has already been done in the preceding chapters.

7.1 Conclusions and short synthesis

The chapters of this thesis examine the CCZ from scale to scale, providing new contributions to the very significant extant body of work. The essential new data supporting this thesis comes from two marine expeditions led by the author to the TOML contract areas, and from data supplied from the NORI and Marawa areas. These areas and data span much of the CCZ.

In Chapter 2, the entire CCZ is mapped a regional scale of 1:4,000,000, based on GEBCO grids, and supported by deep sea drilling program data, magnetic isochron interpretation and some published 12 kHz MBES coverage. The mapped geomorphological and structural units characterise each part of the CCZ, in terms of age, geomorphology, stratigraphy, structure and to some extent nodule prospectivity. This should be of interest to the ISA exploration contractors who work there as well as their regulators and sponsors.

The regional mapping leads to a refined structural model, as the orientation of the mapped units relates to the geometry and geological evolution of the lithospheric plate segment. This is through the interplay of three forces, namely: 1. overall Pacific Plate motion to the NW; 2. WSW-ENE extension (spreading) within the CCZ plate segment; and 3. the relative rate of seafloor spreading between the CCZ plate segment and adjacent plate segments. In this context, geomorphic rises and some lows can be related to changes in relative plate segment speeds and associated widening or narrowing of the bounding fracture zones, and some lows to changes in spreading rates and to propagating tension associated with inter-plate segment spreading rates.

The regional mapping also reveals that there is no simple relationship between regional scale geomorphological units and the distribution of nodule mineralization, but priority areas for developers are often located near unit contacts. This is likely due to locally significant changes in depth and/or related influences on seabed currents.

In Chapter 3, the surface geology for seven discrete areas is mapped at a local scale of 1:250,000. These are located across the central and eastern parts of the CCZ and involve some ~173,000 km² from 116° to 134.5° W (~2,000 km) and 10° to 16° N (~700 km). The mapping is based on 12 kHz ship mounted MBES bathymetry and backscatter, which is data routinely collected by ISA exploration contractors. This mapping is well supported by more detailed data (seabed photo profiles, sidescan sonar, sub-bottom profiles, nodule samples and two drilled sites). Some significant limitations of mapping using the backscatter response are illustrated via integration of the datasets. Where practicable, the detailed data is also compiled into two geological maps and nine cross-section sections, all at 1:25,000 scale. New findings are:

- The mapping reveals distinct geological differences between the seven areas, but a common stratigraphy as follows:
 - Tholeiitic abyssal hills basement. These horst-grabens are generally symmetrical (rather than archetypal asymmetric facing their source spreading centre). They interconnect via classic relay ramps and conjugate relay zones. Their frequency and amplitude can change between areas within geomorphological plains and geomorphological lows (where they can be more pronounced).

There are also flatter areas where the hills are subdued to absent, and these are often in the vicinity of volcanic knolls, but in at least one case seem to result from intrusions that extend from the basement into the overlying stratigraphy, and in some cases to the modern-day surface.

- A basal, 75-90 m thick, sediment unit of Marquesas Oceanic Formation chalk. Regional changes in sedimentation regime are indicated in that the same marker horizons in sub-bottom profiler data can be identified in different SBP profiles in the same area, but not in profiles between different areas (several hundred km away). The chalk shoals in places, with expression of pavement and residual breccia (carbonate chalk being chemically unstable at these depths below the lysocline).

This unit forms potholes on some abyssal hills (being more common in the western and northern areas with older and deeper seafloor) and carbonate strata breccias (newly described) in some abyssal valleys. Some of the potholes are associated with dykes that intrude the chalk.

- An upper, 0-30 m thick, sediment unit of Clipperton Oceanic Formation clay-ooze. This is significantly less consolidated than the underlying chalk. The unit is mobilised by seabed currents and often forms sediment drifts; these can concentrate along the sides (contours) of abyssal hills and around the bases of volcanic knolls. Near the southern limits of the CCZ the unit can have gradationally higher CaCO₃ contents.

The Clipperton Formation clay-ooze is unit is the host to the polymetallic nodules.

- A wide range of volcanic edifices, discrete in form from the abyssal hills basement. These likely have ages likely ranging from syn-crustal formation to current day, as they can underly chalk or be found resting on the clay-ooze. These edifices include single and composite knolls composed of lava and breccia, seamounts composed of lava flows and of talus breccia, sheet lavas, fissure lavas, breaching dykes (with associated surface breccia), and >100 m deep to surfacing sills and laccoliths.
- Mapped differences between the areas mostly relate to variance in the proportions of the different mapped units, especially the proportions of flatter areas, sediment drifts and volcanic knolls. These differences will likely have significant influence on the mineral resource estimates and mineral reserve estimates for the different areas, as these units can be essential in geological domaining.
 - Regarding use of the backscatter response for mapping, a comparison with towed photo-profiles showed that many units overlap in terms of their response. These include: sediment drifts versus shoaling carbonate; and areas with high abundances of small nodules versus a few large nodules versus volcanic breccia. Albedo off slopes is also significant. Thus, use of backscatter in mapping is qualitative as best, but works a little better if bathymetry is also considered. Four groups of mapped units were used to successfully constrain nodule prospectivity during the TOML CCZ15 expedition and then help inform the resultant mineral resource estimate:
 1. Highly prospective nodule bearing clay-ooze areas. These have medium to medium-high levels of backscatter reflection and are located on abyssal hills and flatter areas.
 2. Lowly prospective nodule bearing clay-ooze areas. These have low to very low levels of backscatter reflection and are located on abyssal hill valleys and side slopes (likely sediment

drifts) and less commonly on abyssal hill tops, in some cases with potholes, or adjacent to volcanic edifices (likely shoaling carbonate with minor clay ooze cover).

3. Normally prospective nodule bearing clay-ooze areas. These have low to medium levels of backscatter reflection and are located on abyssal hills and flatter areas.
4. Likely escarpments and volcanic outcrops. These have medium to high levels of backscatter reflection and have distinctive bathymetric forms.

Chapter 4 considers some of the less well documented key physical and chemical properties of polymetallic nodules. There is a strong focus on samples collected by teams led by the author from the TOML contract area, but additional important chemical data from the NORI D and Marawa areas is included.

- Published dialog on the formation mechanism and mineralogy of CCZ type nodules is contextualised a little further with electron microprobe and QEMSCAN results from unpublished studies associated with the author. Of special note are the proportions of Fe vs Mn rich phases (vernadite and buserite growth rings), as well as observations regarding the disposition of key metals into those and various other phases, most notably interstitial smectite and zeolite.
- Nodule types across the CCZ vary more than local classification systems can handle. Simply adding several size and textural qualifiers to the ISA 2010 classification is shown to work well, across and between different areas. Nodule forms are interpreted to reflect the conditions of their growth, specifically at the scale of mappable facies. The thickness and stability of the geochemically active layer are then interpreted to be the two main controls, with stability is most likely affected by seabed currents. While bioturbation may have an effect, it is likely more important as a process in that it can stop nodules growing together and it helps keep them at the seabed surface by removing and moving the host sediment away (i.e., to alongside the nodules and then underneath).
- A special case is that regarding strongly prolate nodules. These are often found in mixed orientations amongst more oblate nodules, but can also grow mostly alone and aligned along bathymetric contour lines, indicating that long term currents shape nodules.
- Also of note are the diagenetic crusts found in the CCZ (e.g., TOML A and TOML D). These crusts are a natural end member of the mechanisms of nodule formation, namely the cases where stability in the geochemically active layer (including bioturbation) is sufficient to allow ferro-manganese precipitates to amalgamate.
- A study of nodule chemistry, focuses on new multi-element chemistry from box-core data from the sub-areas TOML B1, C1, D1, D2, F, NORI D and Marawa 19,20. This work:
 - places the CCZ nodules (including new box-core sample data), exactly as classified by past workers (mixed oxic and sub-oxic conditions of formation).
 - shows that the TOML, NORI and Marawa nodule samples have remarkably low chemical variance;
 - indicates that there are six clear main element groupings in terms of inter-correlation (in effect phyllo-manganate association; silicate association, barite association, apatite association, cobalt and similar, REE and other transition elements). This helps frame any discussion on geochemical characterization and genesis.

- allows for a more complete interpretation of chemical variations at the regional scale (between sub-areas) and in some cases at the local scale (within sub-areas).

Of note is, that at the regional scale, nodule Co grade trends in the CCZ are almost entirely decoupled from those for Ni, Cu, Mn and that for Fe. A tentative correlation with ocean silicate (silicic acid) levels, as well as a range of other oceanographic and nodule-chemical criteria, suggests that CCZ mineralization is fed by variably blended contributions from calcite bio-productivity (e.g. foraminifera, coccoliths) and silicate bio-productivity (e.g. radiolarians, diatoms), with the silicate contributions being offset to the north of the calcite contributions. This is likely due to the CCZ being located where the circum-pacific North Pacific Current meets the North Equatorial Current.

Within the TOML F/NORI D area, general south to north changes in the Ca contents of nodules and host clay-ooze likely relate to declining primary productivity and net export to the seabed. This variation matches a change observed in multibeam backscatter response. There is also a clear correlation with nodule type in this area, with type 2 (RS) nodules having higher Cu and lower Fe reflecting varied high diagenetic (versus hydrogenetic) contributions. A local scale trend observed in TOML B is deduced to be possibly due to common inclusion of volcanic fragments in nodules coupled with regionally higher silicate bio-contributions.

- The results of a series of physical tests on nodules completes Chapter 4 and these combine to provide an essential first look at some of the nodule characteristics that would need to be considered by future nodule developers. Specifically:
 - Within a tight range, nodules have a wet density of slightly under 2 g/cm³ with TOML B, C and D averaging 1.98 g/cm³ and TOML F 1.93 g/m³.
 - Sediment densities (± 1.2 g/m³) follow a similar locational trend with TOML B and C sediments being slightly denser and increasing in density/consolidating more rapidly with depth than TOML D, which in turn is slightly denser/increasing more rapidly with depth than TOML F. This is interpreted to indicate slightly less consolidation time and/or higher bioturbation rates for more the easterly areas.
 - Moisture content in nodules comprises around 28% free water and 16% structural water.
 - Air drying removes about 12-18% of free water after 200 hours and but then no more, even after 3 – 5 years. Ambient humidity can vary results by about 2 or so percent. After oven drying to 105°C, up to 7% moisture can be reabsorbed into nodule fragments in 18 hours, and pulped nodule samples can reabsorb around 10%.
 - Nodules stored in water at the surface undergo some decompression (likely related to mineralogical and associated micro-fractures) and can absorb an additional 1 to 6% moisture.
 - Drying nodules to 105° C prior to chemical analysis is an acceptable compromise against industry standards when mineral transformations are considered.
 - While starting off solid and stable, nodules have the propensity to crumble when tumbled under wet or dry conditions. This eventually can lead to a potential transport safety risk via slumping of cargo in the hold of bulk carriers due to a high proportion of fines. When handled dry, nodule particles break more, when handled wet, they abrade more. Nodules

can be considered per iron-ore fines guidance as they have more in common with iron-ore fines than other bulk commodities. Per this guidance then, dry only or wet only handling takes 1 to 2 hours to exceed tolerance thresholds. A combined wet and dry handling could however cause more rapid exceedance (1 hour or less), so the detail of handling needs to be considered in any future work as does any testing involving hydraulic risers.

- Nodules have packing densities of around 0.61-0.67 depending on nodule particle size distributions.

In Chapter 5, the ultimate objective of the marine expeditions and much of the above-mentioned research is discussed. This involves mineral resource estimation and reporting for polymetallic nodules. Mineral resource estimation is important to the owner of the resource (all of mankind; and managed by the International Seabed Authority; ISA) and to developers (commercial and government groups with contracts with the ISA). The Committee for Mineral Reserves International Reporting Standards was developed for the land-based minerals industry and adapted in 2015 for ISA-managed nodules. The author contributed to the first polymetallic nodule resource estimates completed and reported to a contemporary standard, as used by the mining industry worldwide.

- Multiple lines of evidence, such as physical samples, seabed photographs and multibeam echosounder survey, lead to a common view of the deposit's characteristics. The sampling methods and scales of mineralization are unique to this type of deposit but are proven to assist rather than hinder in the accurate estimation of mineral resources. The extremely low variance of nodule abundance and grades form a stark and beneficial contrast with most terrestrial metalliferous deposits.
- Mapping of units at 1:250,000 scale from 12 kHz MBES can be used to define domains to constrain mineral resource estimation even at an inferred level of confidence.
- Nodules can be sampled in a meaningful manner using mechanical devices, albeit with minor issues of bias. Support for abundance estimates using photographs is demonstrated to be effective, at least in most of the TOML and NORI D areas.
- Grade and moisture content are measured using the established methodology for land-based minerals.
- Contemporary resource estimates for nodules classify the level of confidence in the estimate by considering deposit geology (via domains) and sample geostatistics. This is something that was considered from the outset of the TOML work-programs.
- The commercial mining of polymetallic nodules has not yet been achieved; therefore, there are no precedents to draw upon for the estimation of mineral (ore) reserves. Nevertheless, successful pilot mining of polymetallic nodules in the CCZ in the late 1970s, a long history of deep-water oil and gas operations, and the apparent amenability of polymetallic nodules to various proven metallurgical processing methods all indicate that there are reasonable prospects for defining mineral reserves and developing viable production systems on the deep seafloor.

In Chapter 6, a series of publications are summarised in which the author was involved as lead author or co-author. These contribute to the knowledge base that will be needed to derive modifying factors. In turn these factors will allow for the estimation of the mineral reserves that are needed for further development

and valuation of polymetallic nodules projects. The conclusions from these publications are manifest but at a high level include:

- Nodule particles are found in readily predictable distributions, that can be used for easier and more accurate abundance estimation.
- With industry and academic collaboration providing more extensive datasets, ongoing study of megafauna morphotypes within and external to the CCZ is resulting in a greater understanding of their regional scale diversity, distribution and variation, which will be important in estimating likelihood of serious impacts if deep seabed mining proceeds.
- Pilot mining of nodules was achieved in the late 1970s, but efficiencies of the systems tested then are expected to be low. The total nodule mining and lifting process can very likely be decoupled into several more effective and efficient steps, with attendant material handling benefits. Some of the novel aspects of this approach have been successfully tested.
- Published testing indicates that processing technology for polymetallic nodules already exists. However, more efficient pyrometallurgical processes (e.g., involving slightly lower temperatures) seem possible from optimisation of the slag and alloy systems at a benchtop scale. Production of more readily saleable and refinable matte intermediates also seems possible.

7.2 Way forward

Looking to the future there are two general themes.

Firstly, the range of possible scientific research topics is tremendous, and just a few ideas are:

- Refinement of the regional geomorphological-structural interpretation especially as/if improved data becomes available. An obvious avenue is to extend to approach to other parts of the Pacific and to build a more unified development model.
- Future more detailed study of the carbonate mega-mound should consider use of site planning based on MBES survey, seabed geotechnical drilling rigs, more extensive sub-bottom profile surveys, and smaller, cheaper expedition vessels (this would equate to more, better located holes with potentially equivalent or better core recovery).
- Improve local attempts to calibrate backscatter using detailed photographic coverage of key nodule types and by resampling both datasets at different scales. This ideally supporting additional 1:250,000 scale geological mapping for other contract areas covered by 12 kHz MBES.
- A more systematic but relatively simple micro-probe/QEMSCAN study could easily add to the understanding of mineral disposition of metals in different nodules from different areas.
- The subject of dynamic seafloor in the CCZ needs urgent attention, there are now numerous examples of active sediment transport mechanisms including mega-ripples and contourite sediment drifts.
- The hypothesis that CCZ wide metal distributions are due to two disparate biogenic sources (siliceous and calcareous), needs to be more rigorously tested, probably on the basis of more systematic purpose collected data, perhaps incorporating mass-balance type calculations.

- Mineral resource estimates, especially for the higher levels of confidence (and extending into short term mine planning models), can very likely be improved through integration of nodule size (weight) distributions.
- Data integration regarding the marine environment (regarding megafauna morphotypes) has shown to be effective and has clearly helped in understanding the baseline. It would be great if this can be expanded further within the CCZ, especially using existing high-quality data likely held by other contractors.

But secondly, the ultimate development objective of UNCLOS remains unfulfilled, that of sustainable seabed exploitation of polymetallic nodules. The reporting of estimates addresses reasonable prospects for eventual economic extraction, including factors such as mining technology, the marine environment, metallurgical processing, and metals markets. Today we are in the midst of the second serious attempt to commercialise polymetallic nodules, and it will be undoubtably fascinating to see how this proceeds.

This valuable and remarkable mineral deposit is the common heritage of mankind and cannot be simply sidelined. As pointed out at the start of this thesis, proponents of development cite demand for metals that land based deposits increasingly struggle to meet sustainably. Opponents to development cite the sensitivity and currently pristine nature of the marine environment. Administrators of development under UNCLOS, have increased efforts to deliver effective regulations, guidelines and standards. For all of us stakeholders, more knowledge should contribute to better informed decision making, and hopefully the research developed in this thesis will be of some assistance.



Marine Scientist Mele Christina (Tina) Pome'e Fatu

Photo credit: author

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This thesis is a partial result of over seven years of work into the extraordinary mineral occurrence that is the Clarion Clipperton Zone polymetallic nodule deposit. Not included, but of almost equal interest is most of the work I did on the history of human endeavour in this field, the marine environment and ecosystems, associated marine engineering and logistics, mining and metallurgical processes and practices, metals products and markets, some quite diverse social and geopolitical issues, and not forgetting the currently evolving statutes, regulations, guidelines, standards, precepts, and ordinances governing minerals exploration and exploitation.

But it is the geology of the CCZ that I would place first in my list of what is extraordinary. Working on this deposit was truly a privilege that I doubt I will have opportunity to equal. Starting with the scope and scale of this continental scale deposit and its elegant formational processes, then the management of focused expeditions and dedicated teams, the acquisition of fundamentally new data, the interpretation of totally new ground, and then the amazement that so often accompanies scientific discoveries big and small. This all culminated in managing and contributing to the first estimation and reporting of polymetallic nodule mineral resource estimates, to contemporary standards, and to the highest level of confidence.

Obviously, such an endeavour is not a solo effort. My first accolade is to those pioneers of marine exploration of the 19th and 20th centuries. My ~50 page attempt to record their remarkable achievements is in Item 6 of (Lipton et al., 2016). The investors in the company I worked for, Nautilus Minerals, also have my sincere appreciation. Grateful acknowledgment to both Deep Green Metals (Anthony O'Sullivan) and Deep Sea Mining Finance (Chris Jordinson and Matthias Bolliger), who supported this thesis via access to data, time and equipment. Working at sea for protracted periods of time has never been described as easy, and so the complements of the CCZ13 and CCZ15 expeditions, for whom I acted as Chief Scientist, have my profound respect and thanks, especially Christina Pome'e Fatu, Rod Conroy and Anatoly Sapiridi. My then manager Jonathan Lowe envisioned and championed our efforts tirelessly, especially when needed most. Ian Lipton and Matthew Nimmo, who were my lead and co-qualified persons for the mineral resource estimates demonstrated true innovation in this area of expert judgment. A wide range of other stakeholders also supported our work, especially warm acknowledgements to Adrian Flynn, Anthony Manocchio, Baojun Zhao, Blaze Riada-Horn, Charles Morgan, Davey Banning, David White, George Seely, Georgy Cherkashov, Jim McCluskey, João Carvalho, Keiran Schneider, Mercy Pringle, Shaun Kenny and Ted Brockett, who all gave above and beyond regarding the above-mentioned expeditions and subject matter in this report.

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The time to write this thesis came courtesy of a 2020/21 COVID 19 lockdown, and my wife Nicola bravely and tolerantly persisted with my now permanent presence at home, as well as with the particular demands that writing such a document invariably seems to incite. Love, I clearly owe you a 'big one'...

Finally, this thesis would simply never have happened without the encouragement, pragmatic guidance and solid supervisory support of Pedro Madureira - thanks so much for all your help!

To those that I believe in, you have my respect and admiration.

To those that believe in me, you have my gratitude and appreciation.



9 Appendices

Appendices that are text-based documents are included here. Other appendices that are spreadsheets, or high resolution images, are included only as links or on a memory stick (attached to printed copies of this thesis), as they can be very voluminous and would be ineffective as printed documents.

- 9.1 Appendix 1A: CCZ13 Complement and short summary report
- 9.2 Appendix 1B: CCZ15 Complement and short summary report
- 9.3 Appendix 1C: Statement of Original Contribution
- 9.4 Appendix 2A Other supplementary figures
- 9.5 Appendix 2B: Hypsometric Analysis
- 9.6 Appendix 2C: Spreading rate calculations
- 9.7 Appendix 2D: Deepsea drilling summary sections
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- 9.9 Appendix 3A: Time-space worksheet
- 9.10 Appendix 3B: Adjusted backscatter values
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- 9.12 Appendix 3D: Slope statistics and characteristics
- 9.13 Appendix 3E: Full resolution seabed photographs
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- 9.17 Appendix 4C: Anglo American Technical Solutions QEMSCAN report
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- 9.19 Appendix 4E: Density measurements and calculations
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- 9.21 Appendix 4G: Photos of moisture determination samples
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- 9.23 Appendix 6A: Other Publications

9.1 Appendix 1A: CCZ13 Complement and short summary report

9.1.1 Expedition Complement

9.1.1.1 Science Team:

Chief Scientist: John Michael PARIANOS
Principal Geophysicist: Sean Michael PLUNKETT
Medic: Mark Benedict EBREO
Scientist: Dody DARMAWAN
Scientist: Paul POLOKA
Observer/Scientist: Akapei Ki Singapoa VAILEA
Winch Operator: Mark William LEICMONAS
Hydrographic Surveyor: Ashton Frederick FLINDERS

9.1.1.2 Vessel Crew:

Captain: Lawrence MISHEFSKI
Chief Mate: Gary RAMOS
Second Mate: Brian POWERS
Third Mate: Robert OVERMON
Chief Engineer: Glen QUINTINO
First Assistant Engineer: Frank HUTTON
Second Assistant Engineer: Mark ALEXANDER
Oiler: Godfrey EDWARDS
Oiler: Denny FORSMAN
Bosun: Waldemar JANCZAK
Able Bodied Seaman: Matt NUNEZ
Able Bodied Seaman: Andy GOMES
Cook: John MILNER
Cook: Malgorzata JANCZAK
Cook: Wardell MOULTRIE
Steward: Gerri DEVINE

9.1.1.3 Onshore:

Exploration Manager: Jonathan LOWE
Offshore Manager: Anthony MANOCCHIO
Contracts: Terry THE

9.1.2 Expedition Summary

This two-month (55 days) cruise to TOML contract areas B to F in the Clarion Clipperton Zone accomplished in its main objective (MBES survey) and three of its four secondary objectives (sample dredging, at-sea training, contract work for another party).

Mobilisation of the R/V Mt Mitchell (Figure 9-1) was protracted as the vessel was not ready for sea, taking 7 days rather than the 2 planned. Transit to site from Seattle started on the 23rd of August and took 11 days including a refuelling stop in San Diego and a consequent conservative 10 knots transit speed to site to maximise endurance (Figure 9-2). Hurricane Kiko was skirted en-route to the first area. After that the weather was a generally acceptable sea-state 4-5 with two days of sea-state 1-2 around mid-way and several days of sea-state 6 towards the end of the cruise. Return from the western end of the program area to Seattle took 10 days with demobilisation taking part of the day of the 16th of October.

Five of the six TOML areas in the CCZ were MBES surveyed, generally from easternmost area to west. A 12 kHz Kongsberg EM120 system was used, the Mt Mitchell's quiet hull and propellers and deck ballast tanks (that slow heave) helped the system to work well at speeds up to 8 knots in sea-states up to 5. Calibration CTD casts were done at the start of survey in each area. Area F was surveyed in a N-S orientation all other TOML areas were surveyed E-W. Line spacing was about 12 km with minor adjustments due to weather, water depth and sediment hardness (signal return). A swath of MBES was also collected at transit speed from the Clarion Island EEZ across the northern edge of the CCZ. Two NORI areas (A or 1 in the figure below and most of B or 2) were also surveyed on a confidential and commercial arms-length basis.

All five areas were 100% covered by the MBES system, all showed: characteristic elongated abyssal hills orientated between due North and 330° and mostly around 355°; and small shield volcanoes, typically several hundred m high and often associated with gentle east-west trending "basins" superimposed on the abyssal hills. From east to west water depths, areas of interpreted higher sedimentation and areas of localised collapse (potholes) on abyssal hill tops all increased. Areas of generally greater backscatter not associated with volcanic edifices could be distinguished in all areas and these in conjunction with historical sampling are interpreted to reflect larger nodules or greater proportion of nodule coverage and by association greater nodule abundances. These greater backscatter areas as well as corresponding low (highly absorbent) backscatter areas show some association with the abyssal hills but only in localised areas. Broader areas of greater backscatter areas are aligned more east-west often associated with more gentle topography and sometimes sub-parallel to the basins.

Analysis of the slopes defining the abyssal hills identified that some were "hard" (i.e. high backscatter) implying a higher possibility of including the basalt scarps remarked on by previous explorers especially those facing east to ESE. Secondary orientations (around to 030° strike) of slopes in parts of Areas B and F suggest reactivation-extension. The sediments in the southern half of Area F are softer which suggests a more calcareous nature, Area D has an area of higher backscatter over a subtle plateau and a nearby seamount reaching 2000 m above the seafloor, Areas B and C have more local/erratic pockets of softer more sediment rich areas, and Area B has several small volcanic cones with relatively soft backscatter that implies either cover or a different composition.

Fourteen dredges were conducted using a specially constructed epi-benthic sled and synthetic line. There were four in Area F, nine in Area D and one in Area B collecting slightly over 2.1 wet tonnes of nodules. Apart from one deployment where the sled could not reach the sea-floor (?currents on the line), returned loads were between 40 kg and 370 kg averaging about 150 kg. Depths were between 4200 and 4800 m. Operating technique of the sled was refined based on feedback from post-processed data collected by an attitude sensor and video collected on several early dredges. The synthetic line (which floats) pulled very straight requiring a heavy leader chain on the sled especially in deeper waters and where available line was limited. The sled clogged with mud quickly meaning that 'tea-bags' (partial lift and resettling of the sled) were required to clear and increase payload.

The samples were each weighed, screened at ~ 6cm, described, photographed and selected nodules separated out for reference. Dredge F1 was composed of small smooth hydrogenetic nodules, but all of the others were mostly larger complex hybrid diagenetic nodules (they were targeted on areas of generally greater backscatter). Three of the dredges from Area D contained significant amounts of manganese crust. Minor amounts of silcrete crust, manganese tubes, sharks teeth mud and biological material were also recovered. Several subsamples have been taken from individual dredges for preliminary metallurgical test-work and about 350 small subsamples taken from across all the dredge samples for grade range analysis and analysis of free and crystallisation water content.

Testing of a large area box-corer (required for a second cruise needed to define an indicated mineral resource) was not successful. The corer was lost 40 minutes into its first deployment when the line was melted by an overheating sheave. Valuable learnings from the exercise include the significant modifications required to the box-corer as supplied, ideas on improving the design of a replacement and the design and implementation of a very safe method of deployment and recovery of the instrument.

At sea training of two ISA sponsored students and a Kingdom of Tonga government observer included practice in interpretation and processing of the multibeam data, back deck operations and other duties. All students found the experience positive.

The roughly 1300 hours covered by the cruise can be broken into roughly 38% each site transit and MBES, roughly 7% each dredging and contract MBES and the remaining ~10% other activities such as transit between blocks dredging for NORI, box core testing etc (Figure 9-3; Table 9-1).

The technical performance of the cruise is analysed in terms of pluses and deltas in main the cruise report but the key point is that the Kongsberg EM120 system on the Mt Mitchell collected bathymetry and backscatter data of high quality, and that analysis of this data interprets considerable detail on the surface morphology, geology and nodule abundance potential. This enabled effective selection of priority areas for sampling work in 2015.

The sampling also not only served to deliver quantity of material for generic preliminary metallurgical test-work, logging of the different samples provided valuable information per different nodule morphologies as well as the frequency of crust in some areas.

This summary does not include budget analysis and operational lessons learnt but it is noted that the project came in modestly under budget and that there are considerable operational learnings to be digested by the team for use in future cruises.



Figure 9-1: The Mt Mitchell Survey Vessel

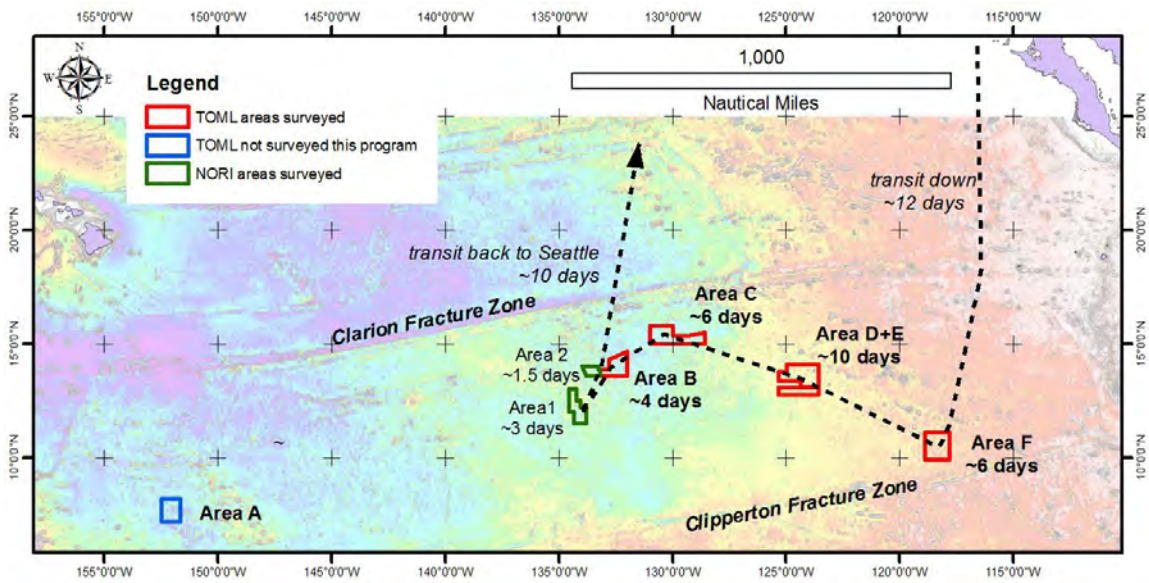


Figure 9-2: CCZ13 Program

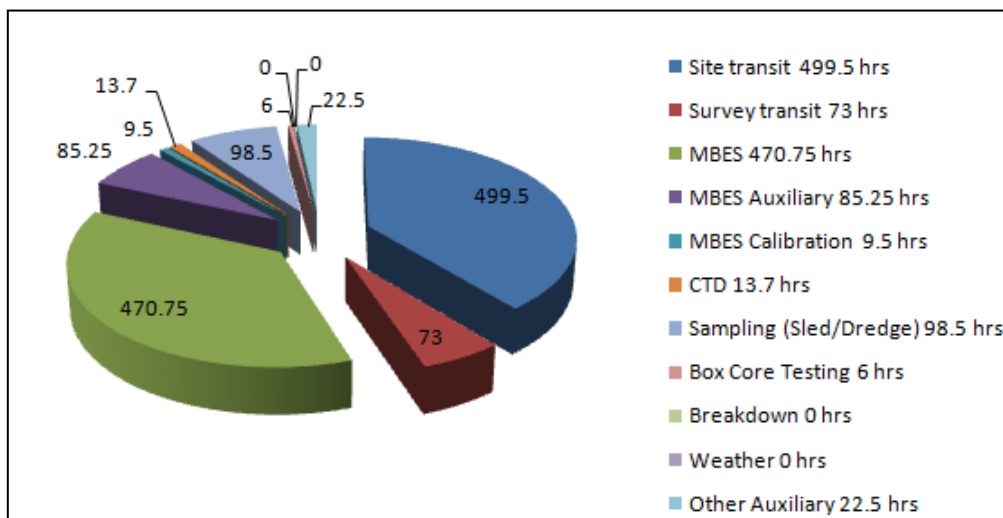


Figure 9-3: Essential Time Analysis for the CCZ13 Expedition

Table 9-1: CCZ13 Production Summary

Production Summary					
Activity	Units		To Date	Comments	
MBES	line km		6964		
MBES Auxiliary	line km		1119		
CTD	# casts		4	to date 1 Aux CTD cast	
Sampling (Sled/Dredge)	# deployments		13	to date 2 Aux dredges	
Sampling (Sled/Dredge)	kg		1825	to date 275 kg Aux dredge samples	
Box Core Testing	# deployments		1		
MBES	km2	%	MBES Auxiliary	km2	%
Planned	64432		Planned	12443	
Surveyed	64472	100.1	Surveyed	12098	97.2
Processed	64472	100.1	Processed	12098	97.2

Note that the auxiliary work was conducted by Nautilus – TOML for Deep Green – NORI on an arms-length contract basis.

9.2 Appendix 1B: CCZ15 Complement and short summary report

9.2.1 Expedition Complement

9.2.1.1 Science Team TOML:

Chief Scientist	John Michael PARIANOS
Lead Scientist	Mele Christina POMEE
Lead Scientist	Rodney Edward CONROY
Scientist (Observer)	Tuamelie Ki Langi Brian FUSIMALOHI
Scientist	Titie Afuhia I Vaha KAUFUSI Jr
Scientist	Nafetalai Siola'a FIFITA Jr
Scientist	Sisilia Kamila FAEAMANI
Scientist	ANDRIHARIZAFY Rantoso
Scientist	Victor Hugo Rocha LOPES
Senior Technician	Peter Andrew FORBES

9.2.1.2 Science Team YMG:

Group chief	SAPIRIDI Anatoly
Technician	ANTIPOV Andrey
Engineer	IVANOV Oleg
Technician	KAZEMIROV Sergey
Group master	SINYAVSKIY Vyacheslav
Technician	CHUYKIN Maxim
Engineer	KULIKOV Victor
Engineer	KUTSENKO Konstantin
Hydrograph	ZELENTCOV Ilia
Engineer	IVASHCHENKO Dmitrii
Group master	IOSHPA Mikhail
Engineer	RUBTSOV Ilia
Engineer	AVETISYAN Alexander
Geologist	AKULOV Aleksandr
Engineer	ELESHEV Andrey
Engineer	EREMEEV Sergey
Group master	IVANOV Vladimir
Engineer	KALININ Oleg
Geologist	KRUGLYAKOVA Maria
Engineer	MAMAIEV Vitalii

Engineer	MARKUVENAS Daniil
Geologist	SAPIRIDI Maxim
Group master	PROKOPTSEV Valeriy
Biologist	POGREBNOY Sergey
Hydrograph	KHILCHENKO Maksim
Hydrograph	SHKANDALIUK Dmitrii

9.2.1.3 Vessel Crew:

Master	MAMEDOV Ruslan
Chief Mate	KHARAMANOV Vladimir
Second Mate	ANIKEEV Oleg
Third mate	RUDENKO German
Chief Radio	MELNIK Evgeniy
Physician	KOLOSOVA Elza
Chief Engineer	MASLENNIKOV Yuriy
Second Engineer	BEGUNOV Anatoly
Third Engineer	GRICHNEV Alexander
Third Engineer	MARINCHENKO Alexander
Fourth Engineer	BEREZHNOI Sergei
Repair engineer	GRECHKA Evgeniy
Chief el. Engineer	KORCHAGIN Pavel
Senior electrician	SALTYKOV Anatoly
Ref. mechanic	PETLITSKII Aleksandr
Boatswain	CHERNYI Vadim
Chief sailor	"PARSHIN Iurii"
Sailor	IGNATENKO Aleksandr
Sailor	ALIFIRENKO Ivan
Sailor	PUSTOVOY Yury
Sailor-man on duty	OGANESIAN Arnold
Motorman	KHOLODNYI Dmitry
Motorman	FESENKO Andriyan
Motorman	ORLOV Maksim
Motorman	BEGIMOV Rustam
Cook	KOSENKO Tatiana
Cook	GUBINA Margarita
Cook	PUSTOVAYA Antonina

Steward	AKHALAIA Angelina
Steward	SAVINA Tatiana
Steward	MARKOVA Nina

9.2.1.4 Onshore:

Exploration Manager:	Jonathan LOWE
Offshore Manager:	Anthony MANOCCHIO
Environmental Program:	Adrian FLYNN
HSEC:	Phil HANNELL
Contracts:	Trevor MCGREGOR
Contracts:	Terry THE

9.2.2 Expedition Summary

This 96 day cruise mobilised in Betio, Kiribati 22 July 2015 and demobilised in Balboa Panama 24 October 2015. Tonga Offshore Mining Limited (TOML) placed a scientific team of ten, mostly trainee scientists, on a vessel called the R/V Yuzhmorgeologiya (Figure 9-4), supplied by the Russian marine research organisation of the same name, and fellow International Seabed Authority contractor, Yuzhmorgeologiya. Yuzhmorgeologiya also supplied an experienced science and engineering team to support a program of towed photo-profiling, towed sonar (side-scan and sub-bottom profiling) and box-coring, as well as water column sampling and measurements and seabed mooring deployment and recovery.



Figure 9-4: The R/V Yuzhmorgeologiya

Photo credit: Nicola Parianos

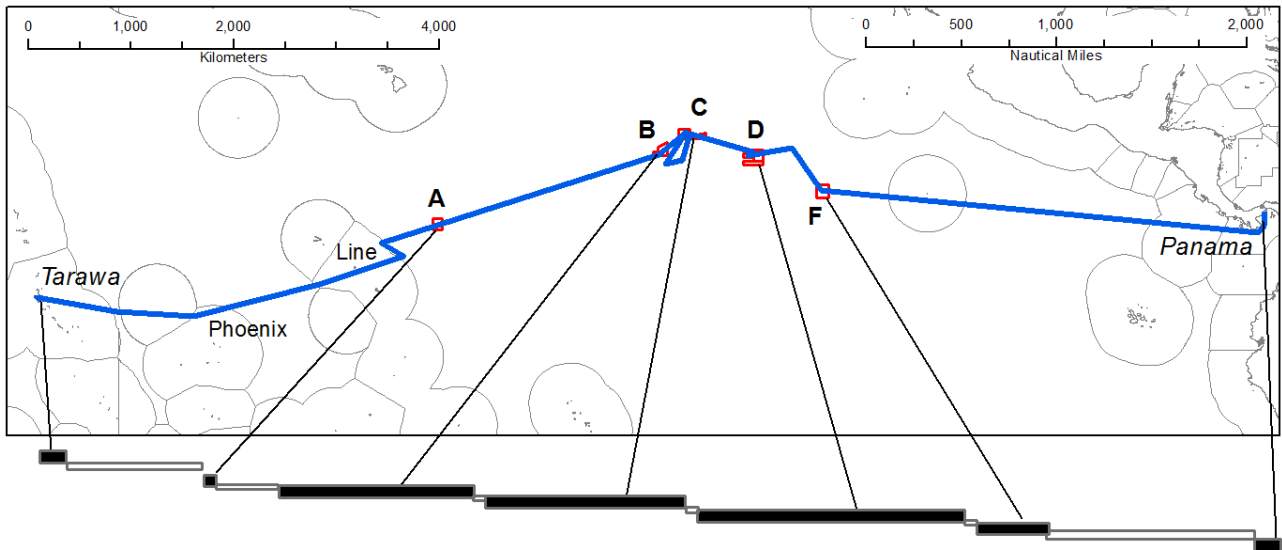


Figure 9-5: CCZ15 expedition path

The cruise has almost certainly exceeded its main objective, which was to sample sufficiently to define a mineral resource of polymetallic nodules, to an indicated level of confidence under Canadian National Instrument NI 43-101, within the TOML contract area, Clarion-Clipperton Zone. The cruise also met or exceeded most of the targets set for six secondary objectives, including baseline environmental data (>20,000 seafloor photos and >3,000 samples), geotechnical data and samples (>100 box-cores) and at-sea training (two persons placed by the International Seabed Authority and four from the Kingdom of Tonga).

En-route to the first main work program at Area B1, opportunistic photo-profiling was done within the Phoenix and the Line Islands of Kiribati and dredging in TOML Area A. At-sea refuelling was completed just outside the Line Islands to ensure fuel supply was not a limiting factor (Figure 9-5, Figure 9-7, Figure 9-8).

The arrival in the first TOML contract area, TOML Area A, was 2 days after the completion of the at-sea refuelling. About a day was spent at this area to complete 2 dredges using the YMG Galatea-trawl dredge. This was the first sample TOML has taken from this area. There was no photo profiling or any other sampling work was done. A diversion around Cyclone Hilda was needed during the transit between Area A and Area B1.

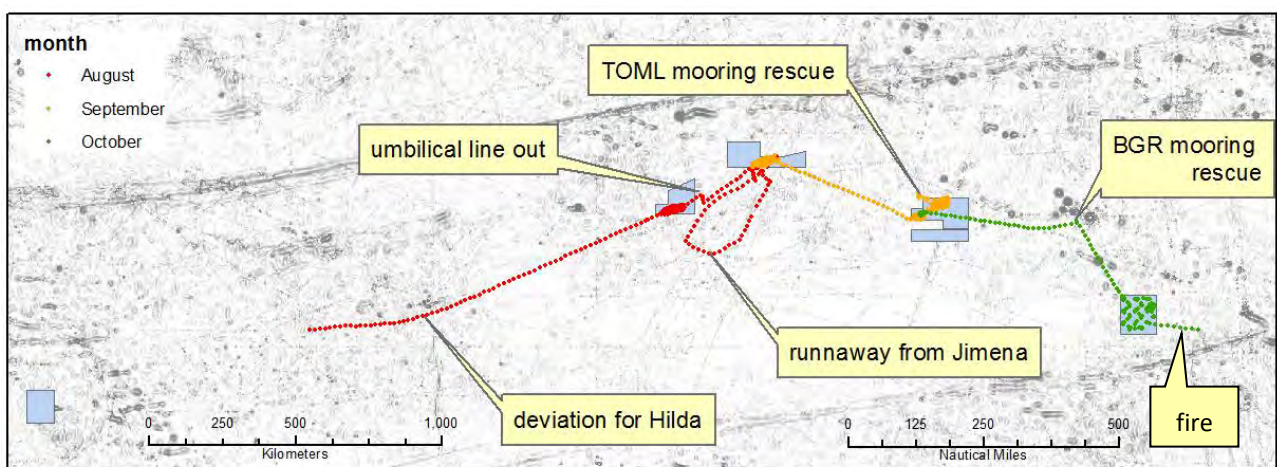


Figure 9-6: CCZ15 Extraordinary incidents

A little over two weeks was spent at Area B1. After completing baseline photo-profiling using Yuzhmorgeologiya's Neptune system, the focus turned to box-coring. The TOML supplied KC box-corer required remediation work and more development and so some of the samples were taken using Yuzhmorgeologiya's smaller, but proven machine. With modification, the KC box-corer improved in performance and proved useful, especially in harder terrain. Additional photo-profiles and deep-towed sonar (using Yuzhmorgeologiya's MAK1M system) completed the program, but deployment of a seafloor mooring was prevented by bad weather (formation of a tropical depression that became Cyclone Ignatio; note that 2015 is the https://news.vice.com/en_us/article/kz9b3m/for-the-first-time-on-record-three-category-4-hurricanes-occurred-simultaneously-in-the-pacific-ocean).

The work in Area B1 led to the definition of 14 discrete "fields", that have been described and ranked in terms of geology, geomorphology and perceived suitability for nodule mining. Mega-fauna logging using ~6,900 photos, have helped establish statistically based relationships between geoform and type of fauna that does support habitat mapping.

The vessel moved next to Area C1, and on arrival, completed baseline photo-profiling. Subsequent box-coring operations were, however, disrupted by the arrival of Cyclone Jimena, necessitating ~two days evacuation of the area. On returning to Area C1, a recently re-discovered relationship between nodule size and weight meant that the number of box-cores could be reduced at the expense of more photo-profiling. Ultimately over 180,000 nodules were measured from photos taken across the entire project area. Twelve days were spent in Area C1, photo-profiling, box-coring, dredge sampling and deploying a seabed mooring. A single line of seafloor characterisation deep-towed sonar completed the program in Area C1.

The work in Area C1 led to the definition of 11 fields, that have been described and ranked in terms of geology, geomorphology and perceived suitability for nodule mining. Mega-fauna logging using ~8,100 photos, have found broadly similar mega-fauna to those in the other areas, although the relative numbers of each animal type vary in some cases. Vane shear tests and the sub-bottom profiler data show the area to have consistent sediment properties.

Next was Area D2, but the original plan to conduct extensive photo-profiling was abandoned after the baseline photo-profiles showed extensive, albeit thin, sediment cover, meaning that nodule sizes could not be reliably measured. An intensive alternative box-coring program was completed. By this stage, modifications to the KC box-corer meant it was working more reliably, especially in the more marginal weather conditions being experienced in this later stage of the program. A second mooring was deployed, but then had to be rescued after the acoustic release frame broke during deployment. This recovered mooring was re-built with a new acoustic release and was deployed in Area B by Yuzhmorgeologiya (Appendix J) during its own cruise in the Clarion Clipperton Zone in late 2015, shortly after this cruise. Three lines of towed sonar provided detailed geology and bathymetric data on the central part of Area D2. Twelve days in total were spent on the program in this area.

The work in Area D2 led to the definition of five fields that were described and ranked in terms of geology, geomorphology and perceived suitability for nodule mining. The lower number of areas relates to distinctly different and gentler seafloor bathymetry in this area. Mega-fauna logging using ~5,600 photos (including nearby Area D1 and the intermediate area between D1 and D2), has found broadly similar mega-fauna to those in the other areas, although the relative numbers of many animal types is highest in this area.

After Area D2, box-coring continued in Area D1. A single dredge sample was taken and a single line of deep-towed sonar for characterisation was completed. This area has distinctive and less consistent geology than

Area D2. With key targets met and the cruise endurance limit approaching, the decision was made to end the program here and move to Area F. In Area D1, seven discrete fields were been described and ranked in terms of geology, geomorphology and perceived suitability for nodule mining. Seven days in total were spent in this area.

En-route to Area F, the vessel diverted and recovered, without problems, a seabed mooring that had pre-maturely released. This mooring is owned by the German research group (a fellow International Seabed Authority contractor, BGR; Figure 9-6).

In Area F the program involved box-coring, sufficient to define a nodule mineral resource to an inferred level of confidence. On arrival, production performance was better than expected in part due to now very experienced team and proven equipment. Improved weather also played a role. This allowed for an additional small program of more closely spaced box-cores to be carried in Area F1, sufficient to define additional mineral resource to an indicated level of confidence. Seven days were spent in Area F including a little less than three days in Area F1.

Area F is characterised by distinctly different, but consistent (softer) benthic sediment cover and higher and less variable nodule abundances. In Area F1, four discrete fields were described and ranked in terms of geology, geomorphology and perceived suitability for nodule mining.

On 10 of October, the R/V Yuzhmorgeologiya set sail for Panama but two days later, an engine room fire forced the vessel to stop (Figure 9-6). While the fire was extinguished within five minutes thanks to skilled response from the crew, some critical systems were out of service and it took two days to effect running repairs. Progress thereafter was at a reduced speed (Figure 9-7). Arrival in Panama was on the evening of 24 October, and demobilisation was completed two days later (Figure 9-8).

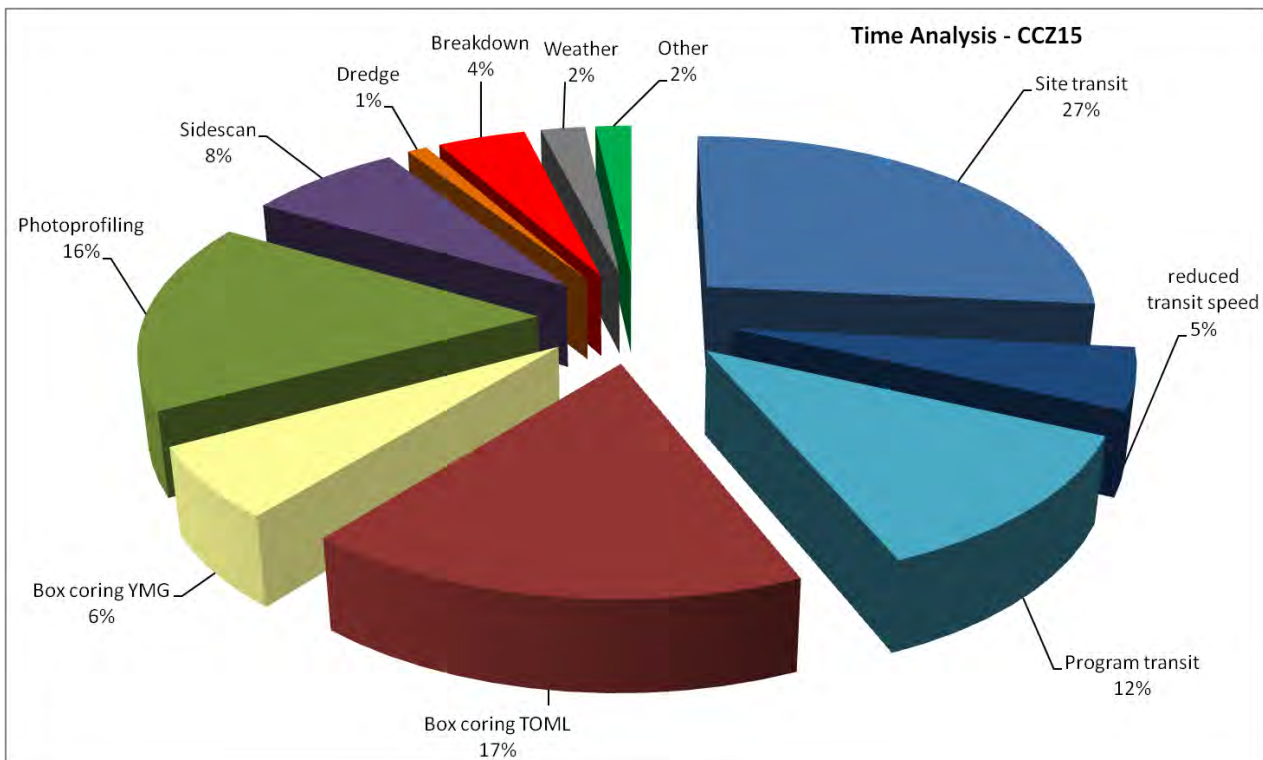


Figure 9-7: CCZ15 Expedition time analysis

9.3 Appendix 1C: Statement of original contribution

This thesis is based on original research conducted by John Michael Parianos, at Universidade de Evora. Except as acknowledged, the contributions of the author, per best current knowledge are as follows.

Chapter 1: Introduction

- conducted literature review, drafted text and produced figures, with review per acknowledgements

Chapter 2: Regional setting

- conducted literature review, drafted text and produced figures, with review per acknowledgements;
- selected contours and interpreted units;
- directed 2014 GEBCO bathymetry downloaded per references and processing into 100 m contours by S. Plunket;
- downloaded 2020 GEBCO bathymetry per references and processed into 100 m contours by using qGIS software;
- researched, and georeferenced public 12 kHz bathymetric images per references;
- acted as Chief Scientist for the CCZ13 Mt Mitchell marine expedition that collected 12kHz bathymetry and backscatter for TOML B, C, D, E, F and NORI A and B areas (refer to section 9.1.1 for full complement list) with survey planning and processing by S. Plunkett and A. Flinders;
- prepared a conference poster presentation on this topic (Parianos and Richards, 2018) reviewed and co-authored by S. Richards, presented by J Jamieson.

Chapter 3: Local scale geology

- conducted all literature review, drafted all text and produced all figures (except as acknowledged), with review per acknowledgements;
- selected and interpreted map units;
- acted as Chief Scientist for the CCZ13 R/V Mt Mitchell marine expedition that collected 12kHz bathymetry and backscatter for TOML B, C, D, E, F and NORI A and B areas (refer to section 9.1.1 for full complement list) with survey planning and processing by S. Plunkett and A. Flinders;
- compiled NORI C and D and Marawa 12 kHz bathymetric and backscatter grids supplied by NORI (A. O'Sullivan and I Stevenson) as well as reprocessed grids from NORI A and B;
- derived all MBES products except for bathymetric slope angles and directions for TOML B, C, D, E, which were derived by A. Flinders;
- acted as Chief Scientist for the CCZ15 R/V Yuzhmorgeologiya marine expedition that collected box-cores, dredge samples, towed photos profiles and towed sidescan and sub-bottom profile data;

- towed sidescan and sub-bottom profile data collected and processed into the images used by the YMG-MAK team with support from the rest of the CCZ15 marine expedition team (refer refer to section 9.2.1 for full complement list). Review and interpretation of this data set specifically benefited from interpretive work done by the expedition science team including discussions with M. Kruglyakova;
- logging of the towed camera photos was first completed by members of the CCZ15 science team.

Chapter 4: Some key properties of CCZ nodules

- conducted all literature review, drafted all text and produced all figures (except as referenced), with review per acknowledgements;
- acted as Chief Scientist for the CCZ15 R/V Yuzhmorgeologiya marine expedition that collected box-cores, dredge samples, towed photos profiles and towed sidescan and sub-bottom profile data;
- client representative (on-shore) for the CCZ17 R/V Gelendzhik marine expedition that collected additional dredge samples;
- derived TOML nodule logging schema derived from existing ISA schema with additions by author after consultation to members of the CCZ15 science team, especially C. Pomee-Fatu. Amendments to logging done as needed by author for this thesis;
- originated and derived nodule space-form concept;
- directed density measurements mostly made by technician L. Johnston, else by author;
- directed and collaborated on moisture content measurements made by technician K Schneider at ALS laboratory Brisbane;
- directed chemical analysis was carried out by ALS laboratory Brisbane under management of S. Kenny
- directed and collaborated on attrition fines test work carried out by B. Riada-Horn and Upkar Bagga at ALS laboratory Brisbane;
- carried out packing factor measurements with assistance by A. Manocchio and G. Yu;
- developed the space-stability nodule growth concept

Chapter 5: Aspects of estimation and reporting of mineral resources seabed polymetallic nodules

- conducted all literature review, drafted all text and produced all figures (except as acknowledged), with review per acknowledgements. Co-authors to the paper are I. Lipton and M. Nimmo;
- directed and contributed to two formative technical reports (Nimmo et al., 2013) and (Lipton et al., 2016),
- acted as Chief Scientist for the CCZ15 R/V Yuzhmorgeologiya marine expedition that collected the box-cores and towed photos profiles used for the indicated and measured mineral resources (refer refer to section 9.2.1 for full complement list).

Chapter 6: Towards Modifying Factors

Publication	Sample and/or data curation	Technical conceptualization	Technical Validation	Drafting and/or review
(Yu and Parianos, 2021)	X	X	X	X
(Simon-Lledó et al., 2020)	X	X	X	X
(Simon-Lledó et al., 2019b)	X	X	X	X
(Parianos et al., 2014a)		X		X
(Parianos et al., 2014b)		X		X
(Berndt et al., 2014)		X		X
(Manocchio et al., 2020)	X	X	X	X
(Yu et al., 2020)	X		X	X
(Xiao et al., 2019)		X		X
(Su et al., 2020b)	X			X
(Su et al., 2021)	X			X

Chapter 7: Conclusions and Way Forward

- synthesized and written and reviewed per acknowledgements

9.4 Appendix 2A Other supplementary figures

Refer also to section 4.5.2.2 for discussion on regional variances in chemistry.

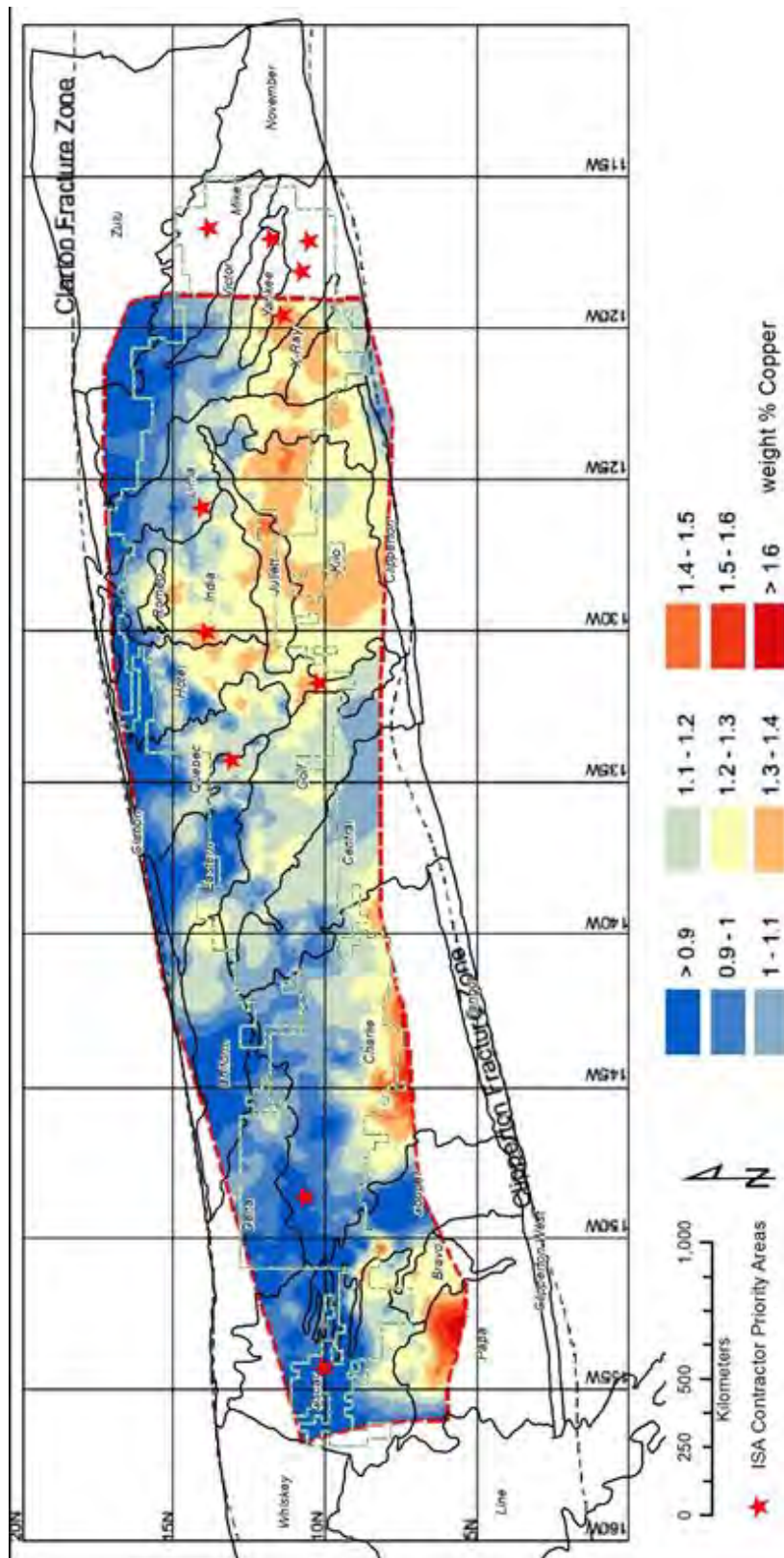


Figure 9-9: CCZ copper grades and geomorphological units

Source of background map: International Seabed Authority (2010a). Map is to GCS WGS84

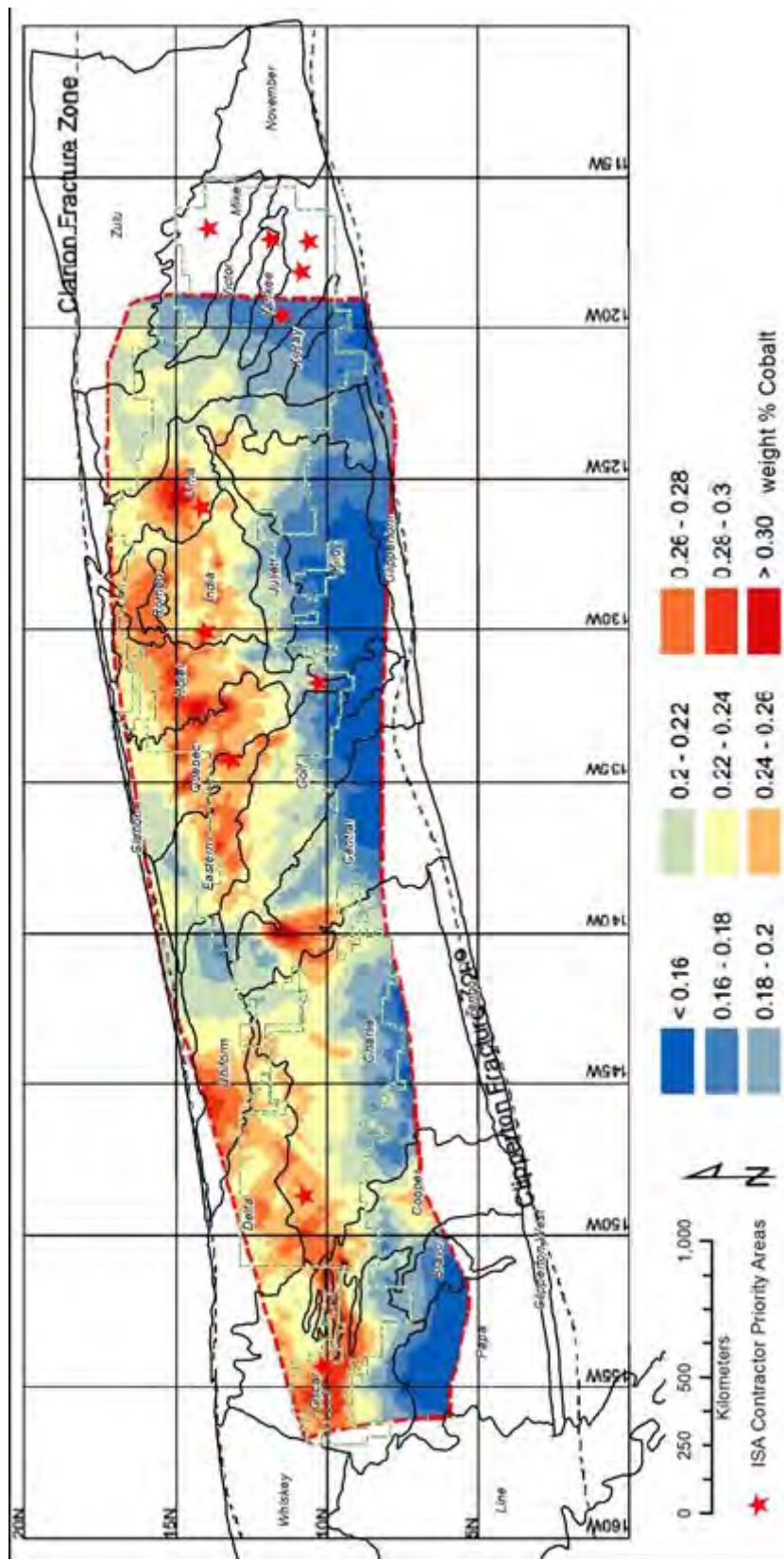


Figure 9-11: CCZ cobalt grades and geomorphological units

Source of background map: International Seabed Authority (2010a). Map is to GCS WGS84

9.5 Appendix 2B: Hypsometric Analysis

https://www.researchgate.net/publication/350741049_0905_Appendix_2B_Hypsometriccurves_CCZ_Gebco?ev=project

9.6 Appendix 2C: Spreading rate calculations

https://www.researchgate.net/publication/350740965_0906_Appendix_2C_Spreadingratecalculations?ev=project

Section 9: Appendices

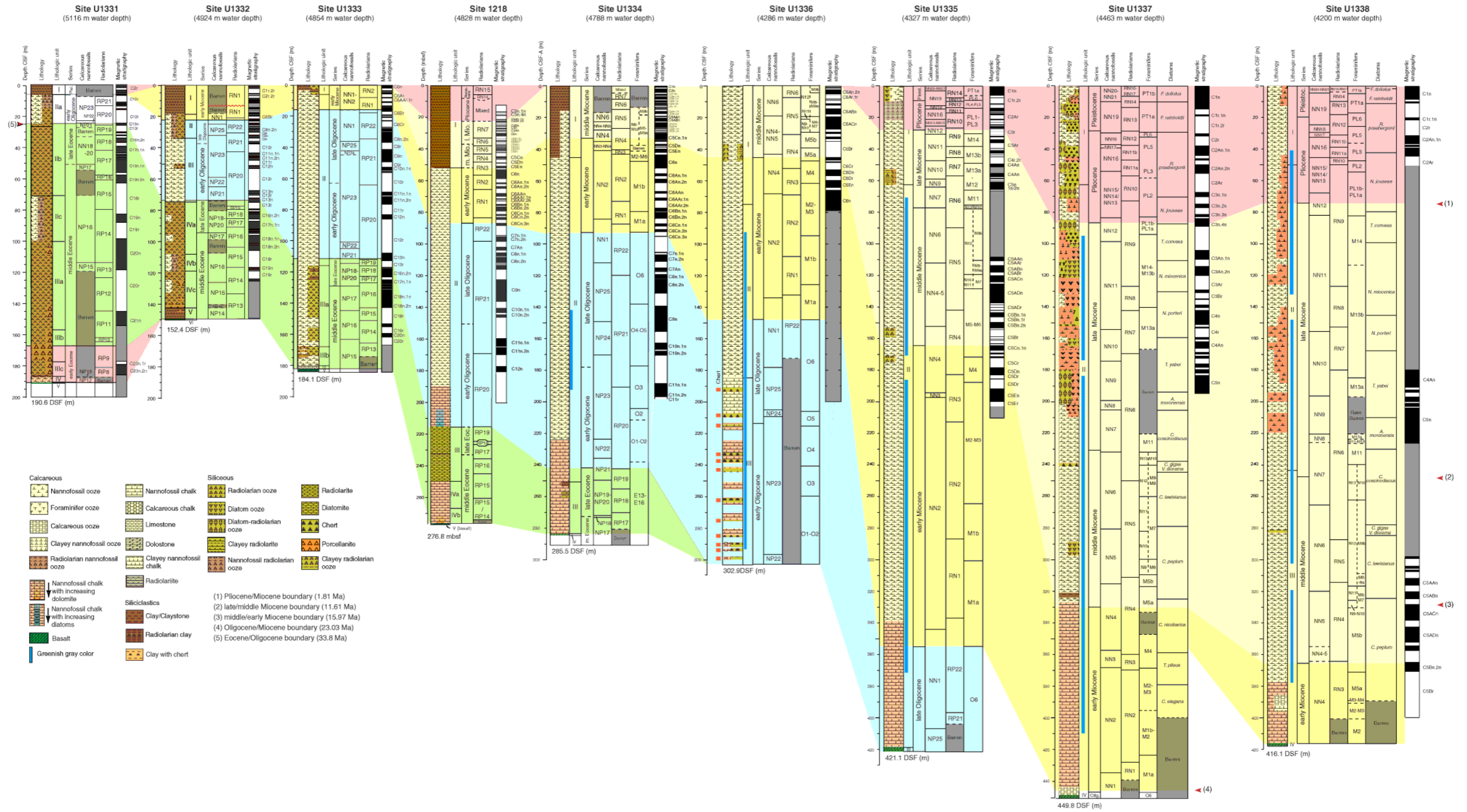


Figure 9-13: Stratigraphic summary plots, PEAT Sites U1331–U1338 and ODP Site 1218.

Green = Eocene, blue = Oligocene, yellow = Miocene, pink = Pliocene–Pleistocene Source: reproduced from Pälke *et al.*, (2009a) http://publications.iodp.org/preliminary_report/320/320_f13.htm#1017937

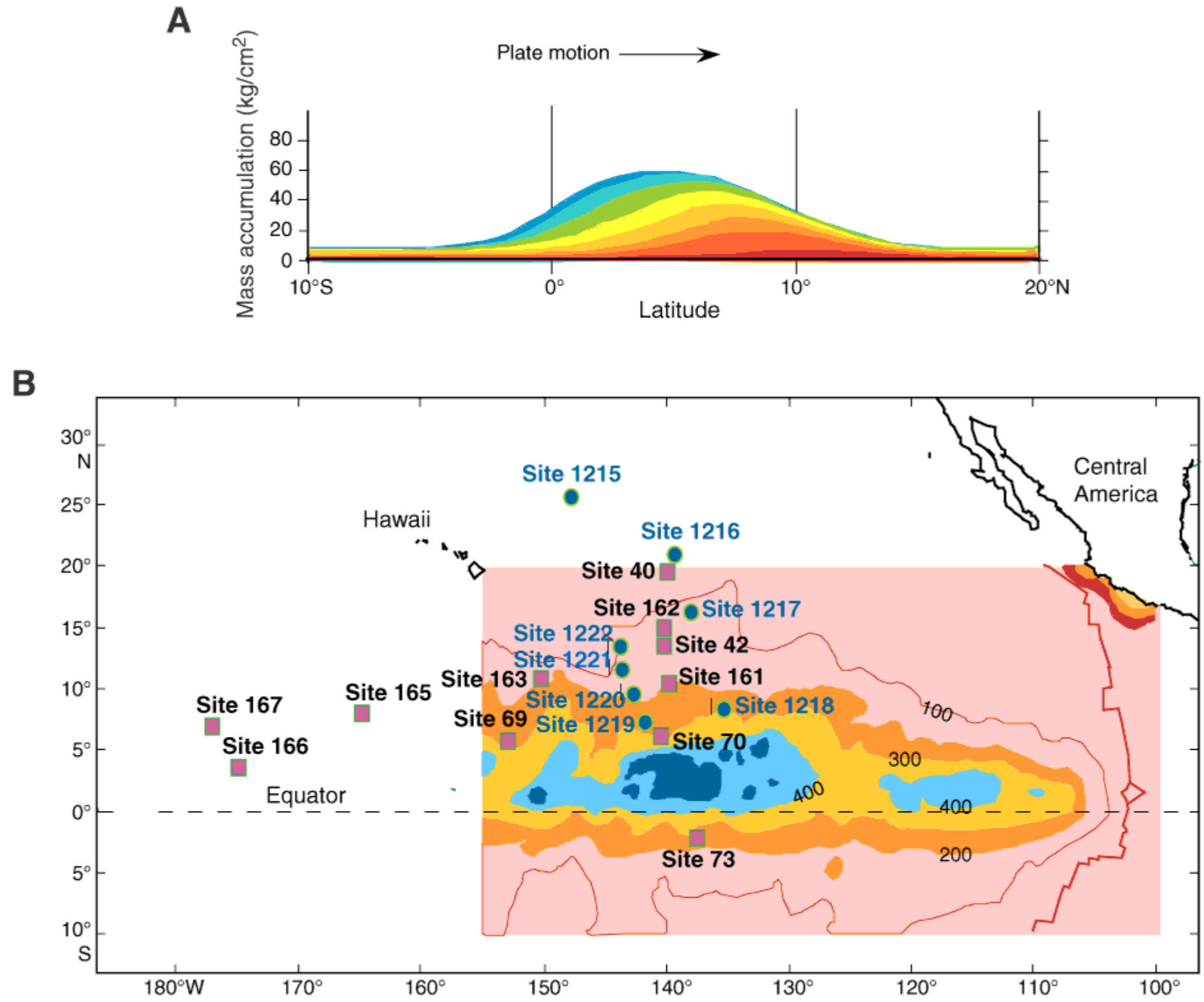


Figure 9-14: Model cross-section of equatorial sediment mound taking into account northward drift of Pacific plate.

B. Mapped thickness of Pacific equatorial sediment mound. Color code = thickness of mound. Source: reproduced from Pälke *et al.*, (2009a) http://publications.iodp.org/preliminary_report/320/320_f13.htm#1017937

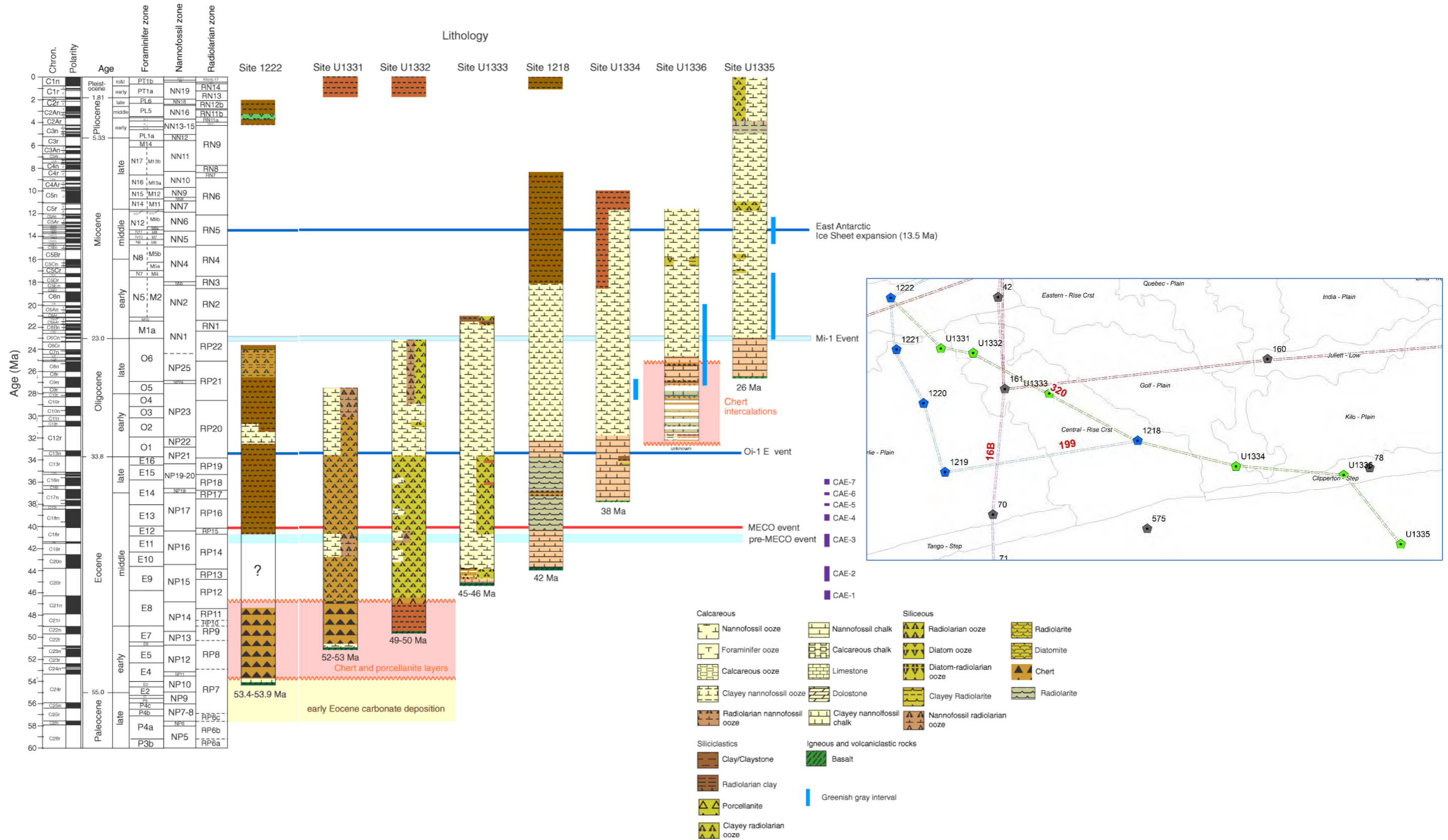


Figure 9-15: Transect 320

Source: reproduced from Pälke *et al.*, (2009a) http://publications.iodp.org/preliminary_report/320/320_f13.htm#1017937 ; sites 1219-1221 excluded refer 199 transect below

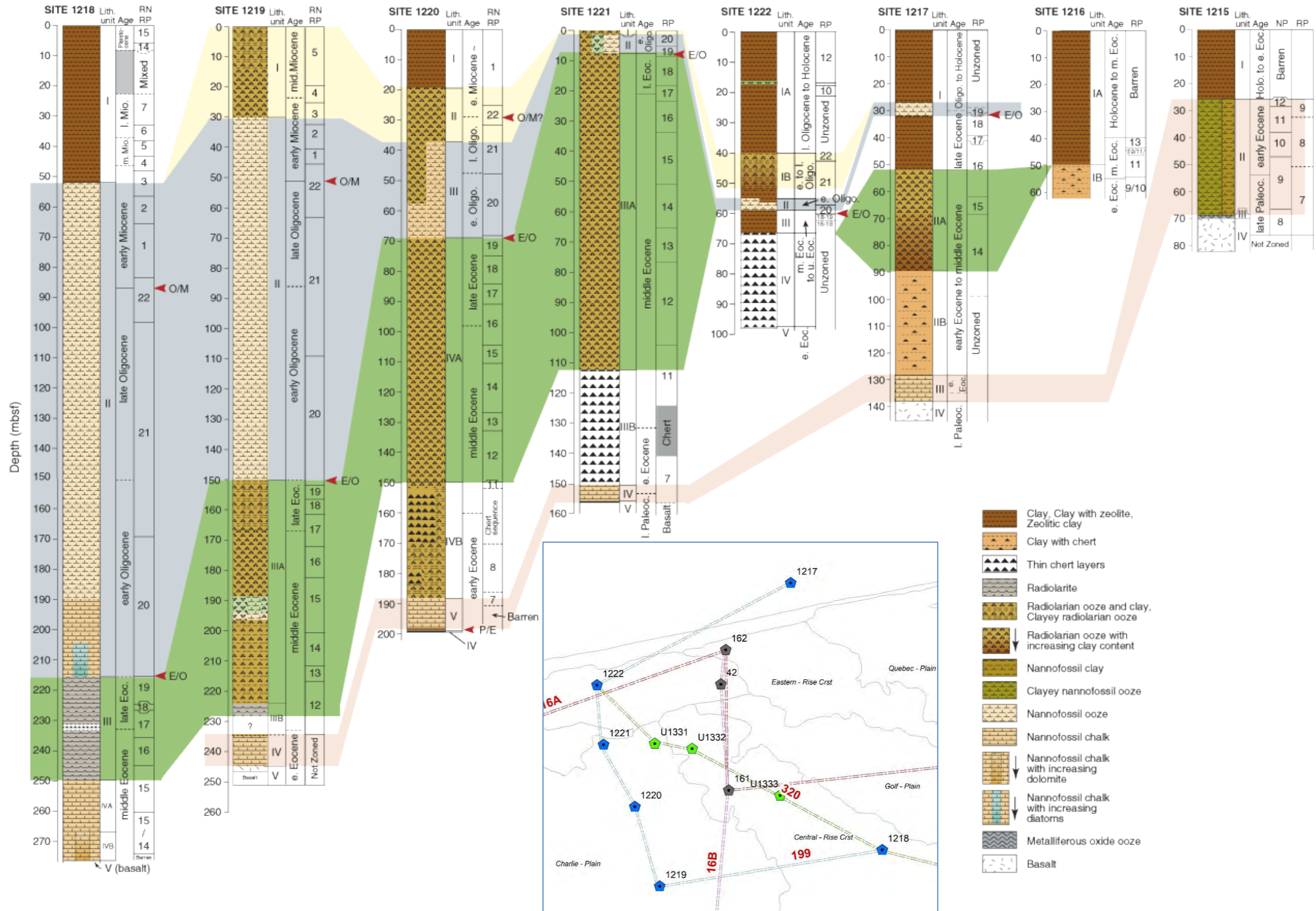


Figure 9-16: Transect 199

Source: reproduced from The Shipboard Scientific Party (2002) http://www-odp.tamu.edu/publications/199_SR/synth/syn_f2.htm

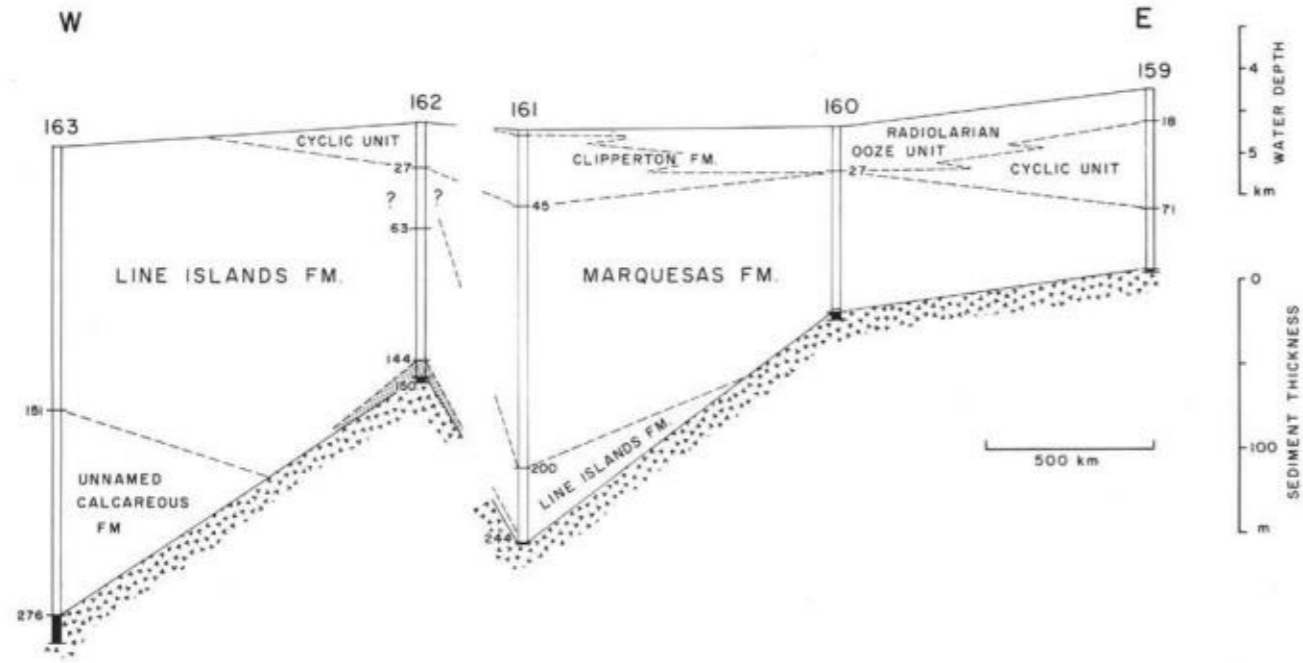


Figure 4. Pelagic sedimentary formations in boreholes of Leg 16 on west flank of East Pacific Rise. Formation names after Tracey, Sutton et al. (1971b). Profile is approximately parallel to the Clarion Fracture Zone; horizontal scale approximate.

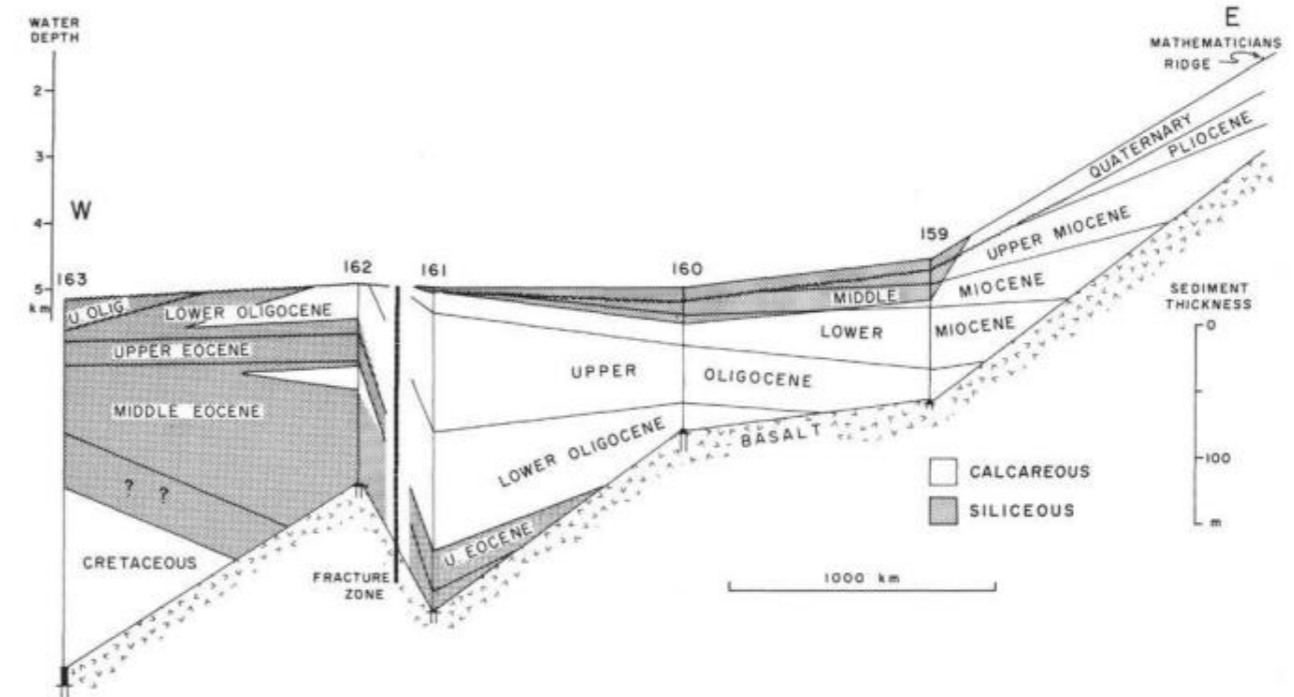


Figure 8. Lithologic units and stratigraphic boundaries in an east-west profile through the drill sites of Leg 16. Note the northward jump of the profile across an unnamed fracture zone between sites DSDP 161 and DSDP 162. Water depth scale on upper left; sediment thickness scale on lower right. Horizontal scale approximate. Wavy lines represent erosional disconformities. No correction for variations in degree of consolidation. Sediment thickness at crest of Mathematicians Ridge from Glomar Challenger reflection profiles. Age of oldest sediment there inferred from Figure 3.

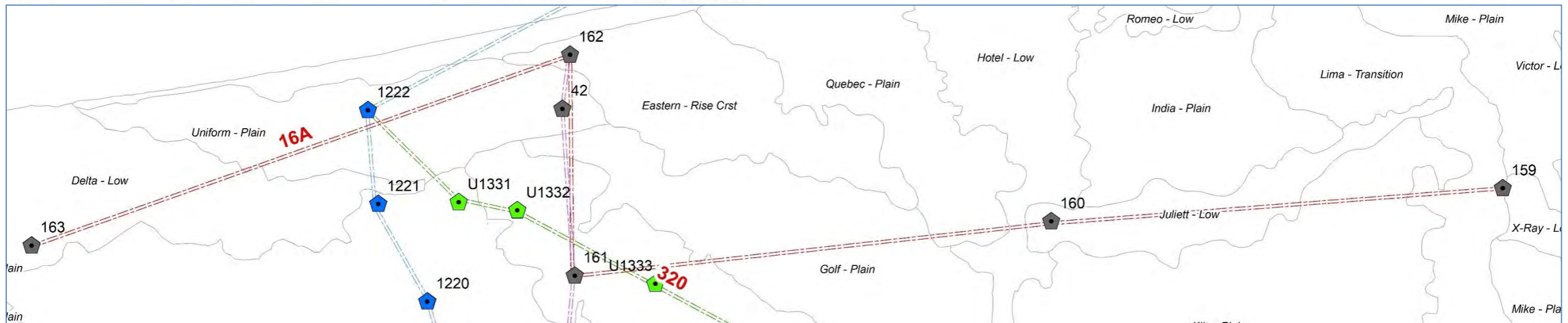


Figure 9-17: Transect 16A

Source: in part reproduced from van Andel and Heath (1973) http://www.deepseadrilling.org/16/volume/dsdp16_37.pdf

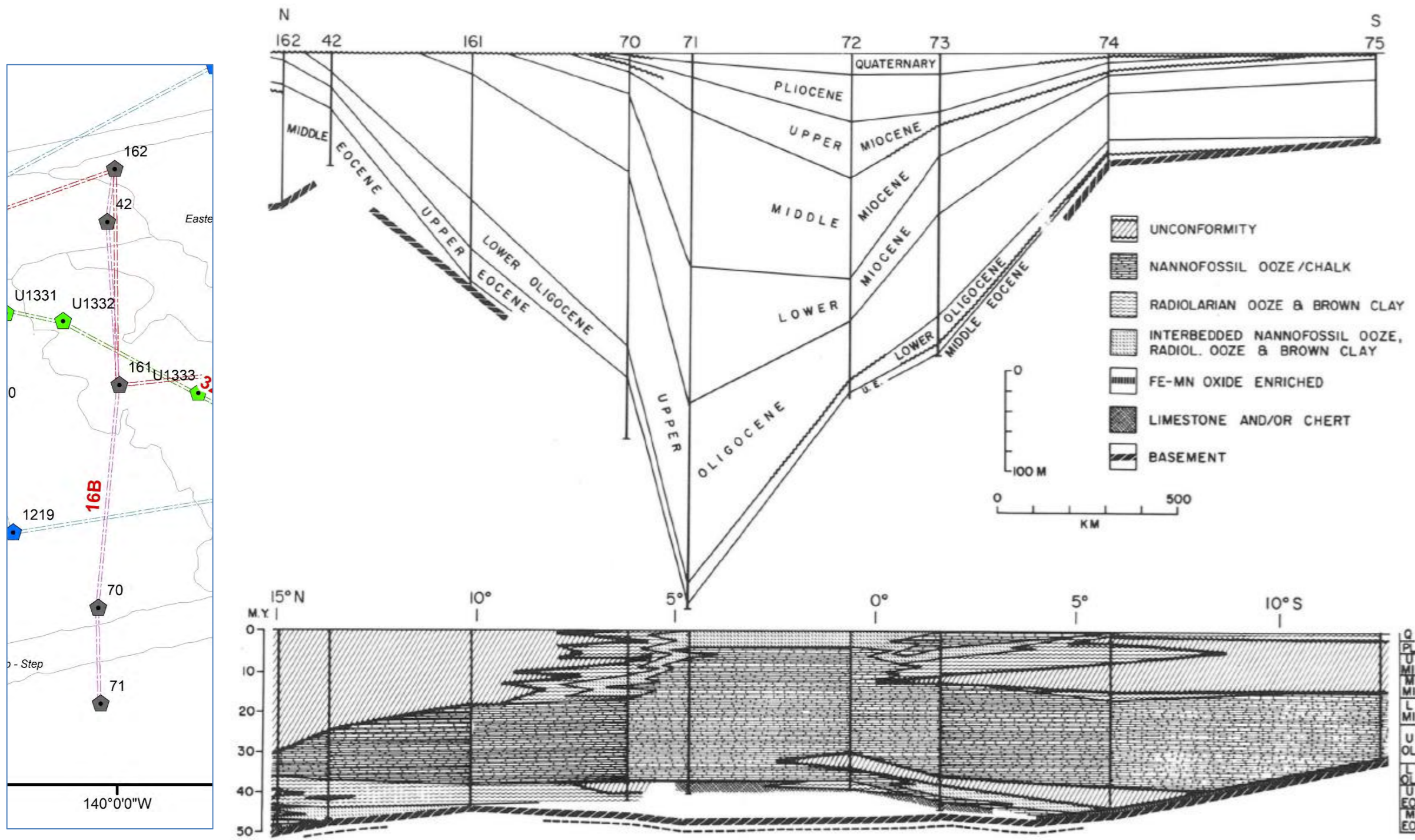


Figure 13. North-south biostratigraphic-lithostratigraphic profile approximately along long. 140° W. Stratigraphic boundaries and lithology from Appendix 3. Location shown in Figure 10. Upper section is based on depth in hole; lower section is based on absolute age.

Figure 9-18: Transect 16B

Source: in part reproduced from van Andel *et al.*, (1975)

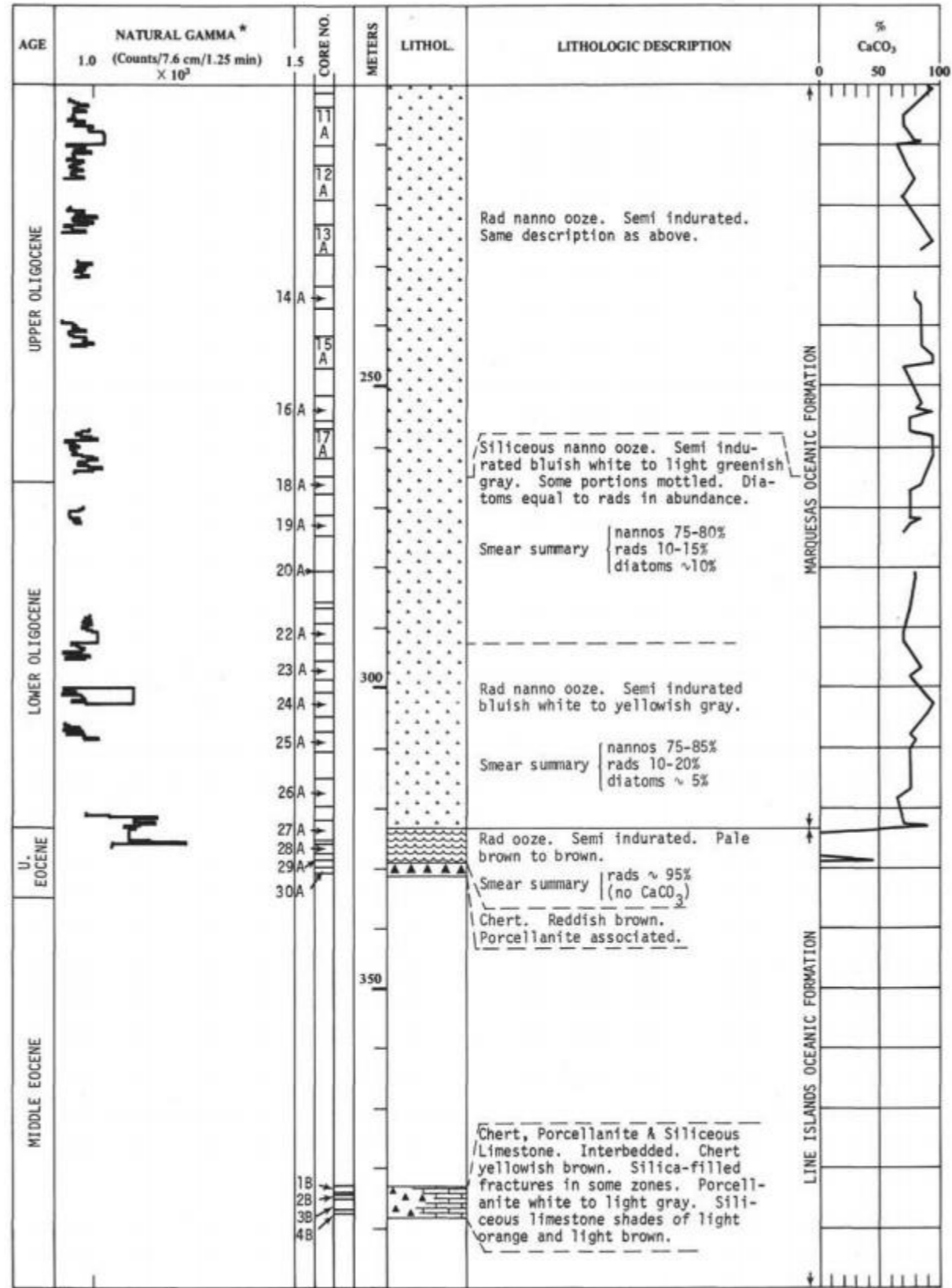


Figure 9-19: Site DSDP70

Source: reproduced from http://www.deepseadrilling.org/08/volume/dsdp08_05.pdf

9.8 Appendix 2E: Deepsea drilling locations and calculations

https://www.researchgate.net/publication/350741067_0908_Appendix_2E_IODPholesummary?ev=project

9.9 Appendix 3A: Time-space worksheet

https://www.researchgate.net/publication/350740967_0909_Appendix_3A_Timespaceworksheet?ev=project

9.10 Appendix 3B: Adjusted backscatter values

Per Chapter 3 The backscatter was compared between areas using three standard stretches:

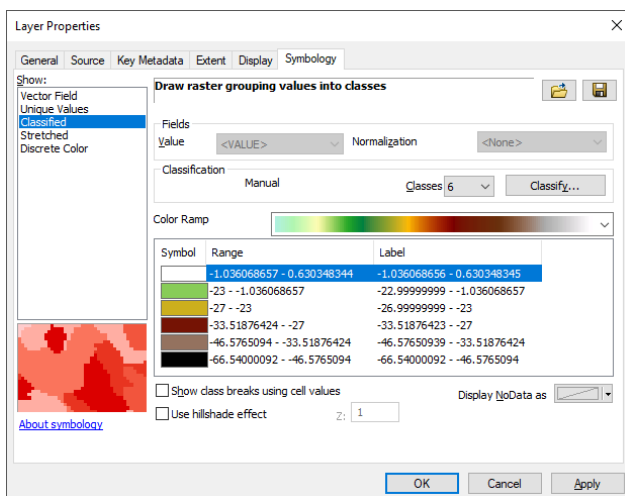
1. A conventional grey scale stretch for volcanic rocks, scarps and to check the interpreted nodule and sediment units;
2. A brown-yellow-green scale to discriminate nodule bearing areas and volcanic units, called the “brown” scale in (Figure 3-5, Figure 3-6);
3. A black-blue-yellow scale to define drift sediments, called the “green” scale in (Figure 3-5, Figure 3-6).

It was apparent that backscatter response between the areas varies, likely due to differences in the sound velocity profile that are not fully accounted for in the processing. Using type units such as sediment drifts and volcanic rock units as a guide, backscatter thresholds for the two colour scales were thus varied slightly between some areas due to ensure consistency in the interpretation. The green scale was “pushed harder” than the brown scale in an attempt to discriminate shoaling carbonates from sediment drifts.

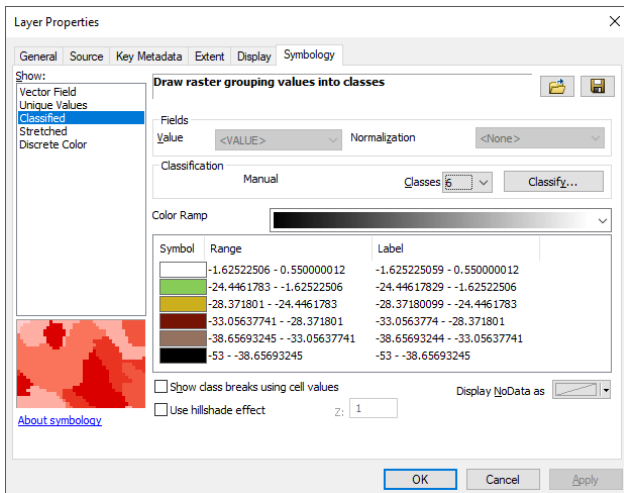
This appendix comprises screen shots of the ArcGIS classification settings used for each area

9.10.1 Brown scale

NORI A, NORI B, TOML B, TOML D, TOML E, Marawa 19,20, NORI C, TOML F, NORI D

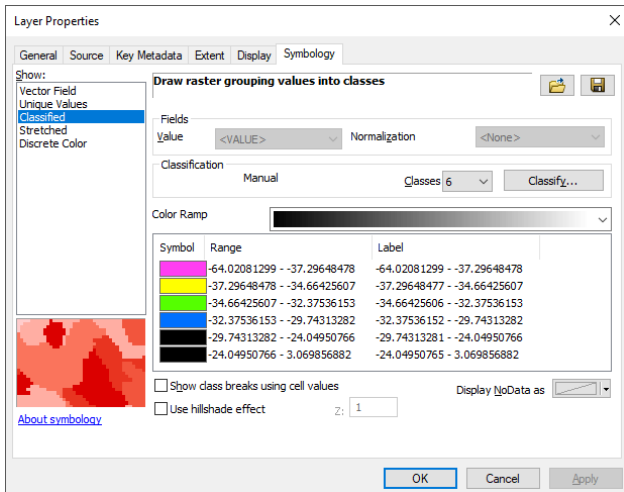


TOML C

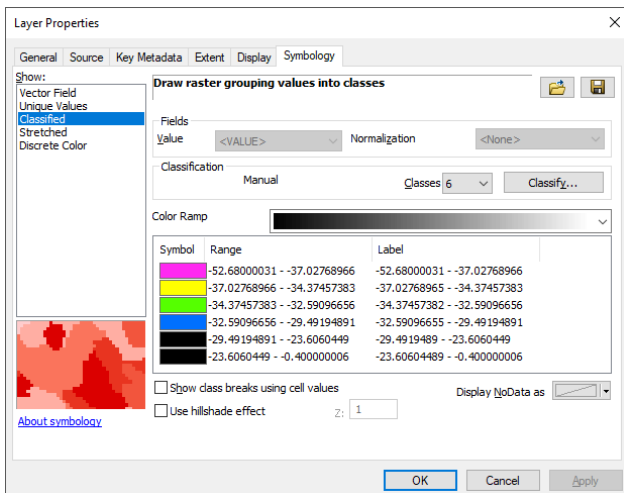


9.10.2 Green scale

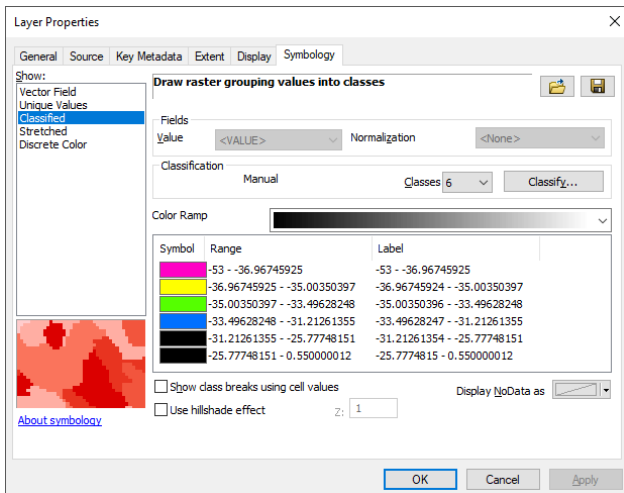
NORI A



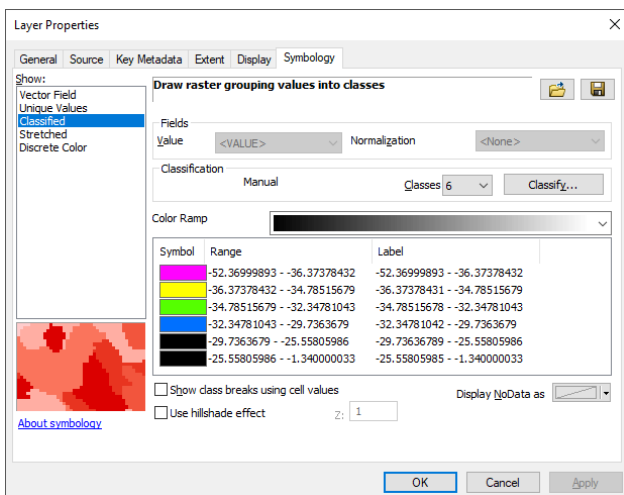
NORI B, TOML B



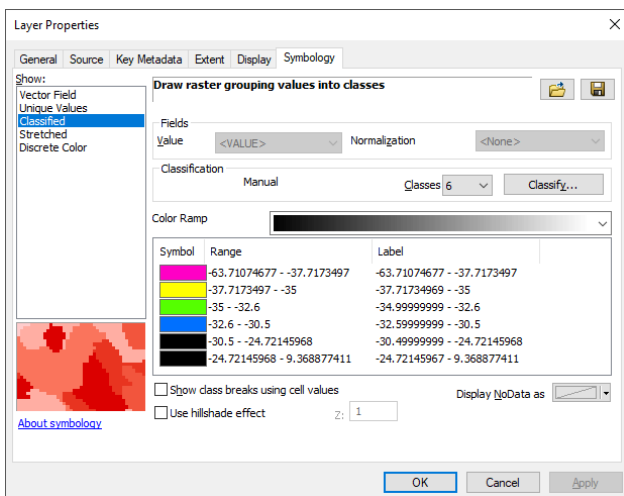
TOML C



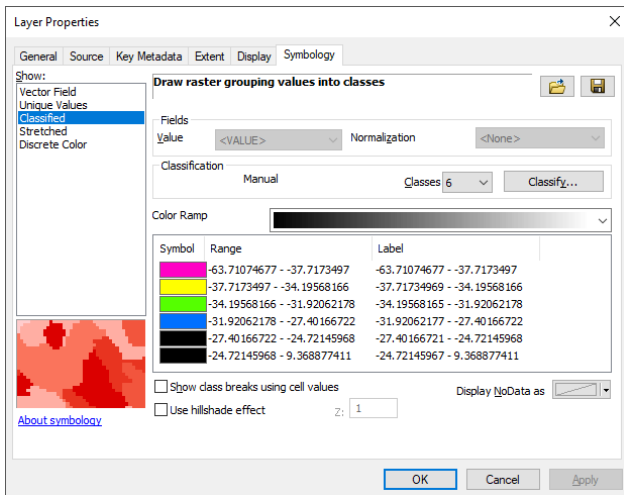
TOML DE



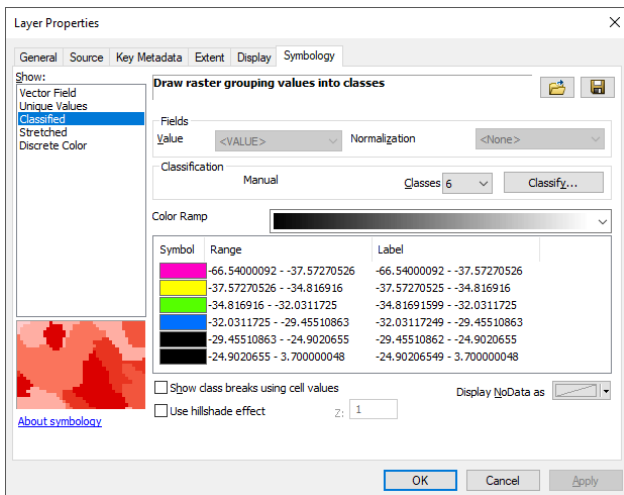
Marawa 19,20



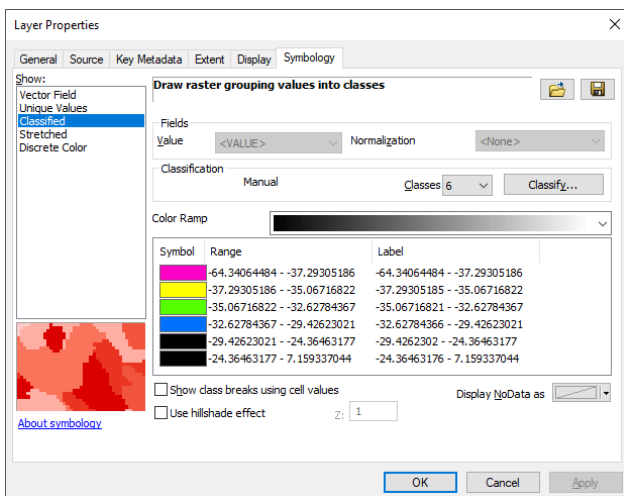
NORI C



TOML F



NORI D



9.11 Appendix 3C: Processes to derive slopes and abyssal hills classes

9.11.1 Process for derivation of slopes

Scope set: ie significantly long slopes likely to reflect abyssal hill fault escarpments (includes valley and hill heads)

Does not include volcanics, tries to exclude minor slopes more likely to reflect original volcanic terrain

Tries to exclude karstic features (e.g. pot holes) but included scalloped edges of abyssal hill that might reflect karstic 'lavaka' formation from original fault escarpments

Step 1: assessment of definition angle of a slope

- Refer to histograms – 6° selected
- Also rule of thumb used by workers at TOML and DGR

Step 2: derivation of slope maps

All maps had slopes facing SW as positive angles and slopes facing NE as negative angles

1. For NORIA, TOML B,C,D,E,F maps supplied by Ashton Flinders during the CCZ13 cruise used, these had been filtered
2. For NORIB, C, F, Marawa qGIS used to
 - a) derive slope maps using "Slope"
 - b) denoised using "SAGA Mesh Denoise" (*threshold 0.9; 5 iterations for normal and 50 for vertex updating*)
 - c) derive facing direction using "Aspect"
 - d) integrate the two rasters using "Raster Calculator" e.g.
`("NORIA_BY_ASP@1"<=135)*1+("NORIC_BY_ASP@1">135) AND ("NORIA_BY_ASP@1">315)*1` then
`("NORIA_BY_ASP@1"<=135)*-1+("NORIA_BY_ASP@1">315)*1`
 - e) `"NORIA_BY_slope@1" * "NORIA_BY_ASPfact@1"`
3. then both types or product rasters
 - a) contoured using "Contour" with an interval of 6 degrees, extraction only of +6 and 6 degree units
 - b) polylines combined into polygons using "Lines to polygons"
 - c) areas for each polygon estimated from local utm coordinates system using ArcGIS "Calculate Geometry" (as there were issues with "Add Geometry Attributes" in qGIS).
 - d) polygons smaller than 0.2 km² deleted (this removed most of the remaining noise from the nadir and survey edges)
 - e) visual inspection removing obvious volcanic features and any remaining irregular features at the edge of the survey areas where noise generates fake slopes perpendicular to the survey track

- f) Bounding rectangles using qGIS “Oriented Minimum Bounding Box” for bearing for classification (primary, secondary other) – note histograms of length and width and rose diagrams of trend
- g) Average BS within the polygons using qGIS “Zonal statistics” for classification – note histograms for each area
- h) Compiled into a single shapefile in wgs-84 per the rest of the map and coded by hardness (30.5 split) and direction NE vs SW
- i) secondaries manually extracted
- j) Smoothed in Arc GIS to 0.0005 decimal degrees

Within the MARA survey block as much of the survey was run sub-parallel to the abyssal hill there were areas near the nadir with too much noise so the auto-polygons were deleted and replaced with hand drawn ones with reference to the slope-aspect map.

9.11.2 Process for classification of abyssal hills

For each survey sub-area/group (NORI A, C, TOML C, D+E, NORI B+TOML B TOML F+NORI D; Marawa 19+20) classes were derived to try to better classify the abyssal hills. Ultimately this supports the mapping of Ab_s versus Abl_s (similarly Ab_c vs Abl_c albeit that these are discriminated from the _s units on the basis of backscatter), and the topographic break lines (tb).

The selected process is Terrain Ruggedness Index (TRI). The process outputs a single-band raster with values computed from the bathymetric elevation; this is the mean difference between a central pixel and its surrounding cells. Then it squares each of the eight elevation difference values to make them all positive and averages the squares. The terrain ruggedness index is then derived by taking the square root of this average, and corresponds to average elevation change between any point on a grid and its surrounding area (Riley et al., 1999).

TRI was conducted at the resolution of the bathymetric maps (50 to 60 m) then the results averaged into 5 km by 5 km blocks (as was the average of the depth). Blocks of this size were selected as they would bridge most abyssal hills and thus provide a better view of the TRI in that area without local effects.

With reference to the US state of Montana and the Rockies, (Riley et al., 1999) propose that

- 0-80 m is considered to represent a level terrain surface;
- 81-116 m represents nearly level surface;
- 117-161 m a slightly rugged surface;
- 162-239 m an intermediately rugged surface;
- 240-497 m a moderately rugged;
- 498-958 m a highly rugged; and
- 959-4367 m an extremely rugged surface.

TRI values at the resolution of the bathymetry almost never exceeded 60 m and once averaged into the 5 km x 5 km blocks discrimination of the order of several m was used.

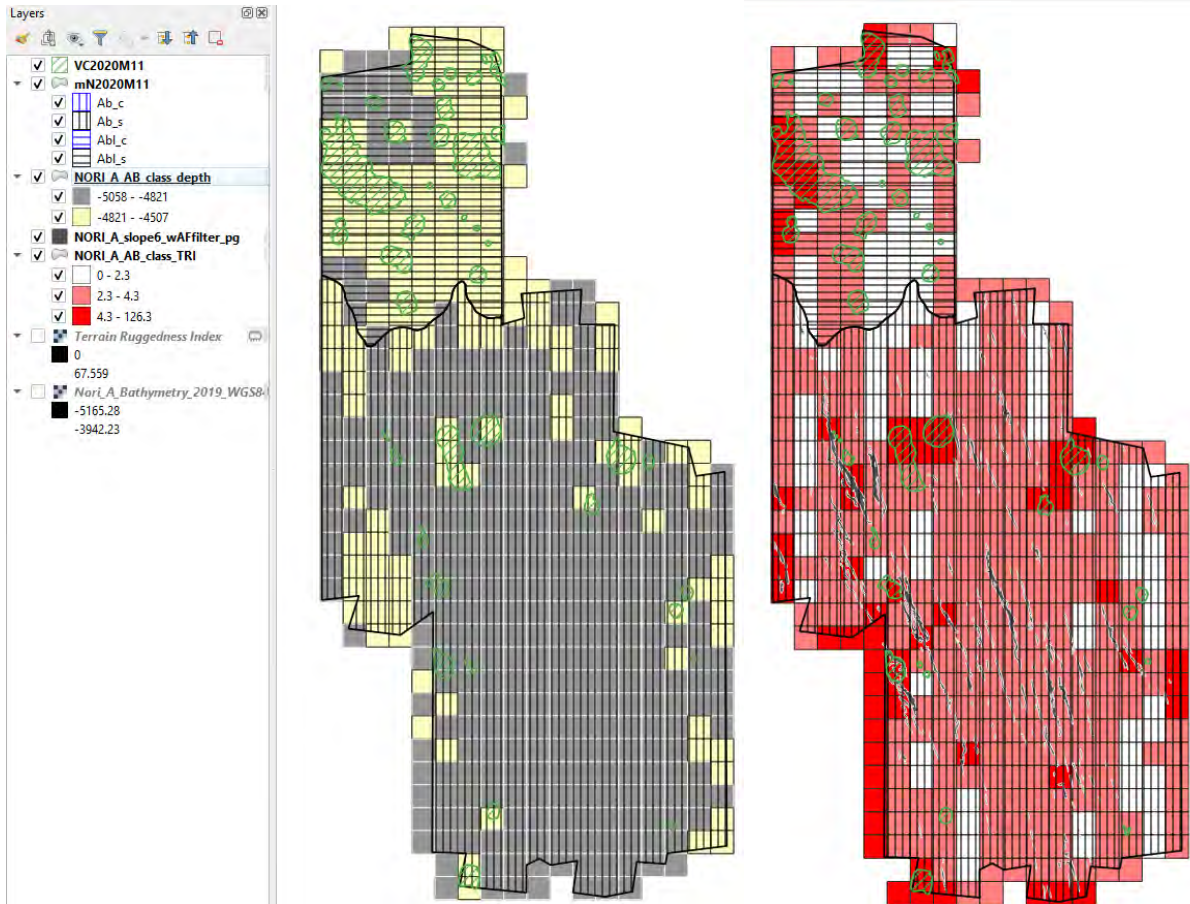


Figure 9-20: NORI A: depth (L) and TRI classes (blocks are 5 km a side)

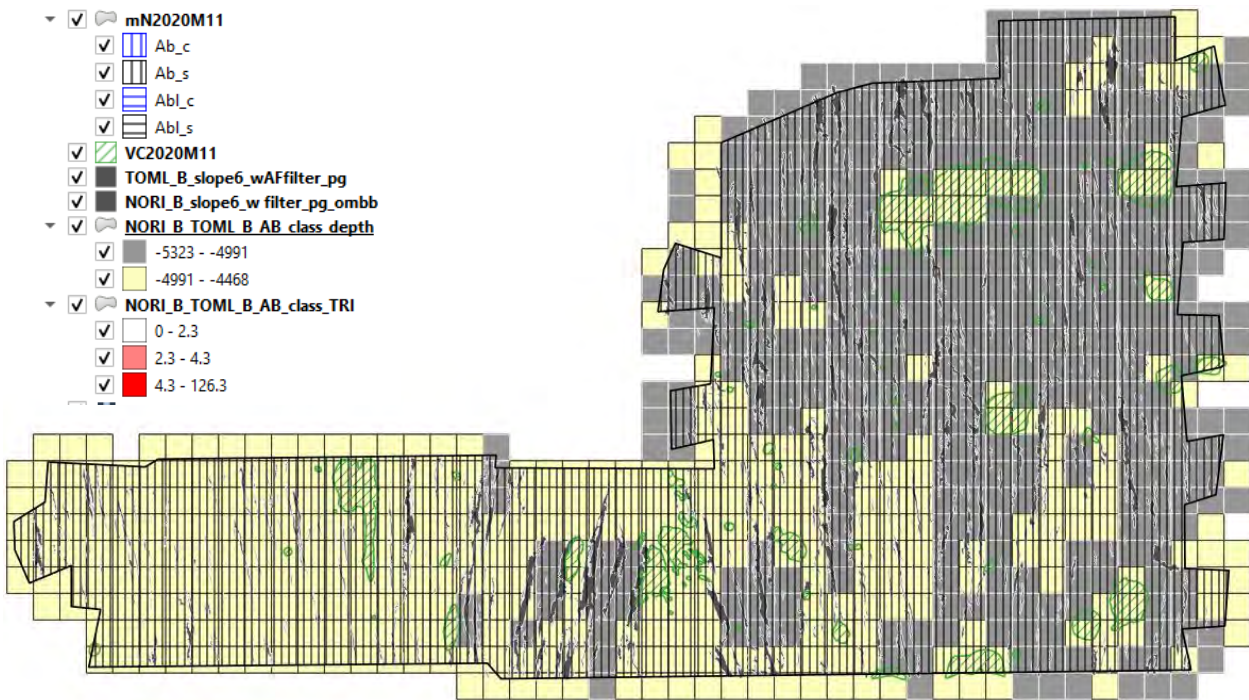


Figure 9-21: NORI B, TOML B: Depth classes (blocks are 5 km a side)

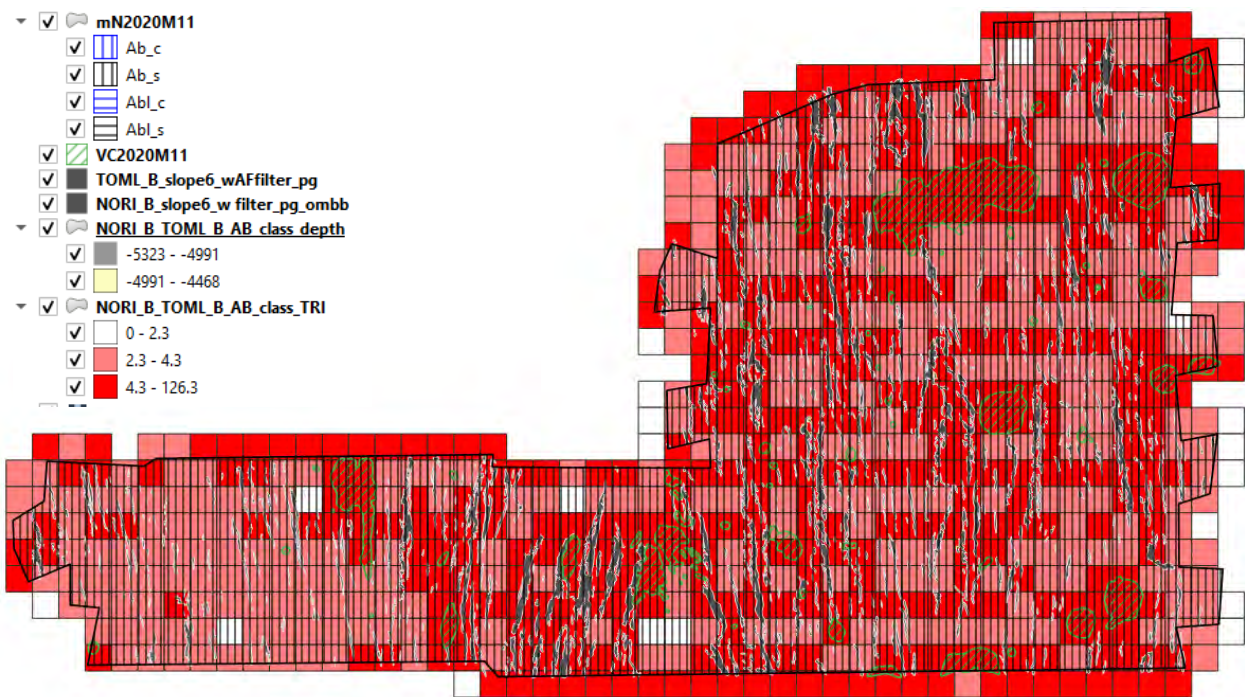


Figure 9-22: NORI B, TOML B: TRI classes (blocks are 5 km a side)

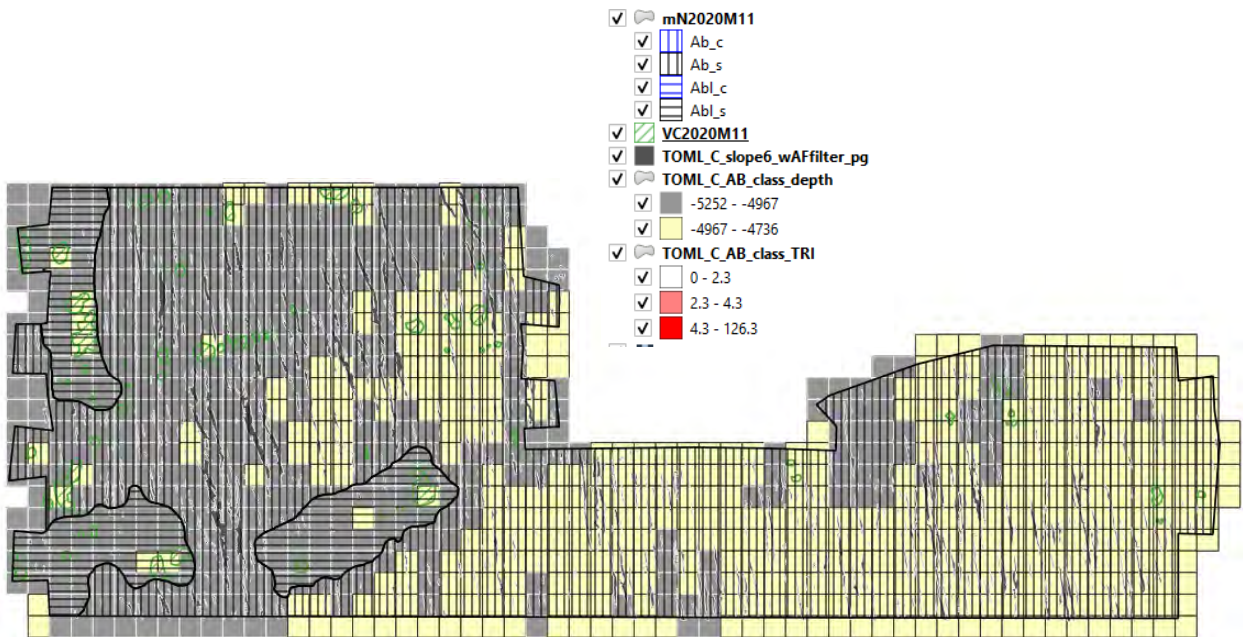


Figure 9-23: TOML C: Depth classes (blocks are 5 km a side)

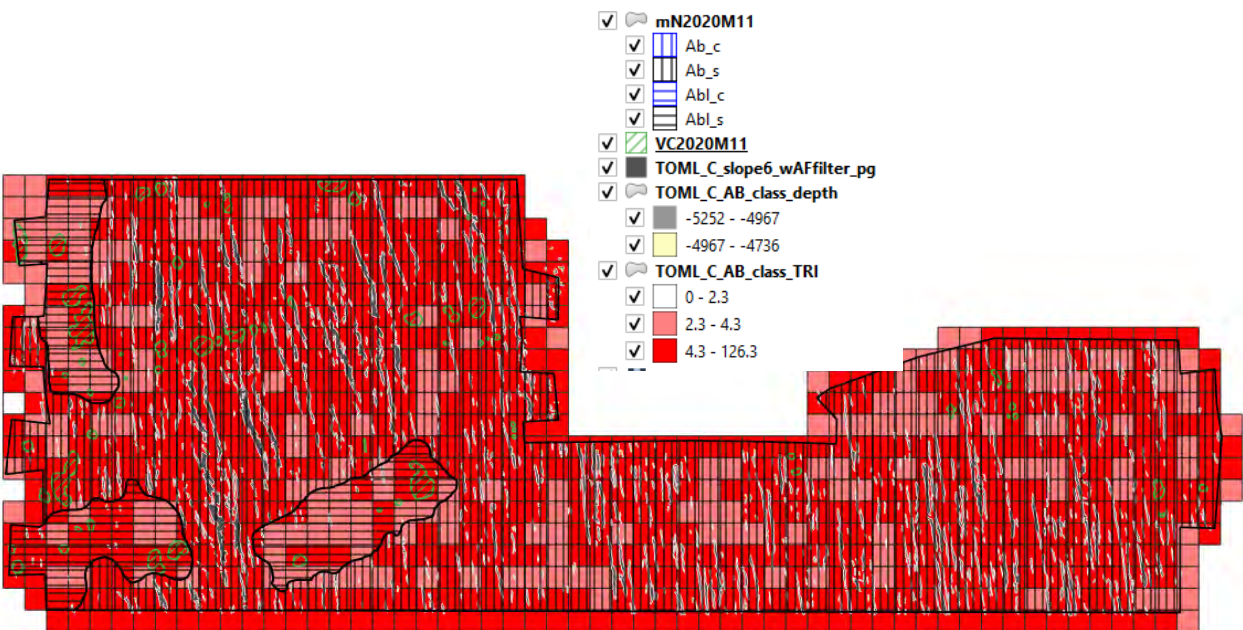


Figure 9-24: TOML C: TRI classes (blocks are 5 km a side)

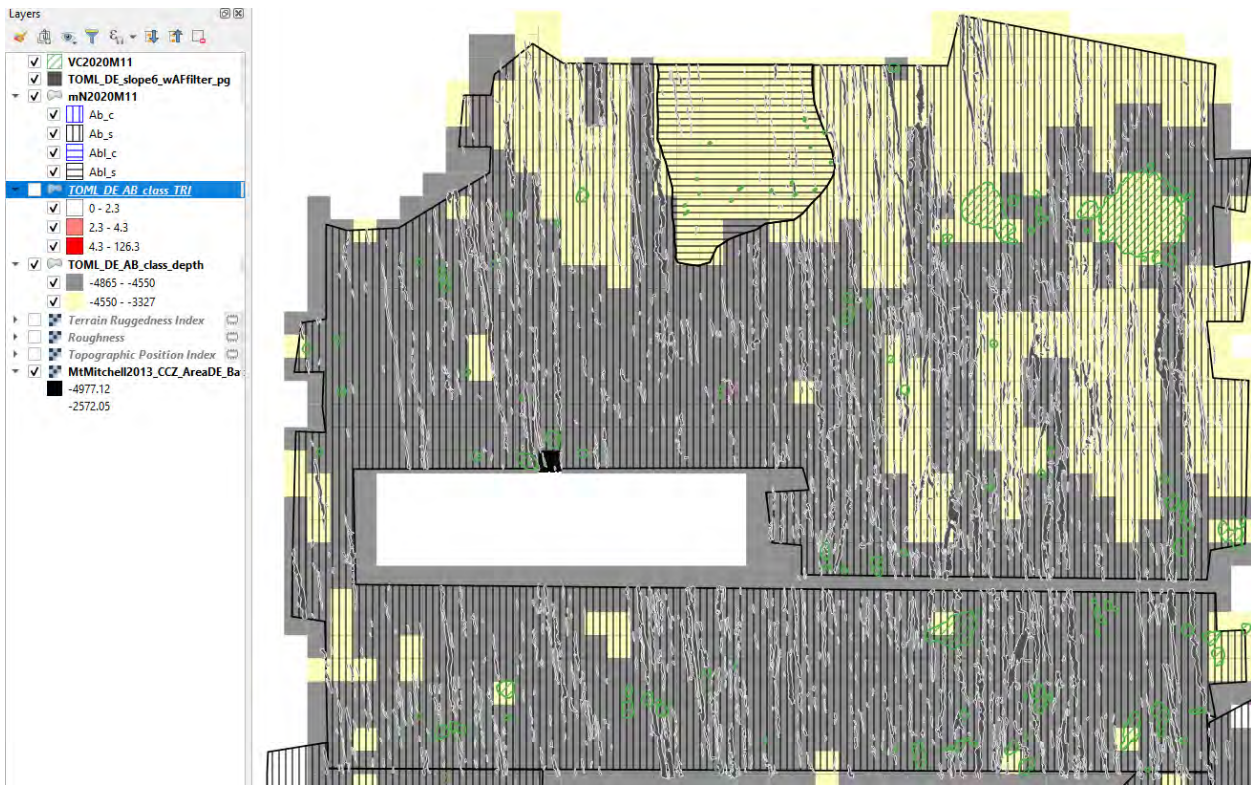


Figure 9-25: TOML D+E: Depth classes (blocks are 5 km a side)

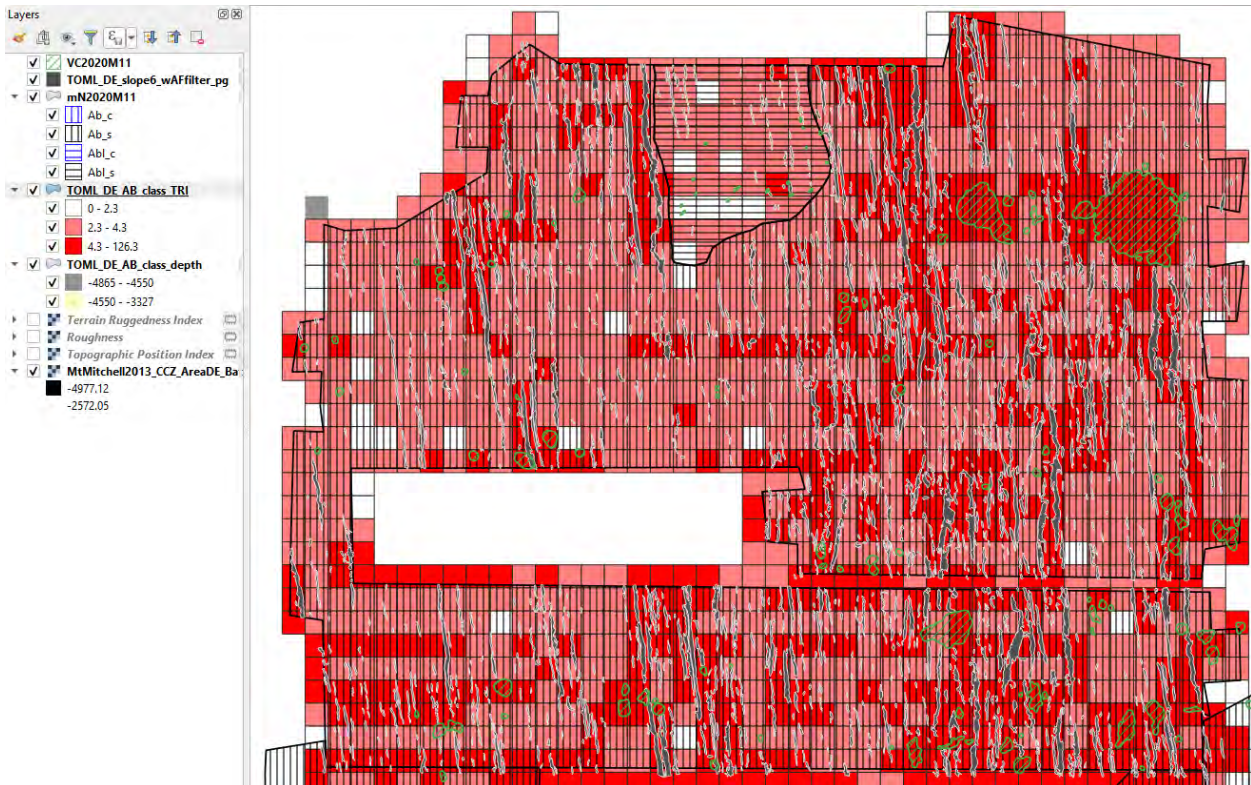


Figure 9-26: TOML D+E: TRI classes (blocks are 5 km a side)

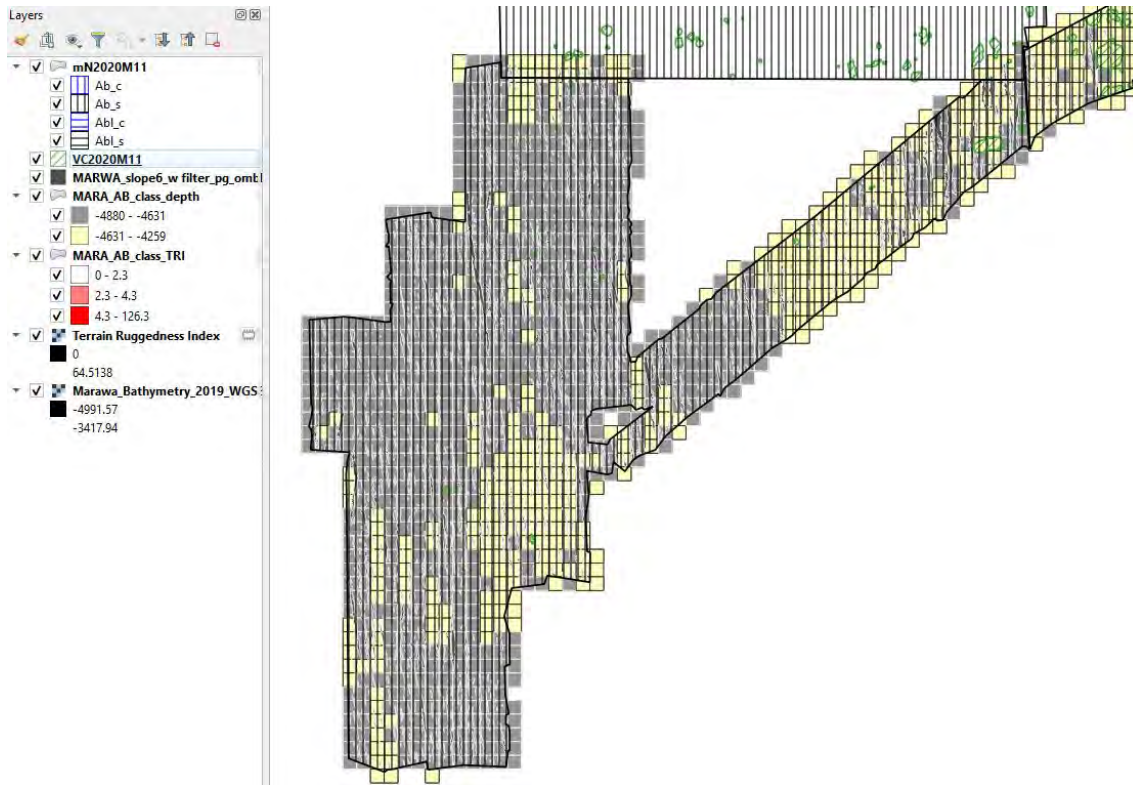


Figure 9-27: Marawa 19+20: Depth classes (blocks are 5 km a side)

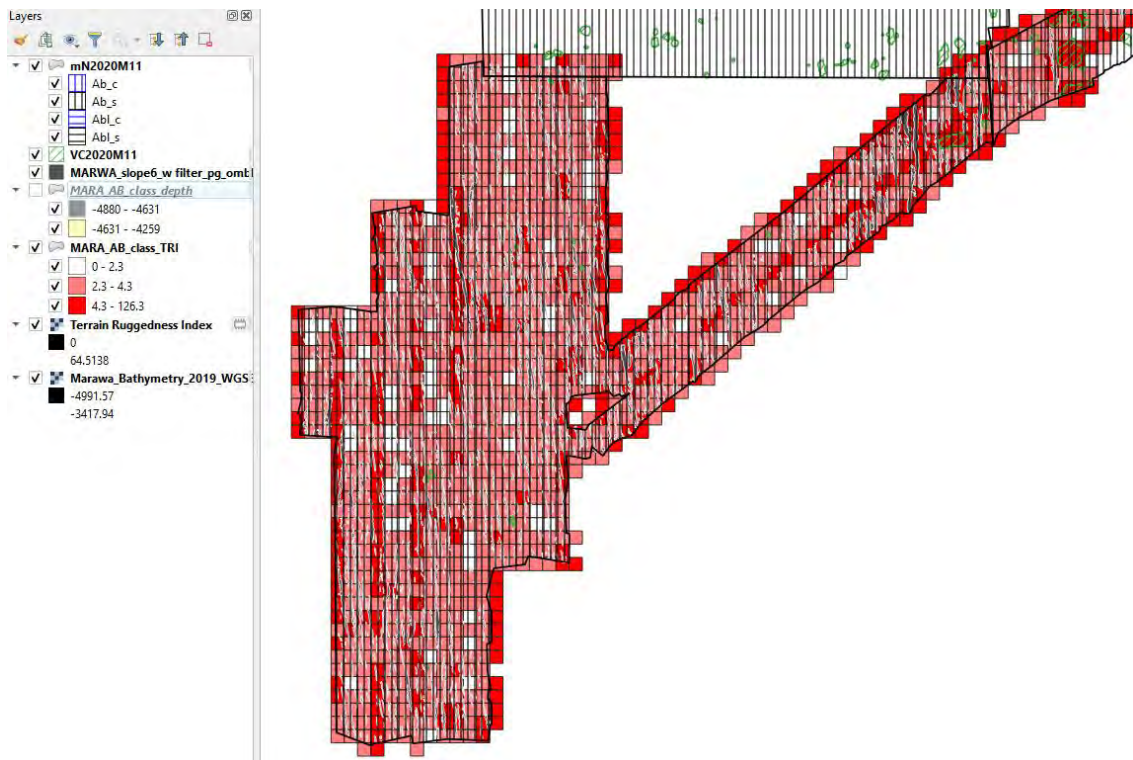


Figure 9-28: Marawa 19+20: TRI classes (blocks are 5 km a side)
note survey run parallel to abyssal hills

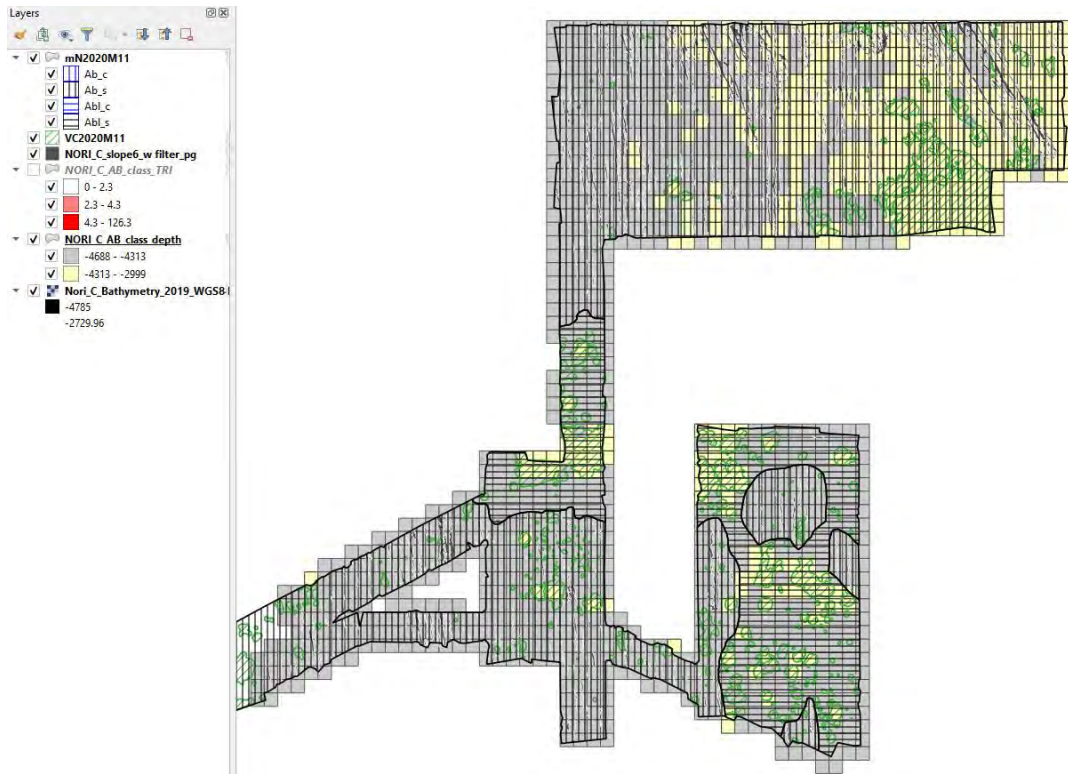


Figure 9-29: NORI C: Depth classes (blocks are 5 km a side)

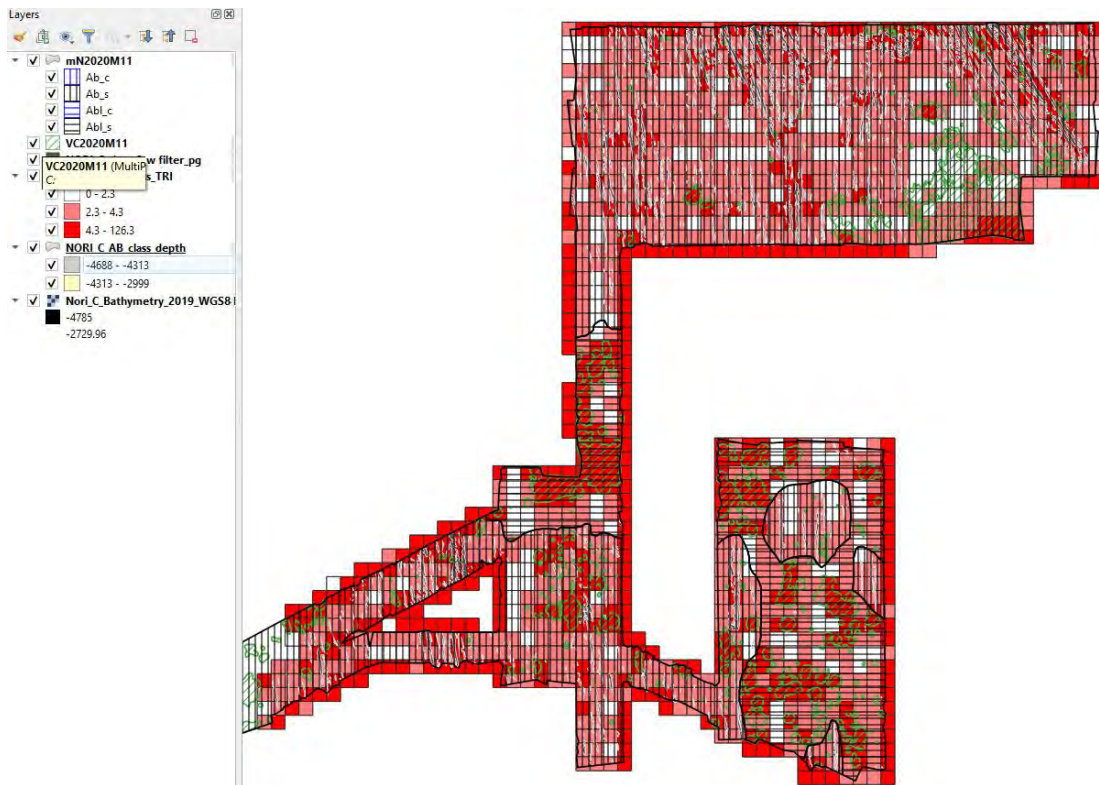


Figure 9-30: NORI C: TRI classes (blocks are 5 km a side)

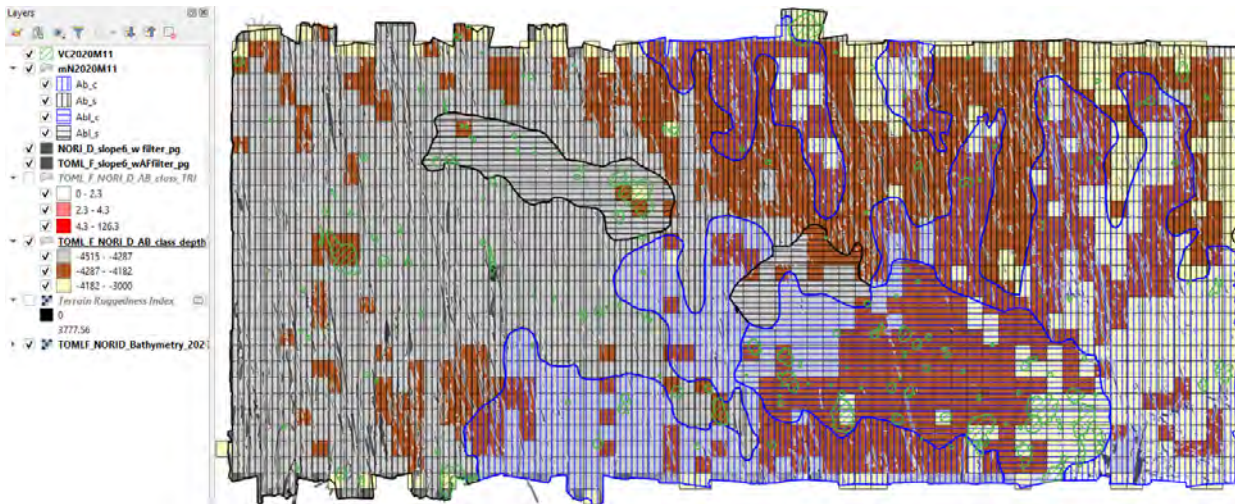


Figure 9-31: TOML F, NORI D: Depth classes (blocks are 5 km a side)

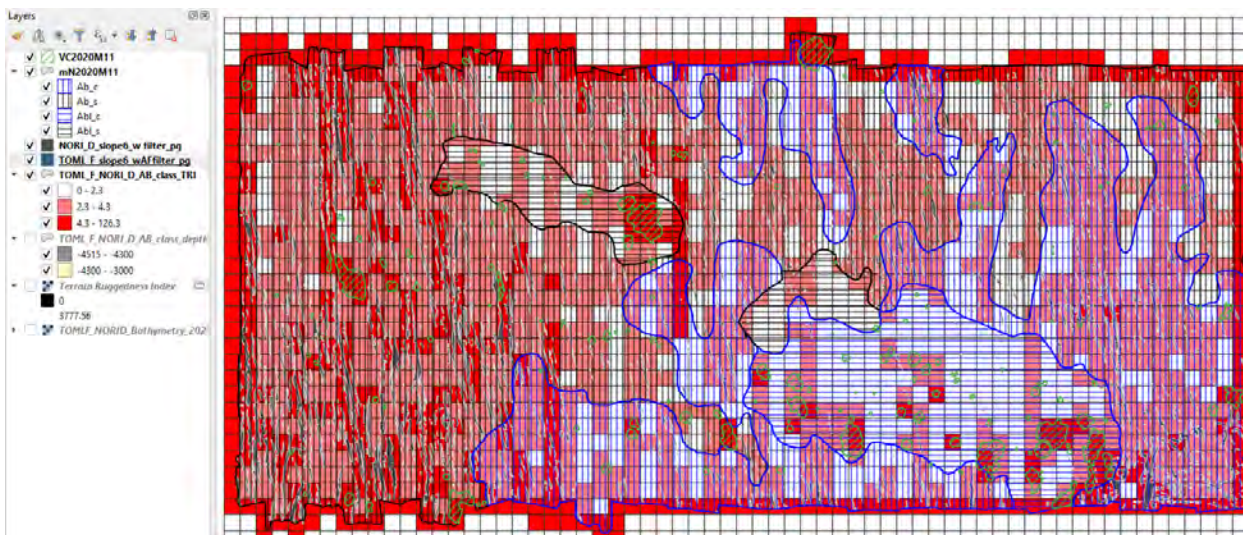


Figure 9-32: TOML F, NORI D: TRI classes (blocks are 5 km a side)

9.12 Appendix 3D: Slope statistics and characteristics

https://www.researchgate.net/publication/350740878_0912_Appendix_3D_SlopeStats_BS_trend_dims?ev=project

9.13 Appendix 3E: Full resolution seabed photographs

https://www.researchgate.net/publication/350740978_0913_Appendix_3E_Full_Resolution_towed_photos?ev=project

9.14 Appendix 3F: Basement and Seamount Geochem

https://www.researchgate.net/publication/350740981_0914_Appendix_3F_Basement_seamount_geochem?ev=project

9.15 Appendix 4A: TOML logging schema examples

Required codes are ss-TT; optional coders are aa-ff-bb as follows. **In all cases the grid is 1 cm.**

ss is size measured from the long axis, i.e.:










Table 9-2: size from long (major) axis			
small	s	=<2 cm	
medium	m	2-5 cm	
large	l	>5 cm	




Table 9-2: size from long (major) axis

small to medium	sm	
medium to large	ml	
mixed	mx	




TT is type per (International Seabed Authority, 2010a) i.e.:

Table 9-3: type		
smooth	S	
smooth-rough	SR	
rough	R	




aa is aspect ie:

Table 9-4: aspect		
oblate high aspect ratio	hi	
oblate regular aspect ratio	rg	
oblate low aspect ratio	lw	
irregular	ir	
prolate	pr	

ff is degree of fragmentation, i.e.:

Table 9-5: fragmentation		
rare	ra	
moderate	md	
common	cm	

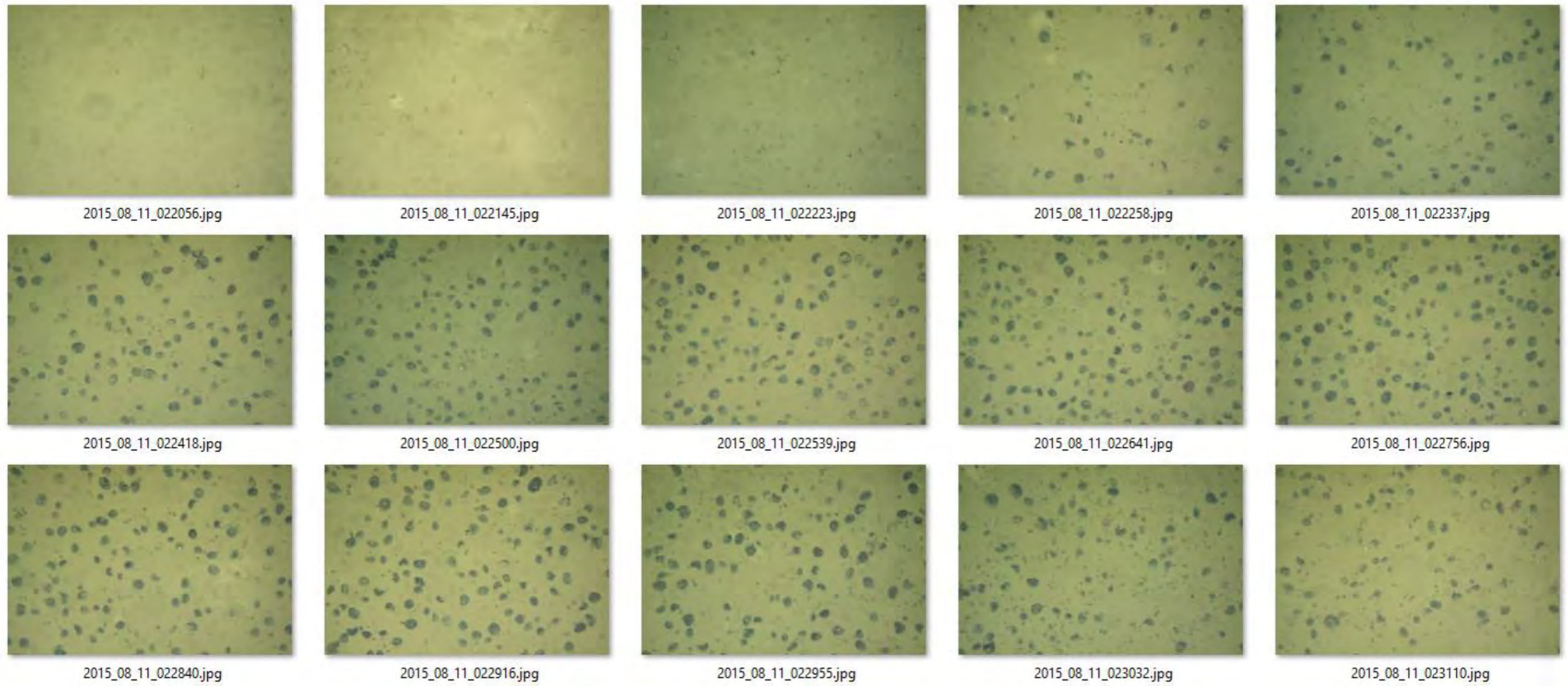
bb is development of botryoidal or mammillate texture ie:

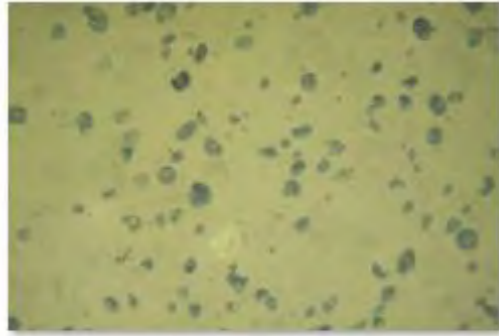
Table 9-6: botryoidal		
well developed	bo	
poorly developed	po	
absent	no	

9.16 Appendix 4B: Organised prolate nodules example in TOML B1

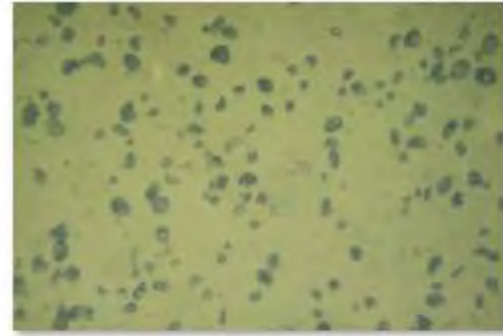
The example presented here (Figure 9-33) is from the CCZ-F01 photo profile line in TOML sub-area B1 (~13 km east of the B5338 sub-area).

The images are all have fields of view of 2.4 x 1.6 m and are about 30 m apart (i.e. the series covers ~ 2 km).

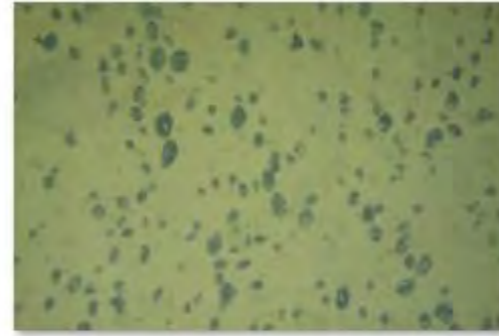




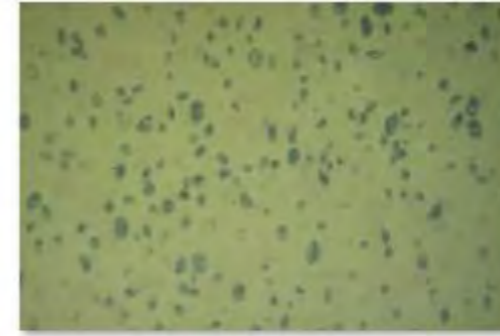
2015_08_11_024512.jpg



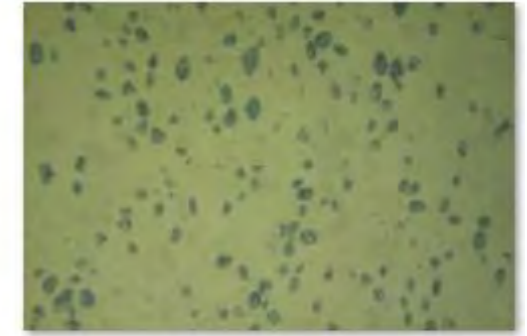
2015_08_11_024547.jpg



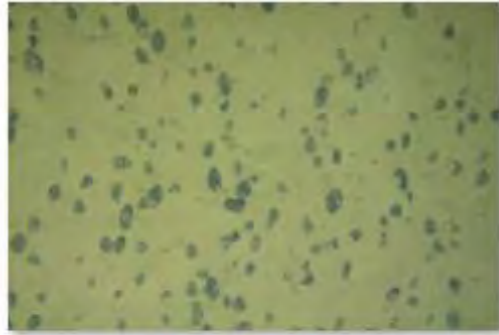
2015_08_11_024625.jpg



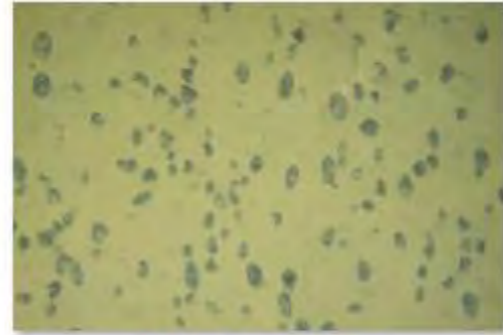
2015_08_11_024700.jpg



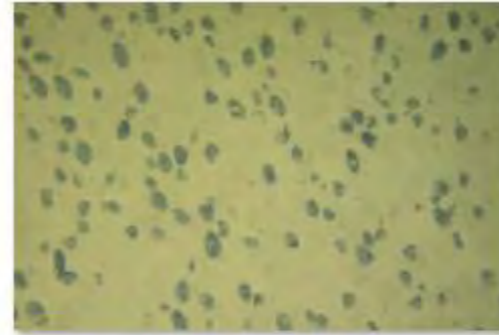
2015_08_11_024758.jpg



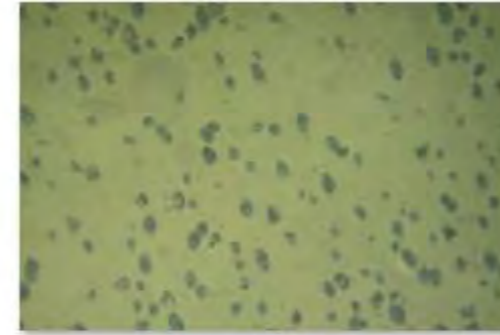
2015_08_11_024837.jpg



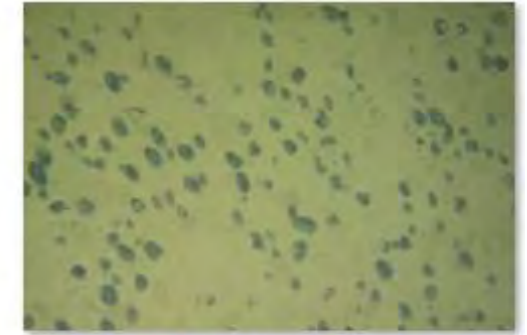
2015_08_11_024926.jpg



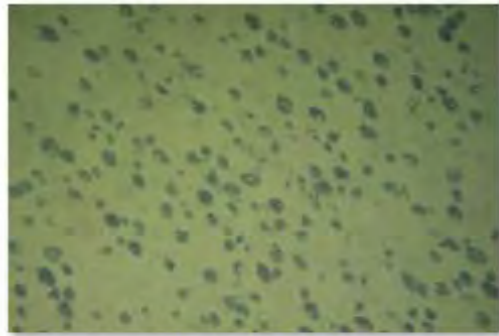
2015_08_11_025005.jpg



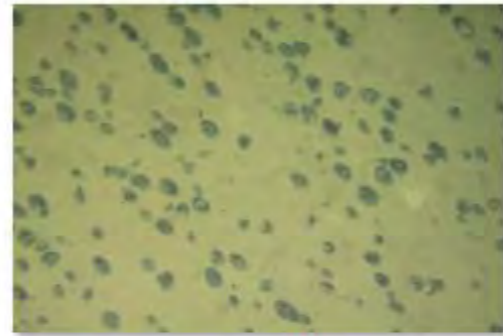
2015_08_11_025053.jpg



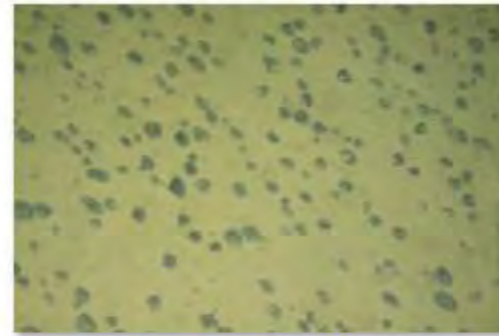
2015_08_11_025133.jpg



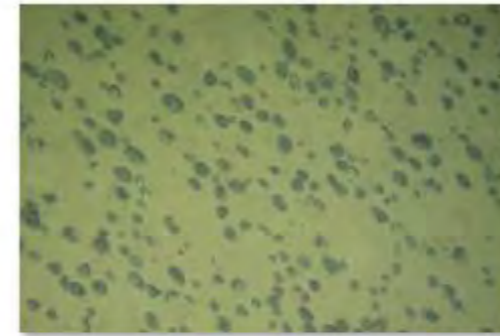
2015_08_11_025229.jpg



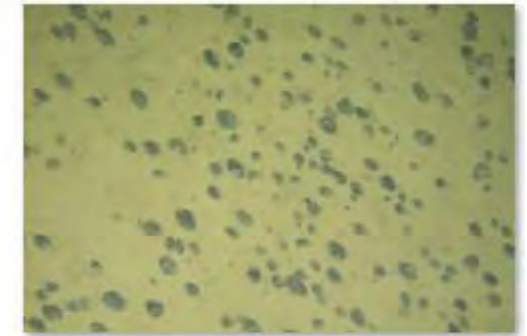
2015_08_11_025324.jpg



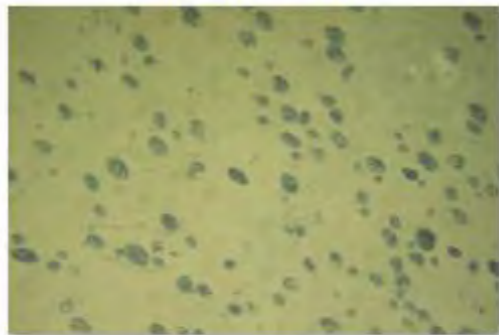
2015_08_11_025407.jpg



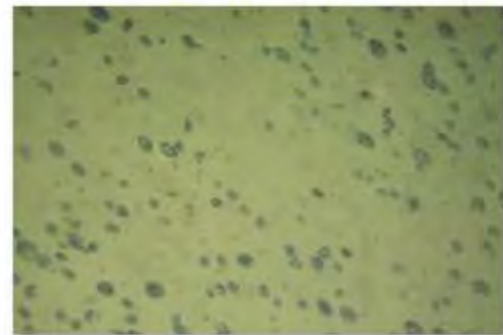
2015_08_11_025443.jpg



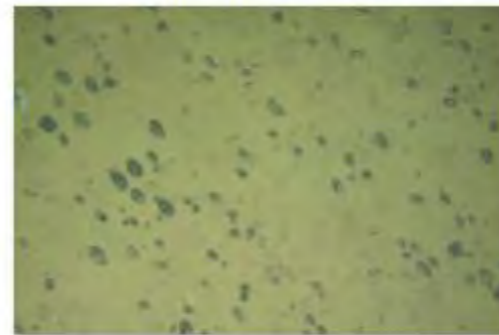
2015_08_11_025530.jpg



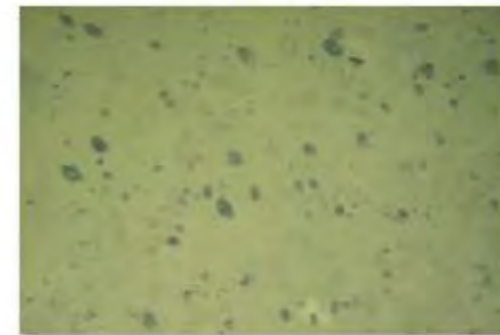
2015_08_11_025624.jpg



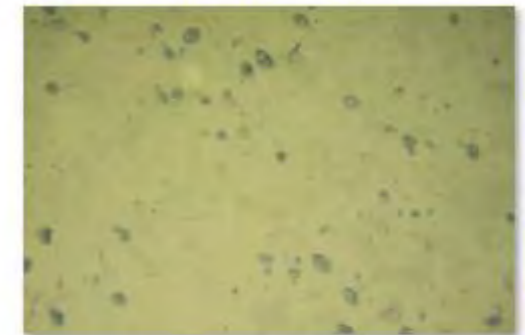
2015_08_11_025659.jpg



2015_08_11_025738.jpg



2015_08_11_025841.jpg



2015_08_11_025921.jpg

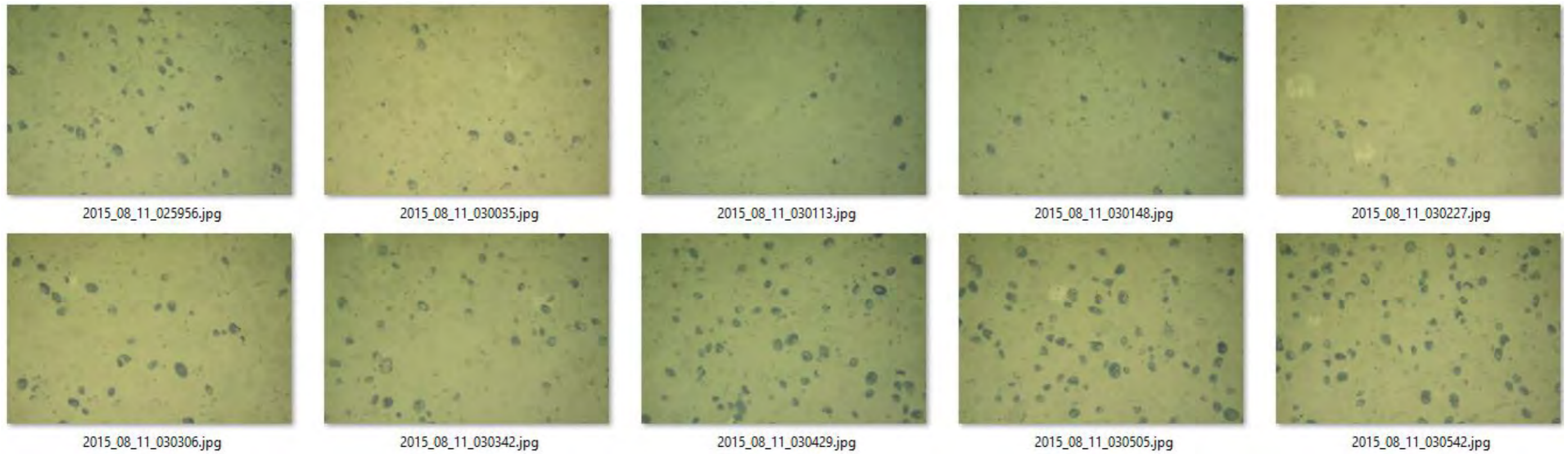


Figure 9-33: Complete series to towed images over an organized prolate nodule field
 Images are named per the date and time stamp and the top of each image is the direction of travel of the photo-sled.

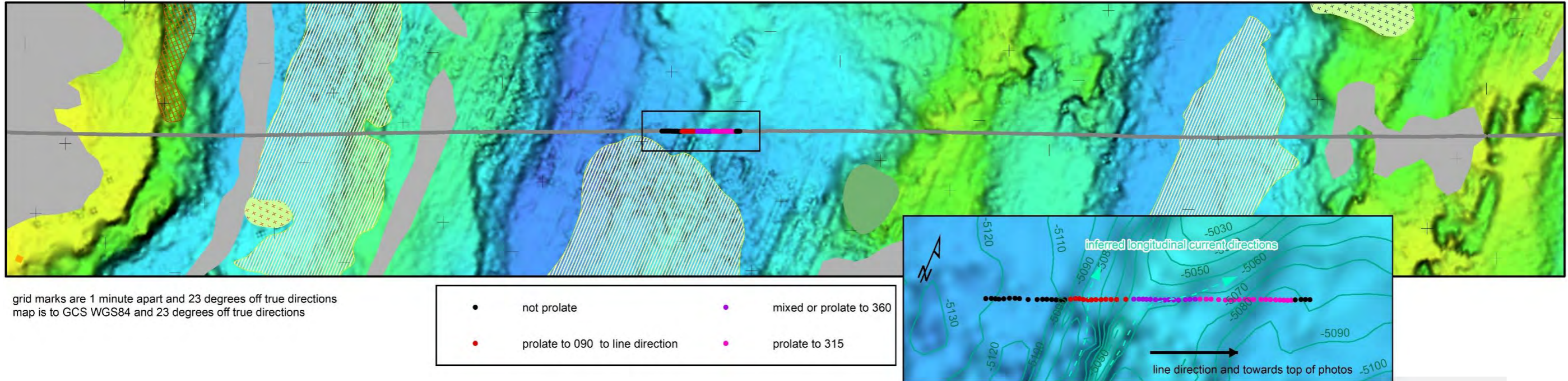


Figure 9-34: Setting of the complete series of towed images over an organised prolate nodule field

9.17 Appendix 4C: Anglo American Technical Solutions QEMSCAN report

This appendix is a modified version of an Angloamerican Technical Solution report titled. The most significant modification is around interpreted mineral names for the silicate and other minor phases. The work was done for the author, unfortunately cobalt scans were not included in the final report and the research division no longer exists.

Mineralogical examination of deep sea polymetallic nodules ex Nautilus.

Original Report Number: MPR/17/27, May 2017

Analysis team P.V. Hey, S. Naik, S. Dhlamini, Y. Scharneck

9.17.1 Summary

A set of nine polymetallic nodules taken from the sea-floor were submitted to Technical Solutions for a mineralogical examination. The samples were taken from the eastern side of the Clarion Clipperton Fracture Zone (CCZ) of the Central Pacific.

The bulk mineralogy of all of the nodules examined is very similar. Buserite is the major mineral present with lesser vernadite and minor silica phase (phillipsite smectite).

The elemental deportment maps show that the buserite contains higher amounts of Ni and Cu with lesser amounts in the vernadite.

9.17.2 Introduction

A set of nine polymetallic nodules taken from the sea-floor were submitted to Technical Solutions for a mineralogical examination. The samples were taken from the eastern side of the Clarion Clipperton Fracture Zone (CCZ) of the Central Pacific, see Figure 1. Polymetallic nodules occur in water depths generally between 4,000 and 6,000 metres. They contain significant grades of manganese, nickel, copper and cobalt and form by the precipitation of metals on the seafloor, either directly from ocean waters or via decomposing microorganisms and/or their effluent in benthic sediments. A list and brief description of each sample as supplied by the client, together with the location of the samples submitted is given

Initially nodule from TOML box-core CCZ15-B104 was chosen to carry out a preliminary examination and to assist in setting up the analysis parameters. The results of this investigation were issued in a draft memorandum in June 2016. Based on the feedback, the parameters were adjusted slightly and examination of the other 8 samples was then carried out. This report gives the results of all 9 samples.

Table 9-7: Logging and other data for the nine samples studied. (Data supplied by TOML).

Area ID	BOX CORE ID	Latitude	Longitude	Depth (m)	Mega-Fauna*	Wet kg/m2	Nodule description	Sediment description
B1	CCZ15-B07	13.811567	-132.480833	4959	None	11.5	medium-large rough-smooth regular rare fragmentation	residual calcareous-siliceous
B1	CCZ15-B21B	13.675477	-132.63251	4862	Xe, Mollusc	13.85	large rough-smooth regular moderate fragmentation well botryoidal	siliceous
C1	CCZ15-B33	15.251767	-129.576667	4900	Xe	5.35	medium-large rough-smooth regular moderate fragmentation well botryoidal	siliceous
C1	CCZ15- B45	15.111783	-129.72761	4890	None	6.1	medium smooth regular moderate fragmentation	residual calcareous-siliceous
D2	CCZ15-B51	13.97681	-124.324117	4532	Xe, Coral, Mollusc	16.5	large rough-smooth regular moderate fragmentation well botryoidal	siliceous
D1	CCZ15- B77	13.55251	-125.16491	4487	Worm	13.5	large rough-smooth regular moderate fragmentation well botryoidal	siliceous
D1	CCZ15-B86E	13.54221667	-125.0207833	4480	2 brittle stars	13.85	medium rough-smooth regular rare fragmentation well botryoidal	residual calcareous-siliceous
F1	CCZ15-B104	10.73546667	-117.9305667	4420	None	10.7	medium smooth regular common fragmentation	siliceous calcareous
F1	CCZ15-B111	10.59633333	-118.0783333	4389	Small coral and Xe	12.6	medium smooth regular common fragmentation	siliceous calcareous

*Xe = xenophyophorida

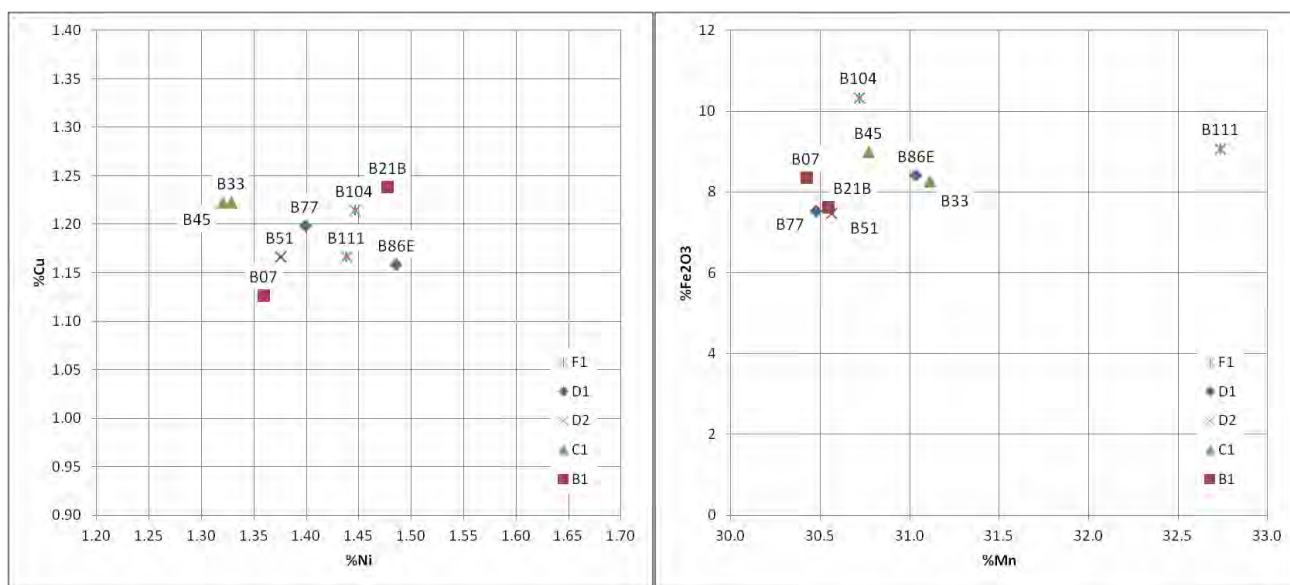


Figure 9-35: Ni vs Cu (left) and Mn vs Fe2O3 for each nodule, as supplied by TOML.

9.17.3 Methodology

For each sample set there were a number of nodules included. In order to assess the variations in the samples, where possible two nodules from each sample were taken and cut using a diamond saw. The cut portions of the nodules were then placed in mould and impregnated with resin under vacuum. A polishing procedure was then carried out such that slabs were able to be examined using QEMSCAN technology and scanning electron microscopy with energy dispersive spectrometry (SEM-EDS). X-ray diffraction (XRD) was also used to try and identify the minerals present but due to the poor crystallinity of the phases this has not been too advantageous.

9.17.4 Results

Based on the backscattered electron (BSE) brightness and the EDS composition various phases within the nodules were identified and then quantified. Due to the nature of the material an exact composition of each mineral phase is difficult to obtain and hence the nomenclature given is at best approximate and has been based upon other studies carried out for the client. There is also a wide variation in composition for some of the Mn- oxides/hydroxides hence a combination of the Mn and Fe content was used to discriminate between the two major Mn-phases. "Buserite" contains a higher proportion of Mn (>45 %) with a lower proportion of Fe (<5 %). "Vernadite" comprises a slightly lower Mn (<45 %) with a higher proportion of Fe (>5 % and may contain up to 20 %). The results given here are based on the data generated and minerals listed as present in nodules in the published literature. This will be refined as more nodules are examined and more data becomes available.

An update was done by the thesis author (Parianos) and is integrated/replaced as follows.

The identified minerals/phases have therefore been classified as follows;

1. Mn rich phase: interpreted by Technical Solutions to be predominantly buserite– a Mn-bearing oxide with minor Fe, Ca, Mg, Na and K. Si and Al may also be present,
2. Fe rich phase: interpreted by Technical Solutions to be predominantly vernadite – a Mn, Fe bearing oxide with minor Ca, Si, Mg, Al and Na. K, Ti and Cl may also be present,
3. FeAlKCaMg-Si phase: likely to be a smectite such as Fe- montmorillonite and potentially intergrown with opal CT but originally interpreted by Technical Solutions to be Amphibole – a Fe, Al, K, Ca, Mg silicate,
4. KNaAlFe-Si phase: likely to be a zeolite such as phillipsite or maybe clinoptilolite Zeolite – a K, Na, Al, Fe silicate,
5. Apatite – CaPO₄,
6. Fe-Si phase discriminated from 4. by minor Mg, Al and K: may be chlorite but originally interpreted by Technical Solutions to be Stilpnomelane – a Fe silicate with lesser Mg, Al, and K,
7. Mixed Ca, ?Ba S phase: likely to be barite and remnant calcite. But originally interpreted by Technical Solutions to be Ca-S-Silicate – this is an unknown phase which contains a significant amount of Ca, S, Fe and Si with lesser Al, Mg, and K. The Ca and S appear to be present together as does the Fe and silica. It is therefore suspected that this phase is a very fine intergrowth of gypsum and maybe the originally identified (never reported from nodules) stilpnomelane or amphibole (only as detrital phase). Ba was unfortunately not analysed for, but as a biogenetic component is more likely to be incorporated with this phase than the others.

Thus in the scans further below the original technical solution legend as shown at left was replaced with an updated legend as shown at right.

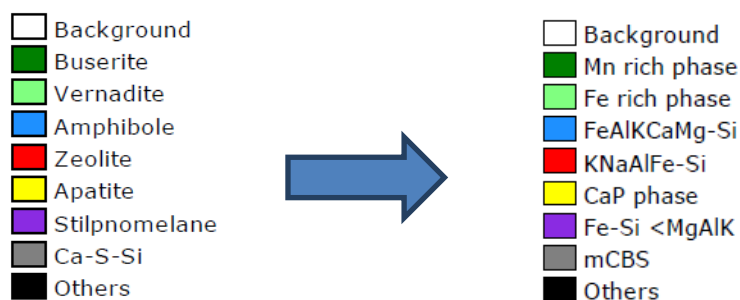


Figure 9-36: translation of phase identifiers

Table 9-8 and Figure 9-37 give the bulk compositions of each nodule using the mineral nomenclature explained above. In some of the samples minor levels of quartz were identified by XRD but discreet particles were not identified by QEMSCAN, hence it must be present as very fine particles intergrown with the other minerals.

Table 9-8: Bulk mineralogical composition of the nodules.

Mineral	B07-1	B07-2	B21B-1	B21B-2	B33-1	B33-2	B45-1	B45-2	B51
Mn rich phase	66.5	71.1	68.3	72.5	66.0	65.2	70.2	67.0	64.8
Fe rich phase	26.5	21.7	23.8	17.2	24.7	27.9	24.7	27.2	19.6
FeAlKCaMg-Si	3.8	4.1	3.0	5.6	4.1	2.9	1.8	2.0	11.2
KNaAlFe-Si	1.3	1.1	0.8	0.9	1.5	0.9	1.4	1.8	1.2
CaP	0.2	0.3	0.3	0.3	0.2	0.2	0.1	0.1	0.2
Fe-Si <MgAlK	0.0	0.1	0.8	0.2	0.3	0.3	0.0	0.0	0.1
Ca--S-Si ?Ba	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Others	1.7	1.8	2.9	3.3	3.1	2.6	1.7	1.8	2.8
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Mineral	B77	B86E-1	B86E-2	B104-1	B104-2	B104-3	B111-1	B111-2	
Mn rich phase	77.6	72.0	69.1	58.5	64.8	59.9	73.1	76.6	
Fe rich phase	12.5	22.0	24.8	36.9	34.0	31.7	22.5	19.2	
FeAlKCaMg-Si	6.8	2.5	3.1	1.1	0.2	1.3	1.8	1.7	
KNaAlFe-Si	1.1	1.6	1.1	1.4	0.4	0.8	1.5	1.7	
CaP	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.1	
Fe-Si <MgAlK	0.2	0.1	0.1	0.5	0.0	0.0	0.1	0.0	
Ca--S-Si ?Ba	0.0	0.0	0.0	0.0	0.0	5.1	0.0	0.0	
Others	1.7	1.7	1.6	1.5	0.5	1.1	0.7	0.7	
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	

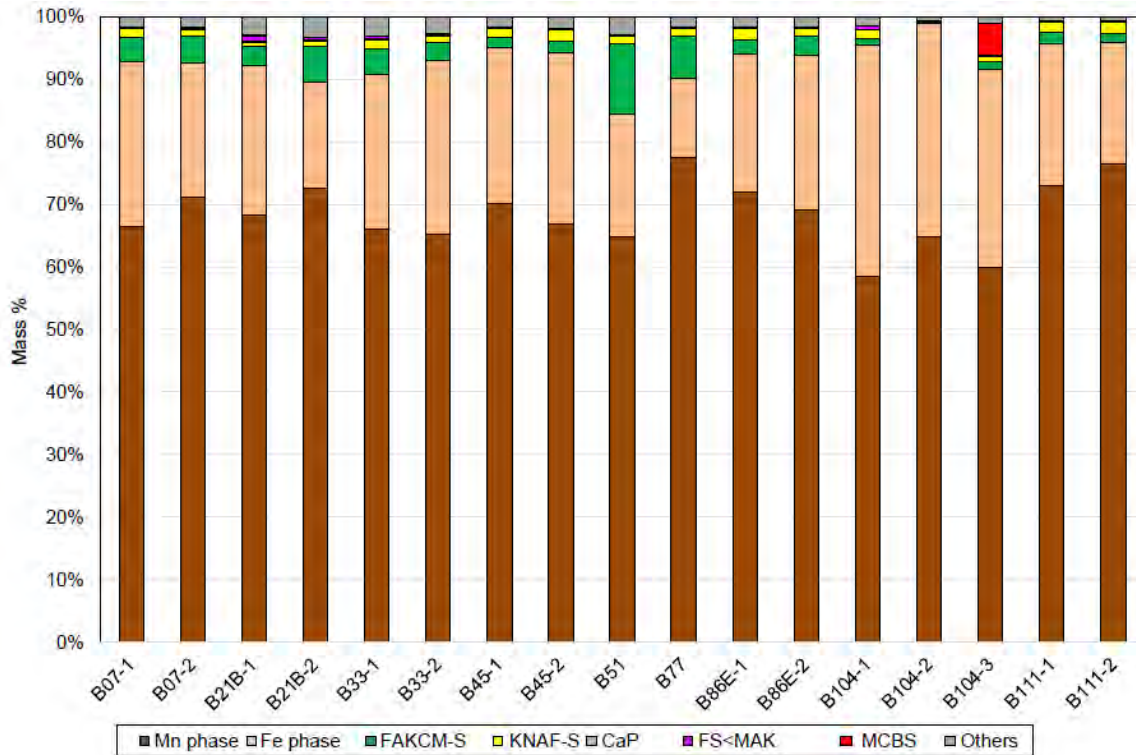


Figure 9-37: Bulk modal composition of QEMSCAN samples

Per Figure 9-36 FAKCM-S = FeAlKCaMg-Si phase; KNAF-S= KNaAlFe phase, FS<MAK = Fe-Si <MgAlK phase and MCBS = Ca--S-Si ?Ba phase

The following figures show a backscattered electron image and the equivalent mineral map produced by QEMSCAN. An elemental distribution map for Mn, Fe, Ni, and Cu have also been produced to determine the department of these elements throughout the nodules.

Note that for convenience the original figure numbers were kept as they are not used (specifically referenced) in the report.

9.17.5 Comments

The bulk mineralogy of all of the nodules examined is very similar. Buserite is the major mineral present with lesser vernadite and minor amphibole.

The elemental department maps show that the buserite contains higher amounts of Ni and Cu with lesser amounts in the vernadite.

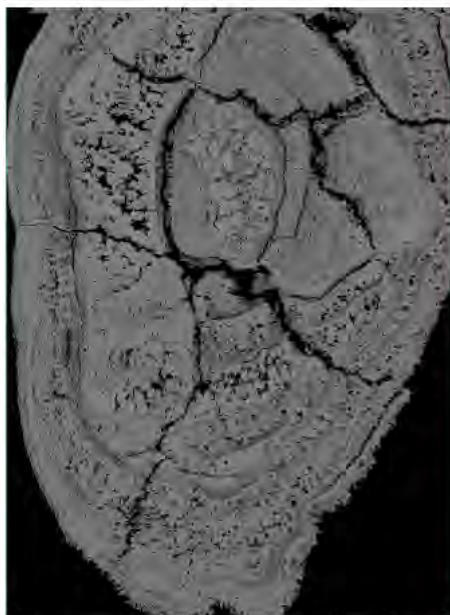


Figure 4: Backscattered electron image of Nodule B07-1.

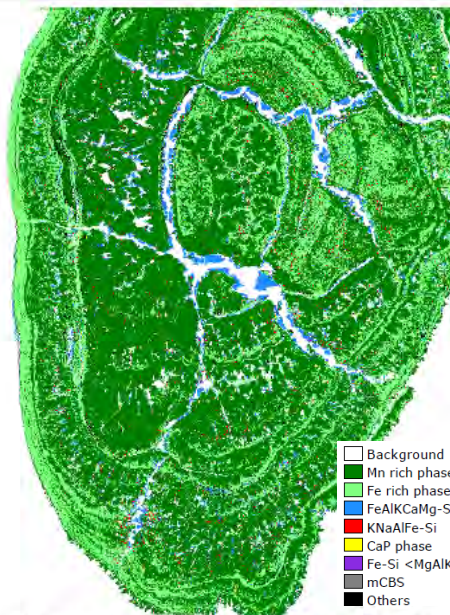


Figure 5: Mineral map of Nodule B07-1

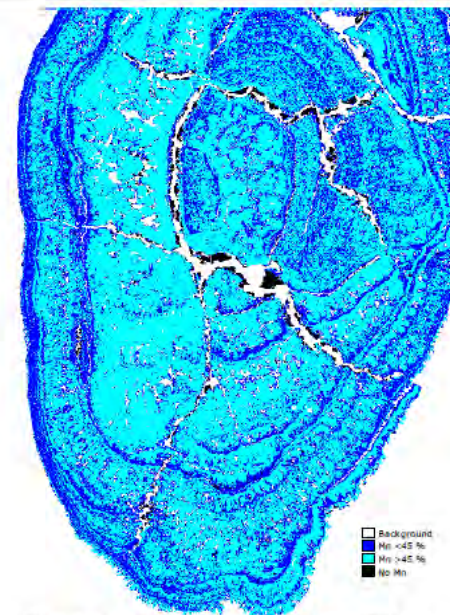


Figure 6: Mn plot of Nodule B07-1

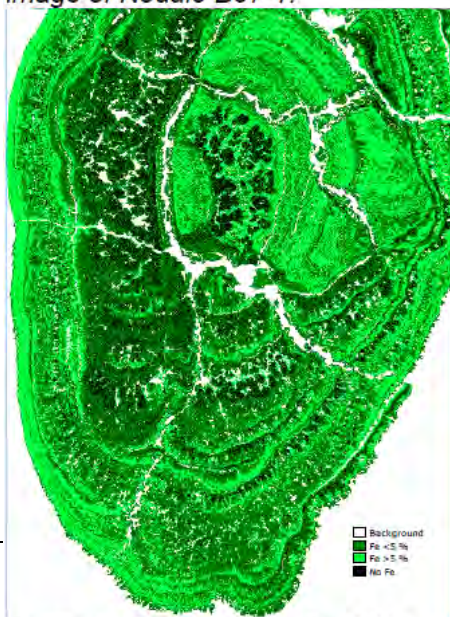


Figure 7: Fe plot of Nodule B07-1

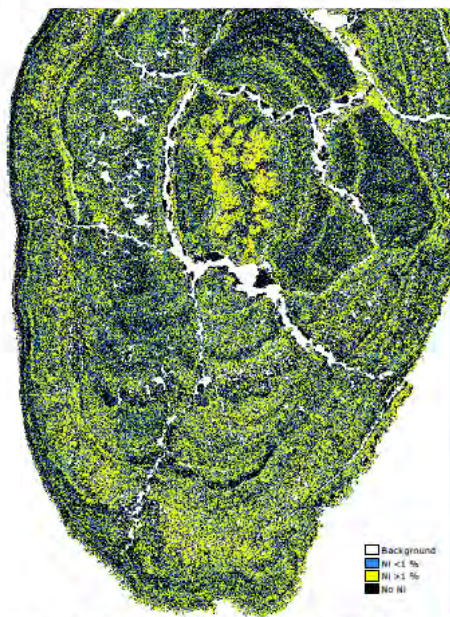


Figure 8: Ni plot of Nodule B07-1

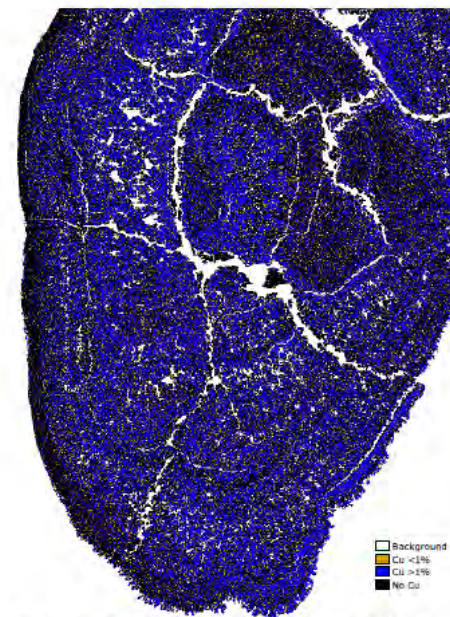


Figure 9: Cu plot of Nodule B07-1

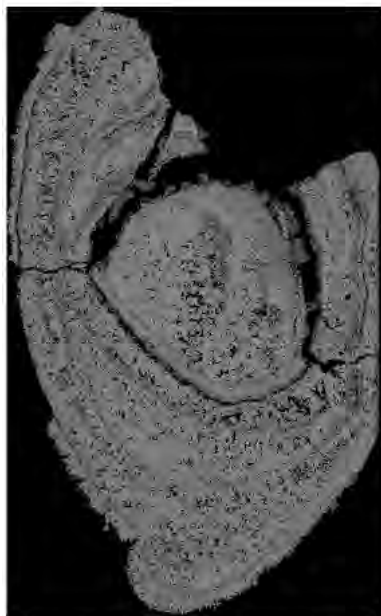


Figure 10: Backscattered electron image of Nodule B07-2.

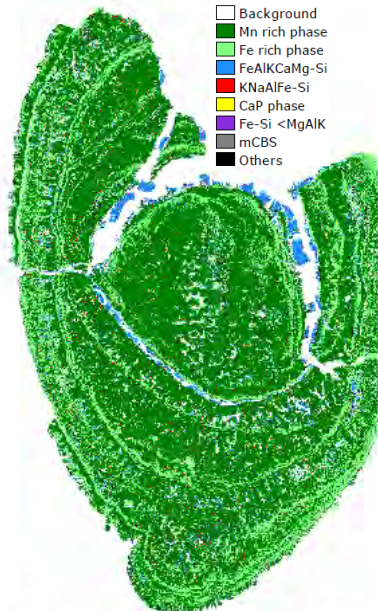


Figure 11: Mineral map of Nodule B07-2.

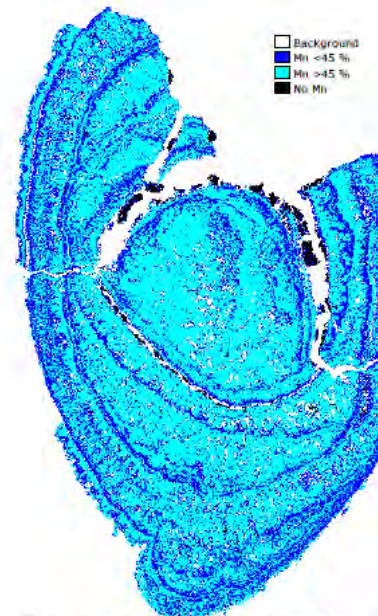


Figure 12: Mn plot of Nodule B07-2.



Figure 13: Fe plot of Nodule B07-2

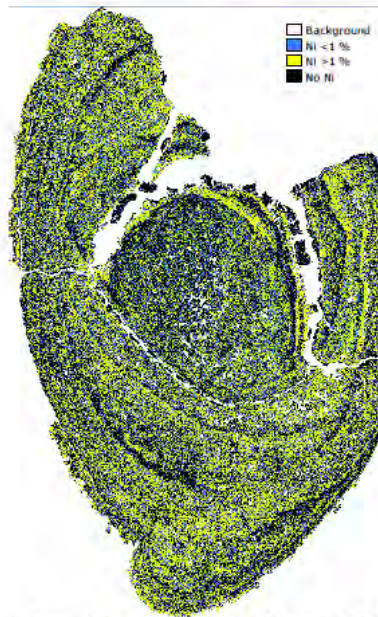


Figure 14: Ni plot of Nodule B07-2

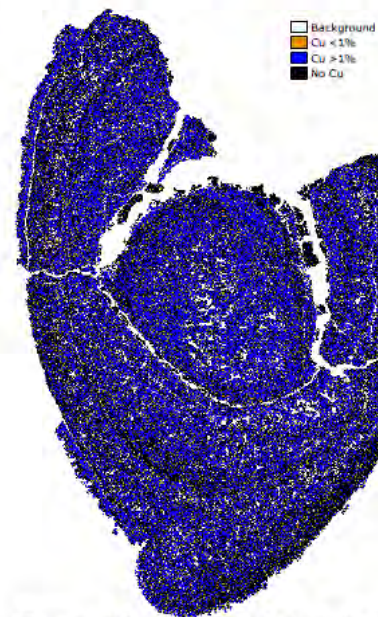


Figure 15: Cu plot of Nodule B07-2

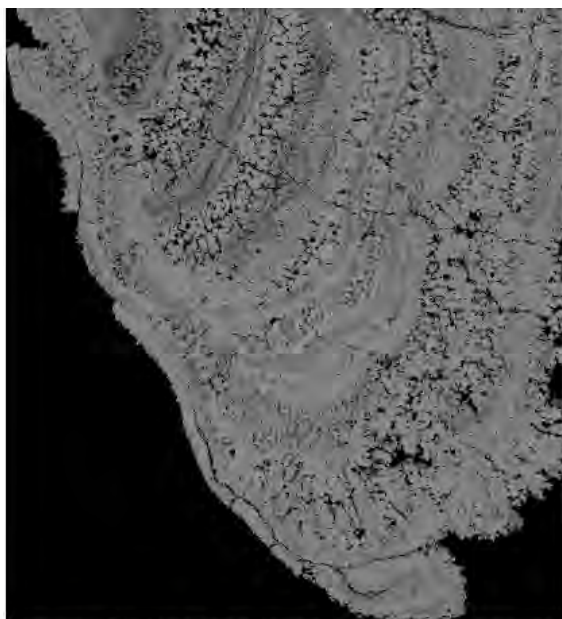


Figure 16: Backscattered electron image of Nodule B21B-1.

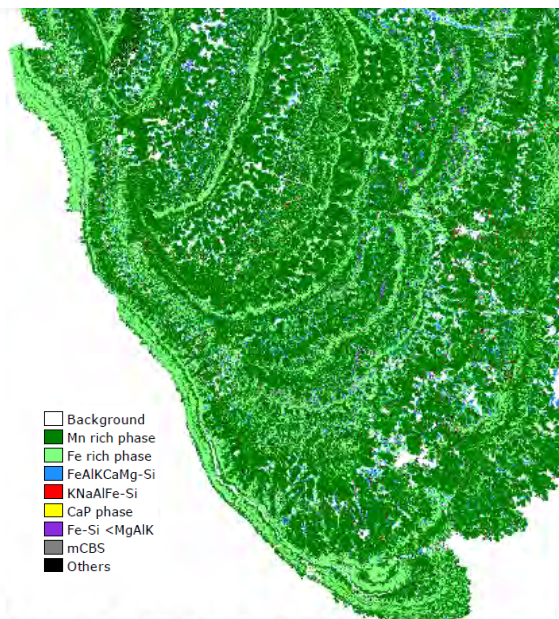


Figure 17: Mineral map of Nodule B21B-1.

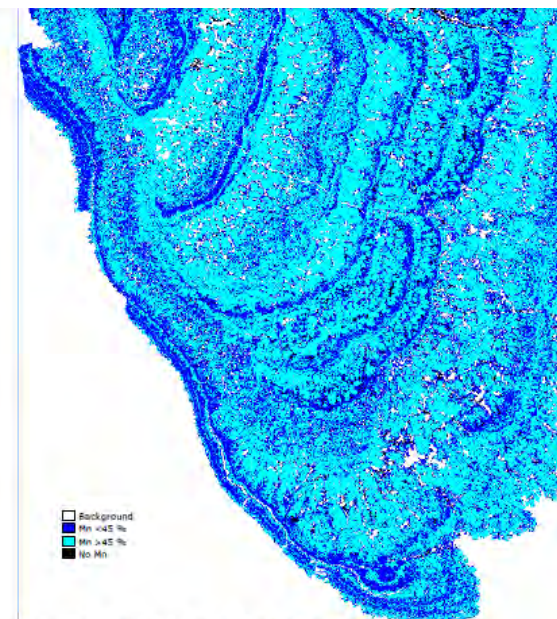


Figure 18: Mn plot of Nodule B21B-1.

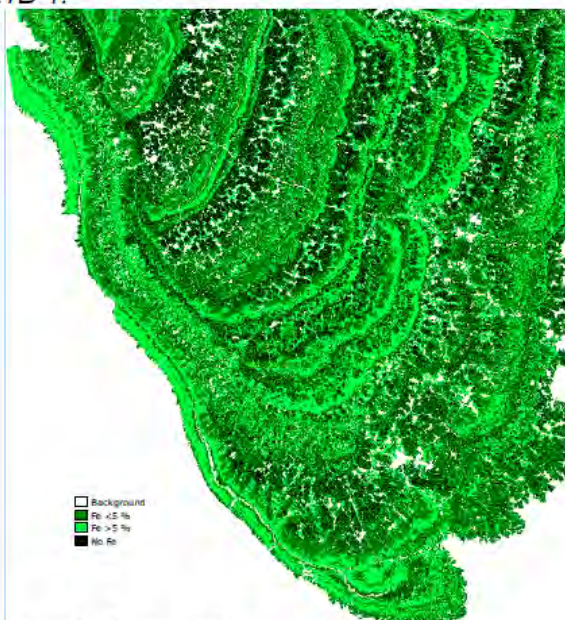


Figure 19: Fe plot of Nodule B21B-1.

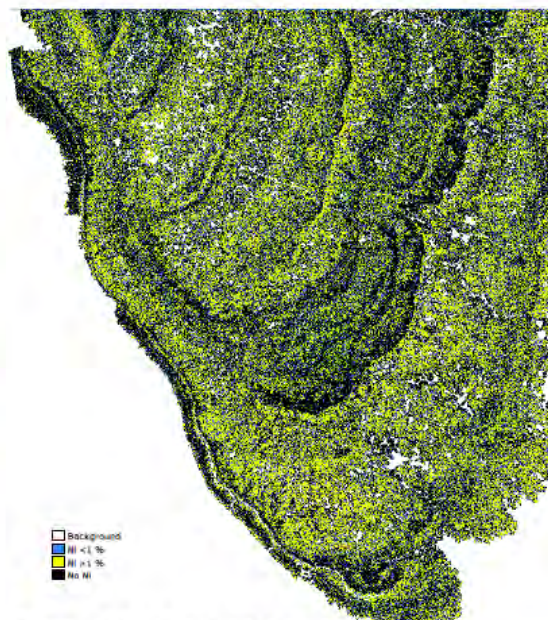


Figure 20: Ni plot of Nodule B21B-1.

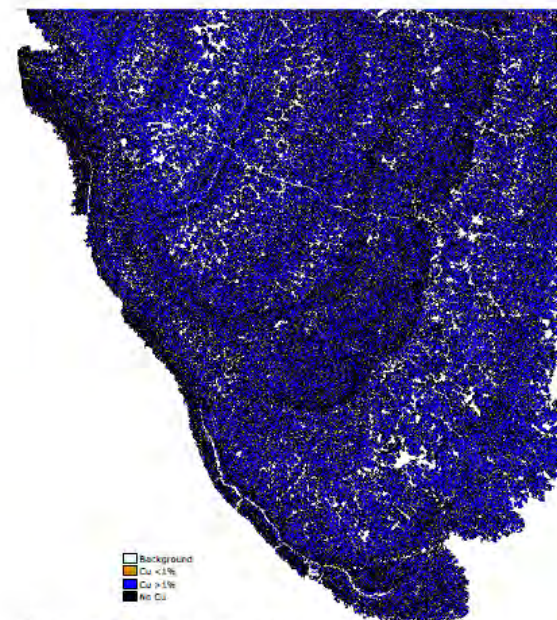


Figure 21: Cu plot of Nodule B21B-1.

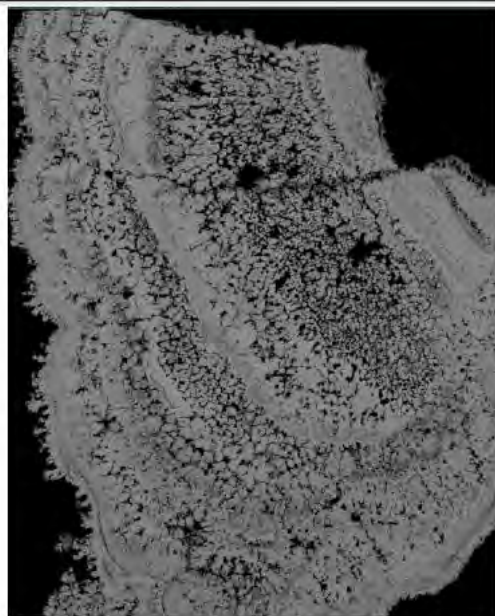


Figure 22: Backscattered electron image of Nodule B21B-2.

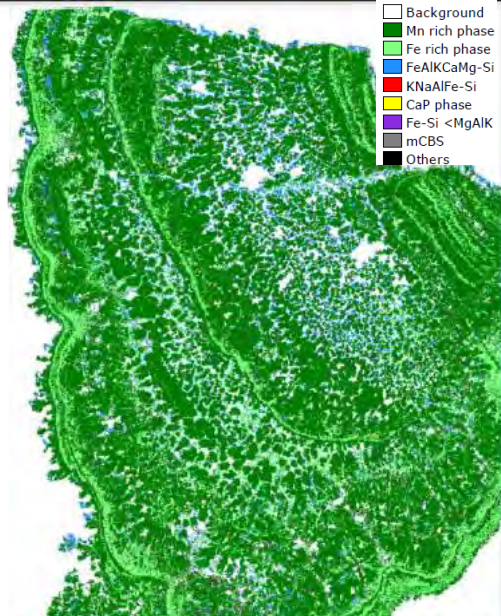


Figure 23: Mineral map of Nodule B21B-2.

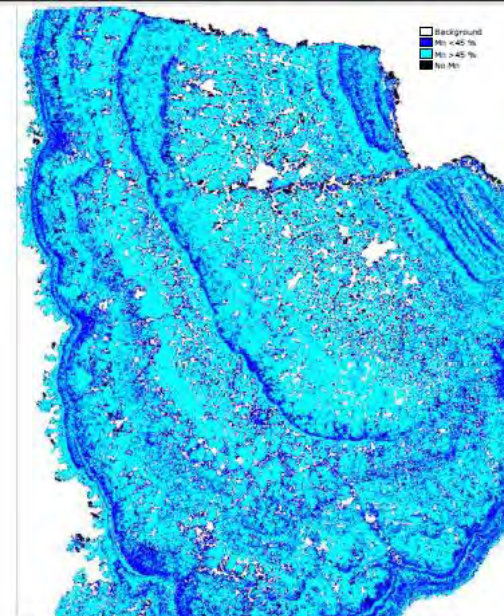


Figure 24: Mn plot of Nodule B21B-2.

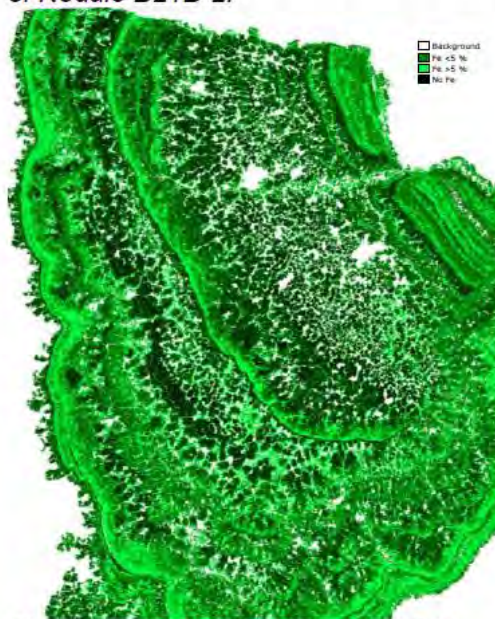


Figure 25: Fe plot of Nodule B21B-2.



Figure 26: Ni plot of Nodule B21B-2.

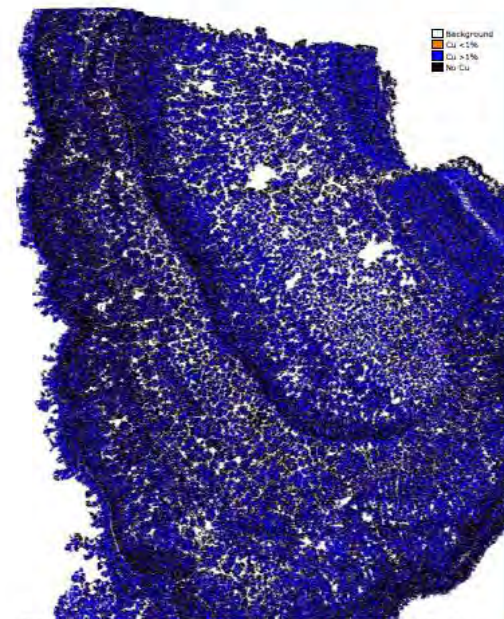


Figure 27: Cu plot of Nodule B21B-2.

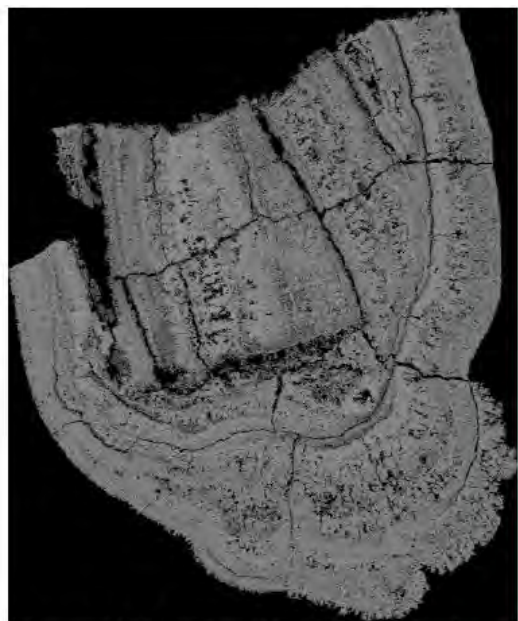


Figure 28: Backscattered electron image of Nodule B33-1.



Figure 29: Mineral map of Nodule B33-1.

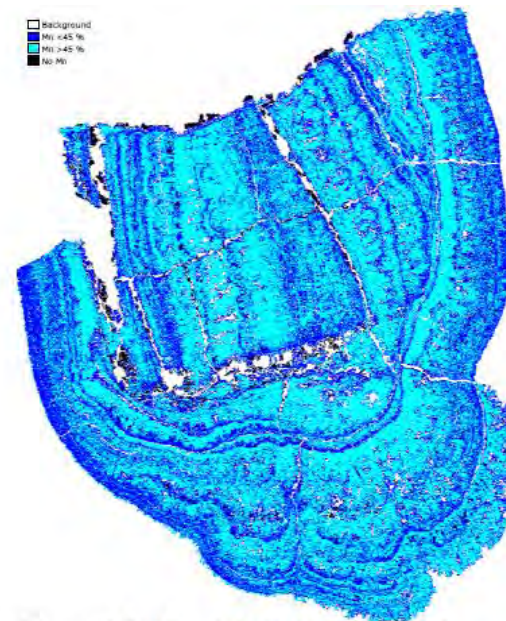


Figure 30: Mn plot of Nodule B33-1.



Figure 31: Fe plot of Nodule B33-1



Figure 32: Ni plot of Nodule B33-1.

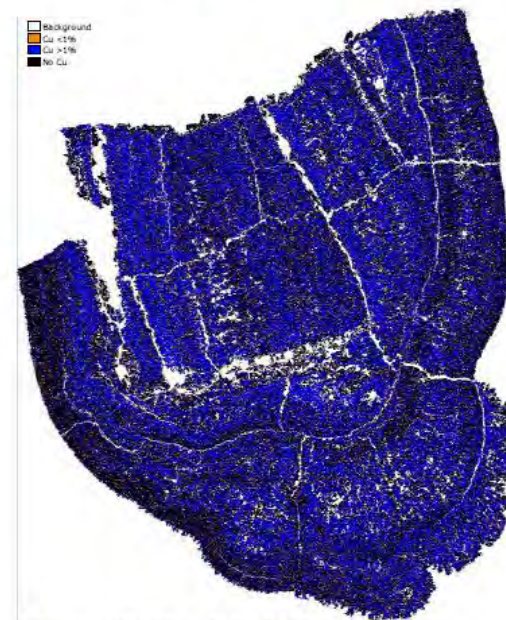


Figure 33: Cu plot of Nodule B33-1.

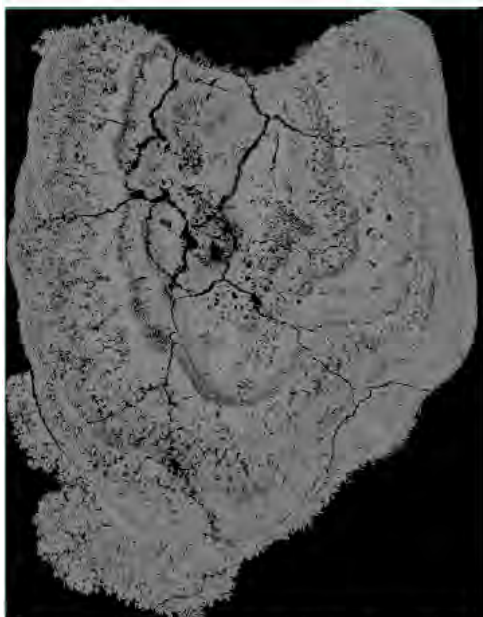


Figure 34: Backscattered electron image of Nodule B33-2.

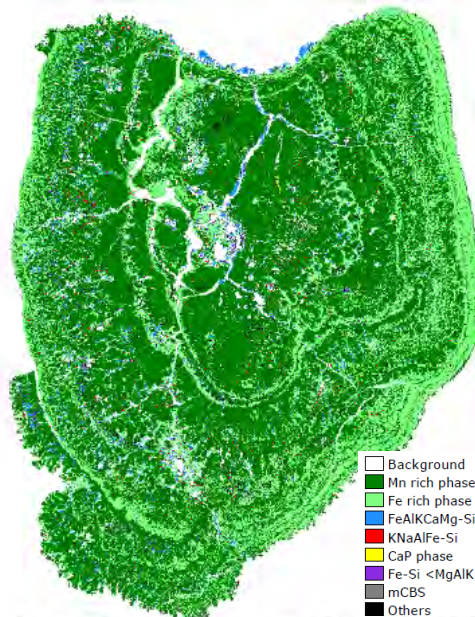


Figure 35: Mineral map of Nodule B33-2.

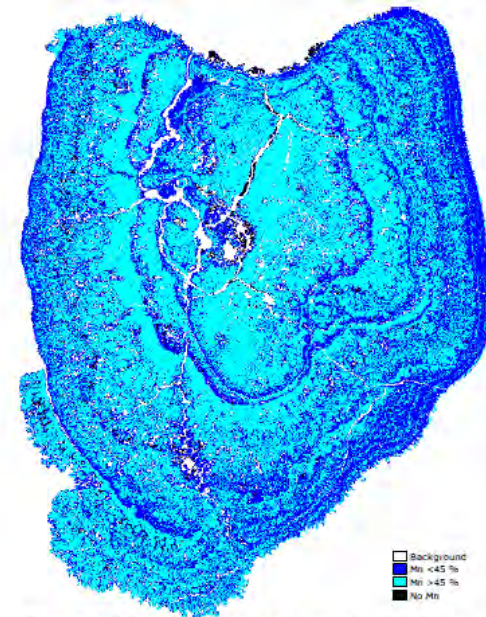


Figure 36: Mn plot of Nodule B33-2.

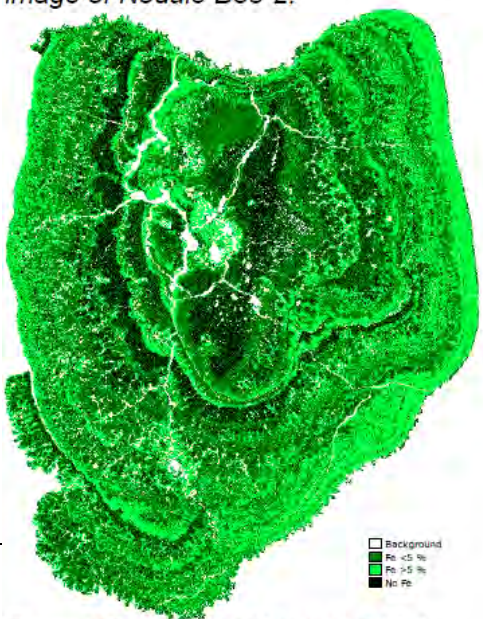


Figure 37: Fe plot of Nodule B33-2.



Figure 38: Ni plot of Nodule B33-2.

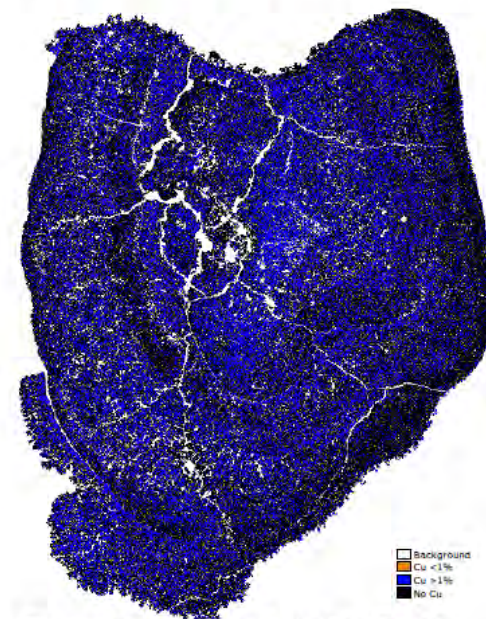


Figure 39: Cu plot of Nodule B33-2.



Figure 40: Backscattered electron image of Nodule B45-1.

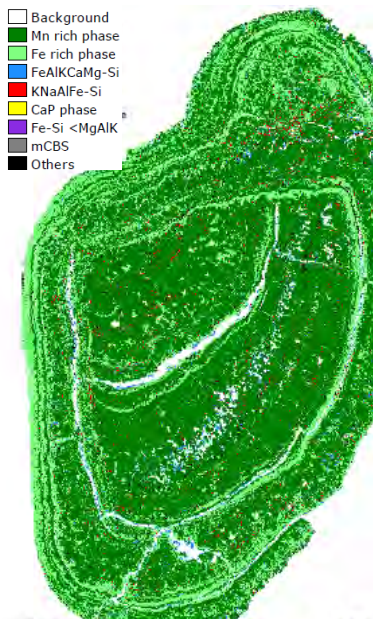


Figure 41: Mineral map of Nodule B45-1.

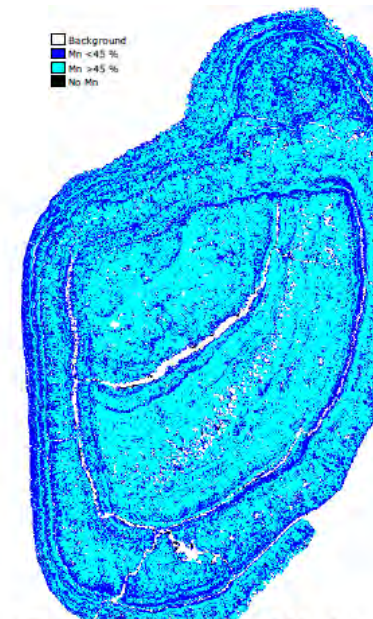


Figure 42: Mn plot of Nodule B45-1.

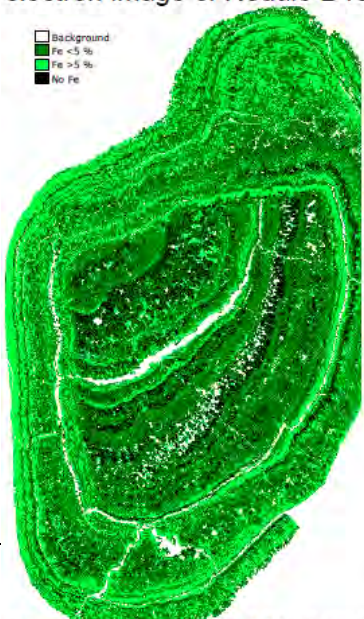


Figure 43: Fe plot of Nodule B45-1.

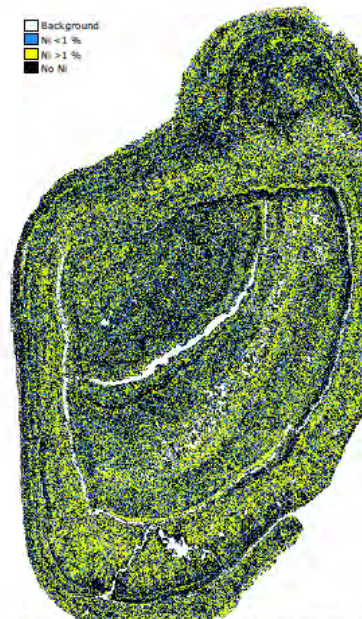


Figure 44: Ni plot of Nodule B45-1.

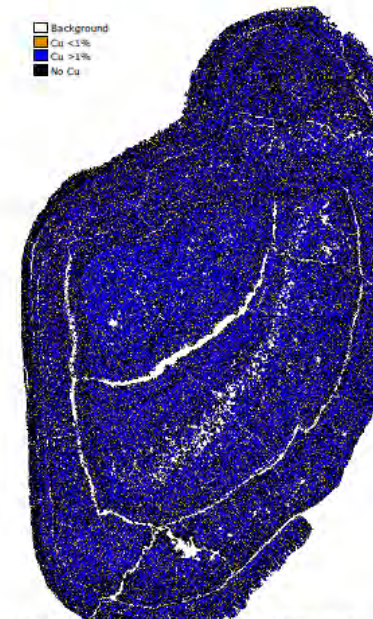


Figure 45: Cu plot of Nodule B45-1.



Figure 46: Backscattered electron image of Nodule B45-2.

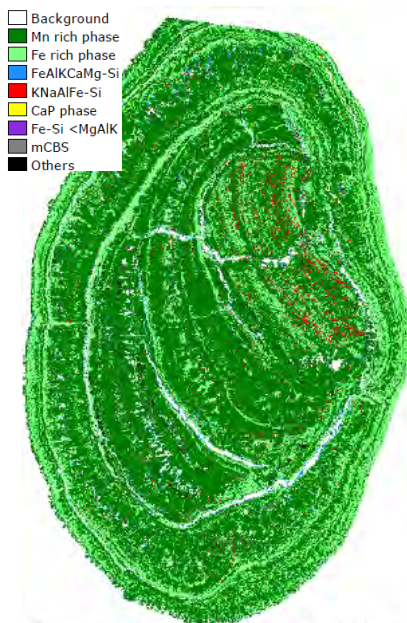


Figure 47: Mineral map of Nodule B45-2.

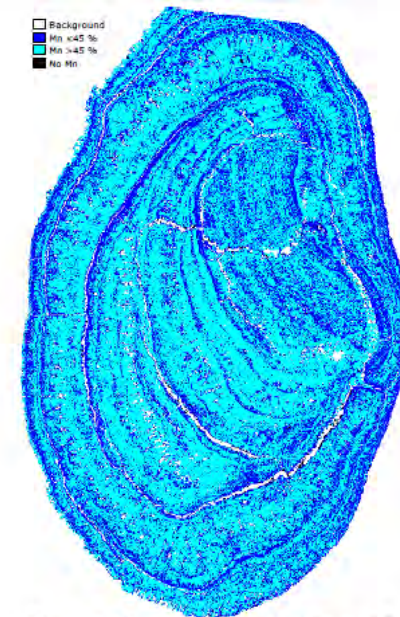


Figure 48: Mn plot of Nodule B45-2.



Figure 49: Fe plot of Nodule B45-2.

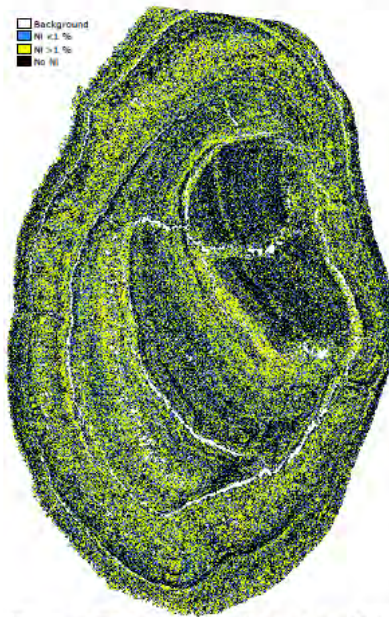


Figure 50: Ni plot of Nodule B45-2.

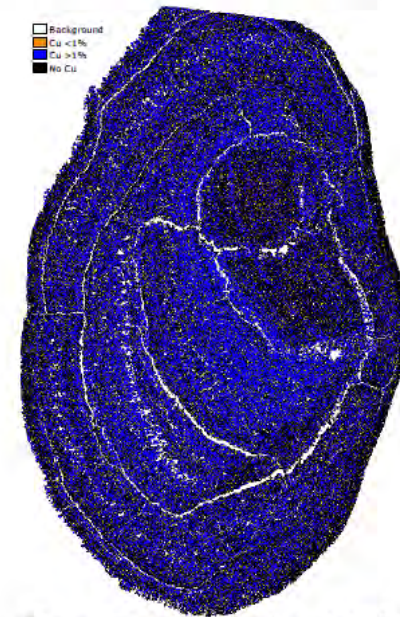


Figure 51: Cu plot of Nodule B45-2.

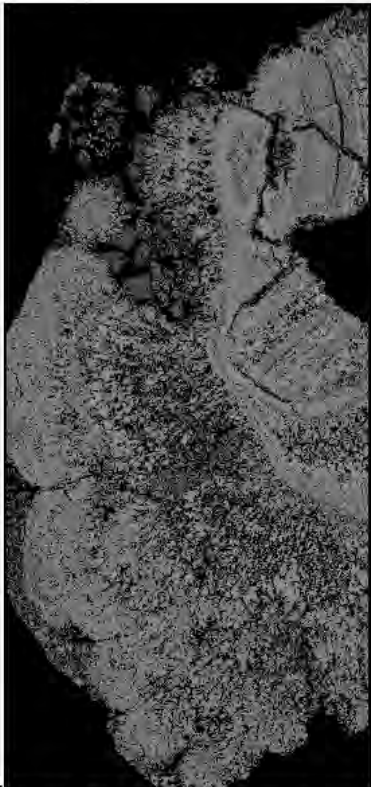


Figure 52: Backscattered electron image of Nodule B51.

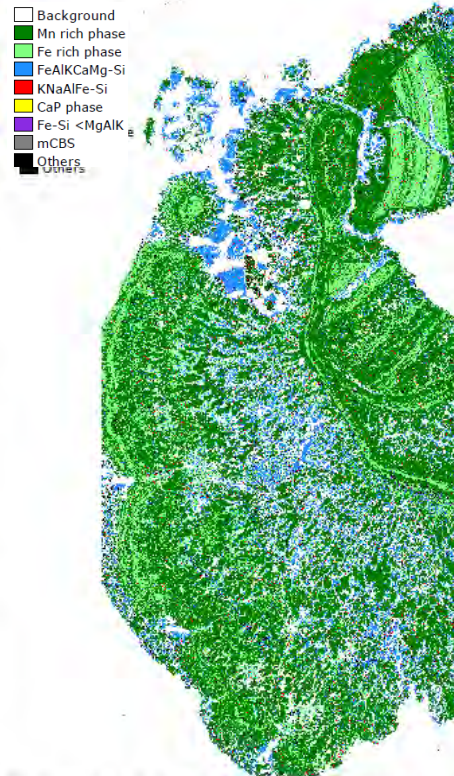


Figure 53: Mineral map of Nodule B51.

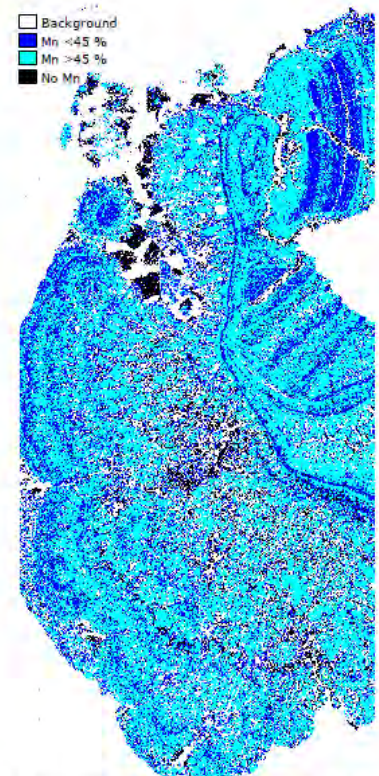


Figure 54: Mn plot of Nodule B51.

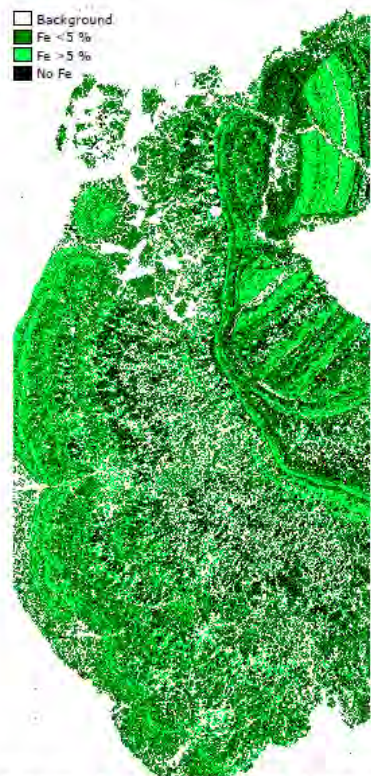


Figure 55: Fe plot of Nodule B51.

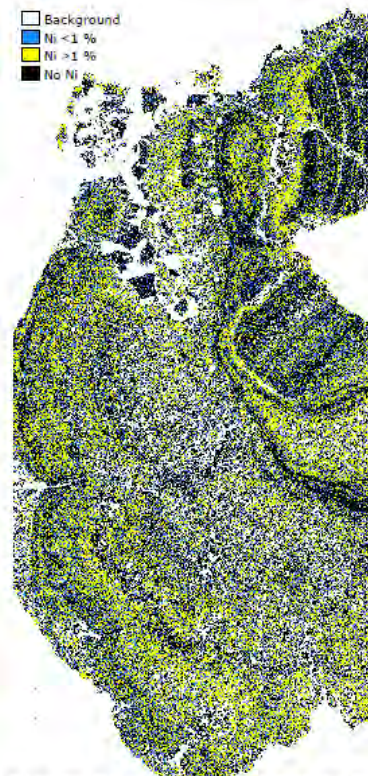


Figure 56: Ni plot of Nodule B51.

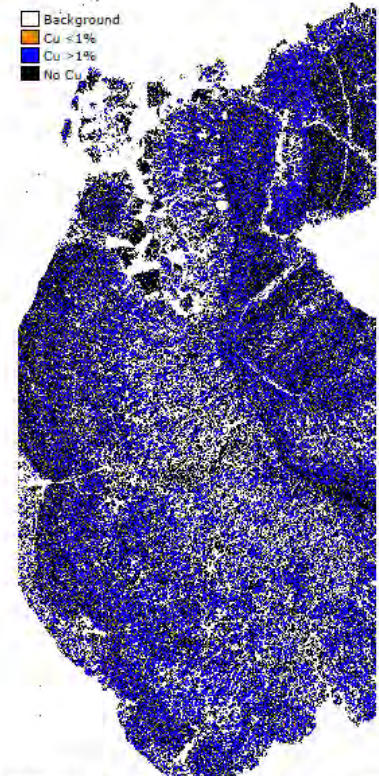


Figure 57: Cu plot of Nodule B51.

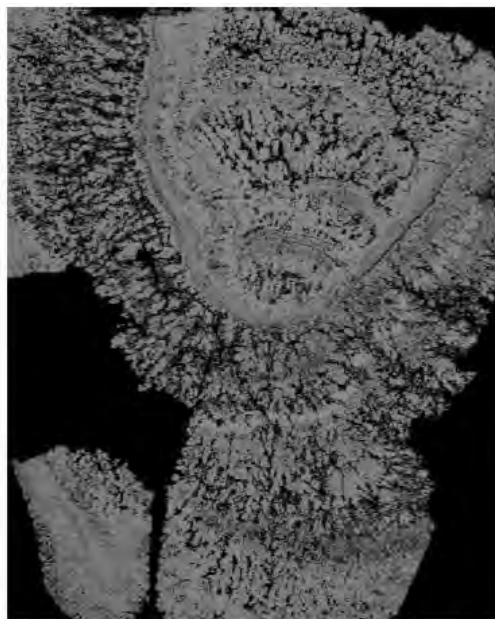


Figure 58: Backscattered electron image of Nodule B77.

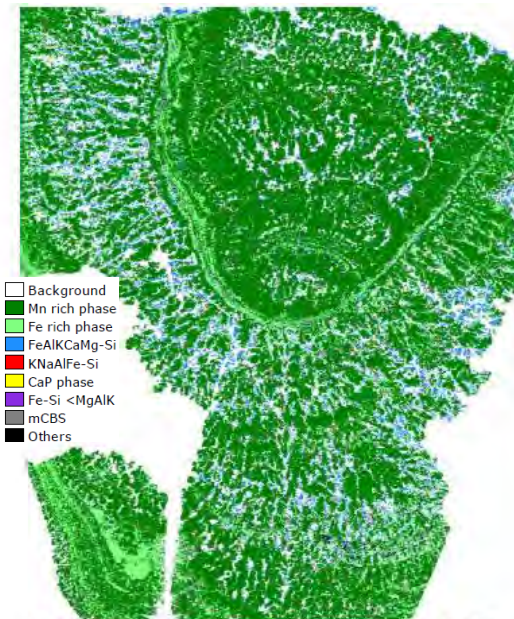


Figure 59: Mineral map of Nodule B77.

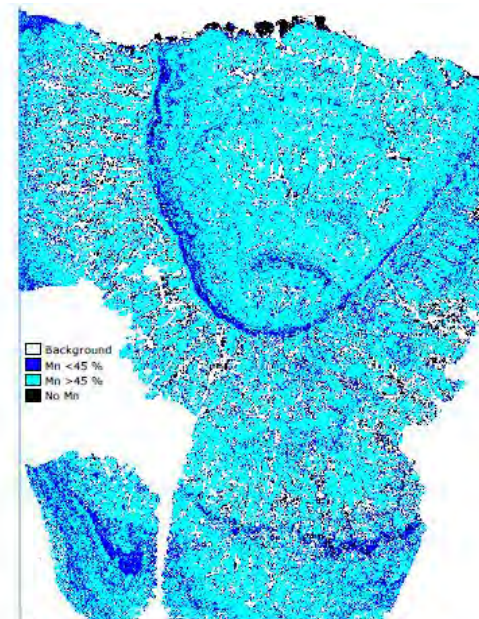


Figure 60: Mn plot of Nodule B77.

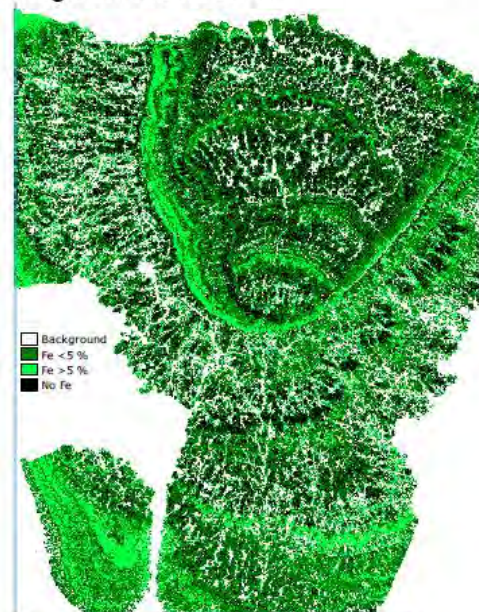


Figure 61: Fe plot of Nodule B77.

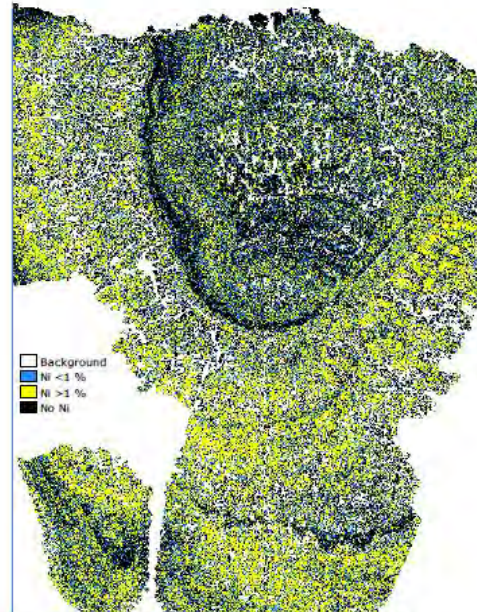


Figure 62: Ni plot of Nodule B77.

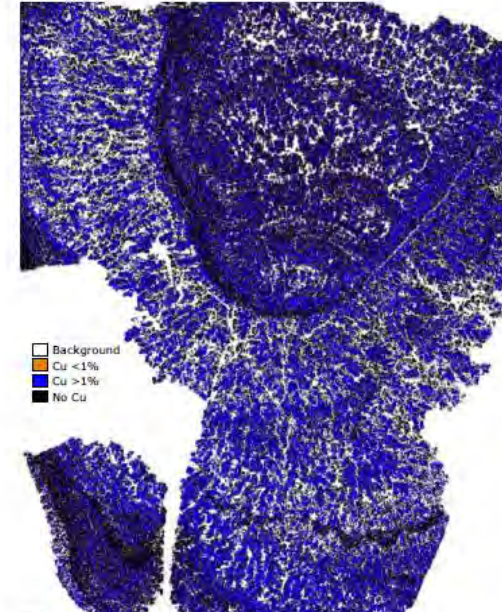


Figure 63: Cu plot of Nodule B77.

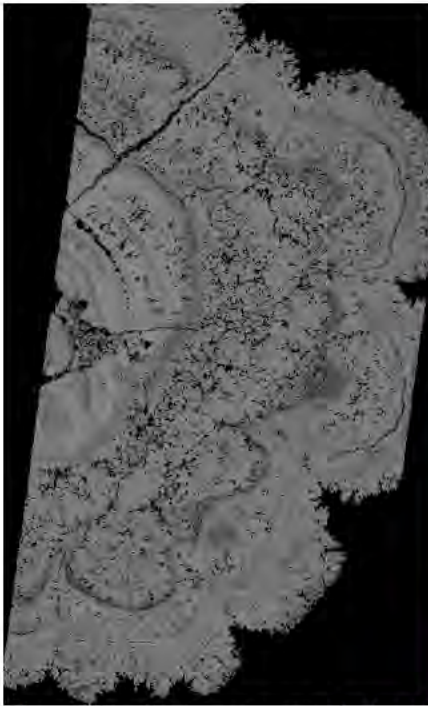


Figure 64: Backscattered electron image of Nodule B86E-1.



Figure 65: Mineral map of Nodule B86E-1.

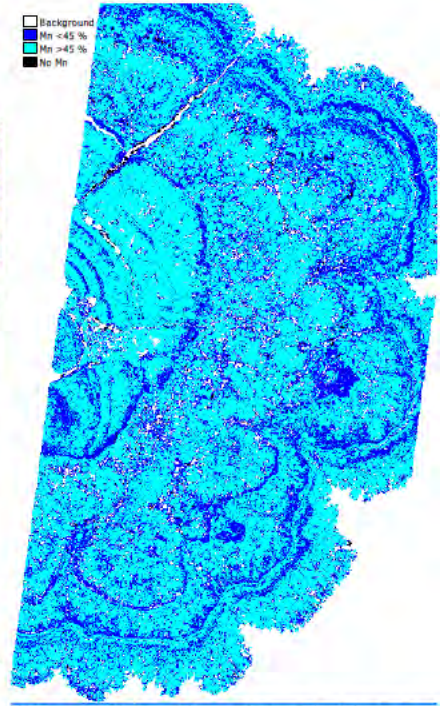


Figure 66: Mn plot of Nodule B86E-1.

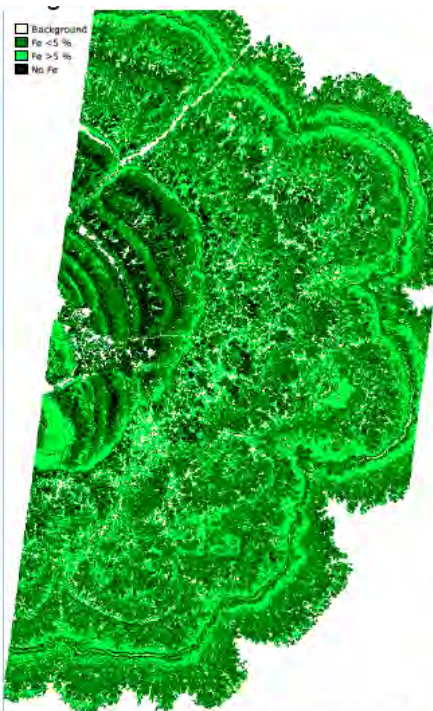


Figure 67: Fe plot of Nodule B86E-1.

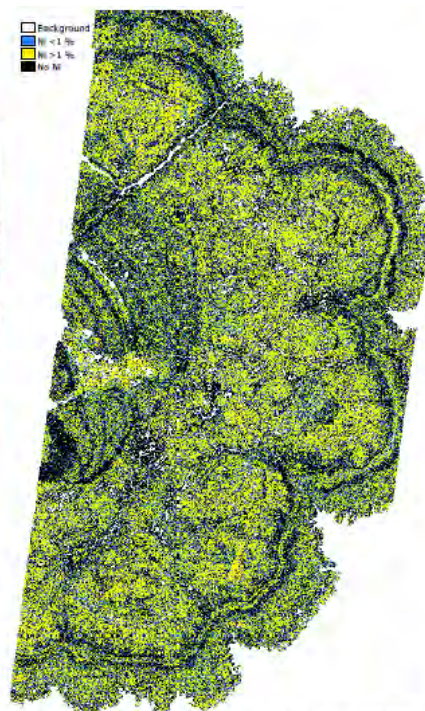


Figure 68: Ni plot of Nodule B86E-1.

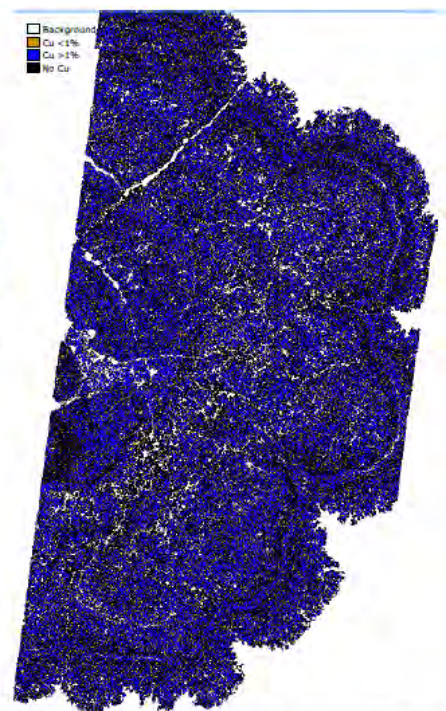


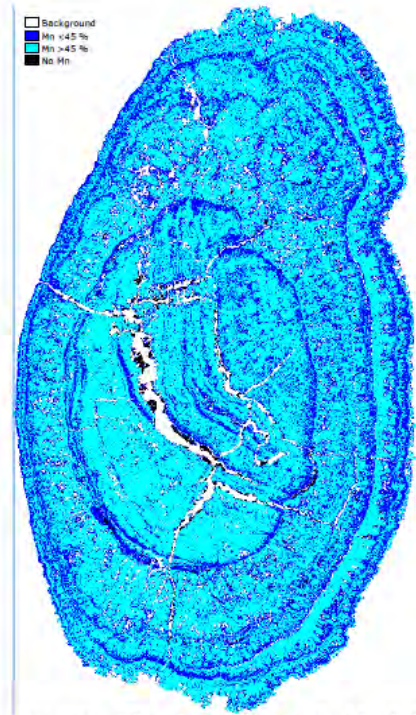
Figure 69: Cu plot of Nodule B86E-1.



□ Background
 ■ Mn rich phase
 ■ Fe rich phase
 ■ FeAlKCaMg-Si
 ■ KNaAlFe-Si
 ■ CaP phase
 ■ Fe-Si <MgAlK
 ■ mCBS
 ■ Others

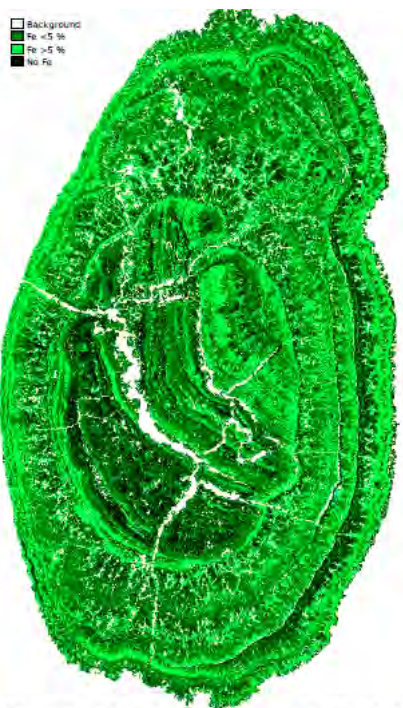


Figure 71: Mineral map of Nodule B86E-2.



□ Background
 ■ Mn <4.5 %
 ■ Mn >4.5 %
 ■ No Mn

Figure 72: Mn plot of Nodule B86E-2.



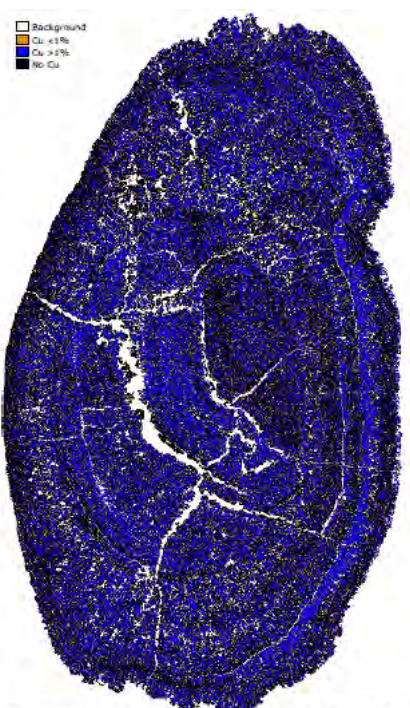
□ Background
 ■ Fe <5 %
 ■ Fe >5 %
 ■ No Fe

Figure 73: Fe plot of Nodule B86E-2.



□ Background
 ■ Ni <1 %
 ■ Ni >1 %
 ■ No Ni

Figure 74: Ni plot of Nodule B86E-2.



□ Background
 ■ Cu <1%
 ■ Cu >1%
 ■ No Cu

Figure 75: Cu plot of Nodule B86E-2.

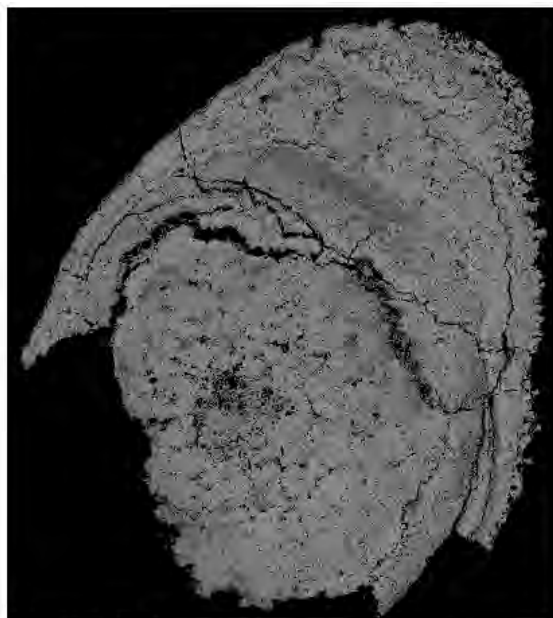


Figure 76: Backscattered electron image of Nodule B104-1.

- Background
- Mn rich phase
- Fe rich phase
- FeAlKCaMg-Si
- KNaAlFe-Si
- CaP phase
- Fe-Si <MgAlK ne
- mCBS
- Others

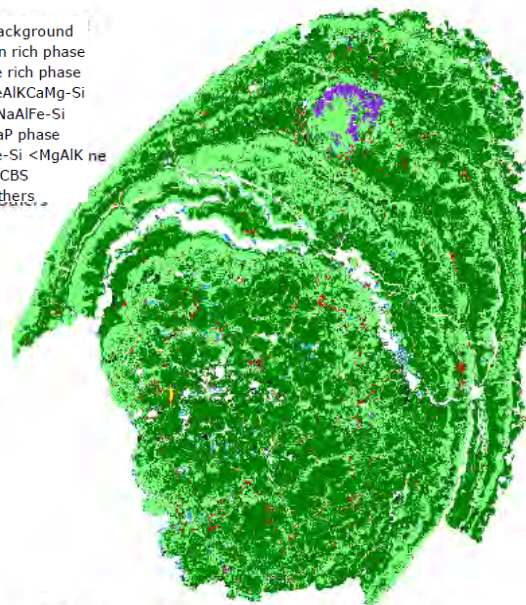


Figure 77: Mineral map of Nodule B104-1.

- Background
- Mn <45 %
- Mn >45 %
- No Mn

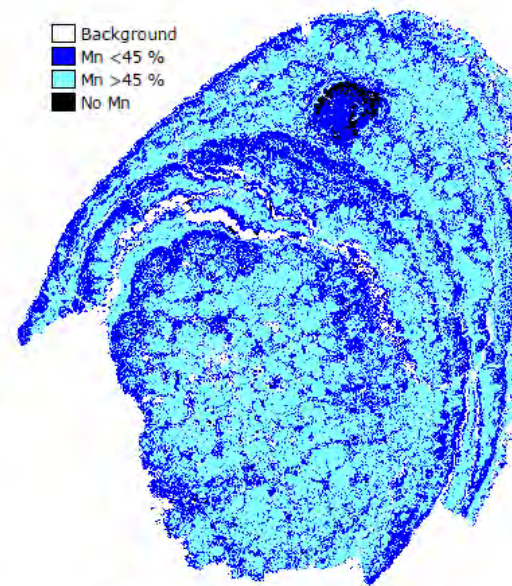


Figure 78: Mn plot of Nodule B104-1

- Background
- Fe <5 %
- Fe >5 %
- No Fe

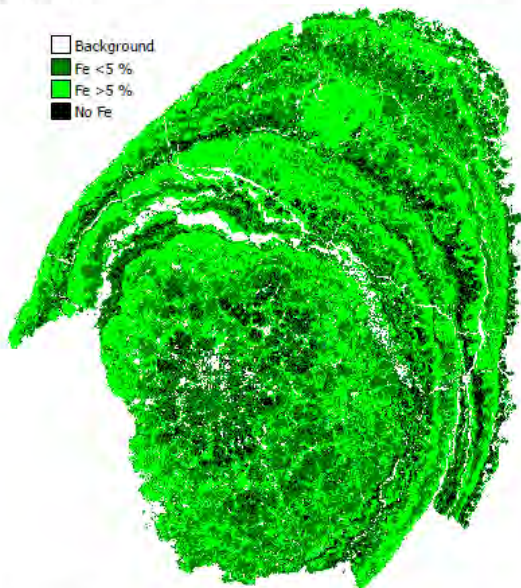


Figure 79: Fe plot of Nodule B104-1.

- Background
- Ni <1 %
- Ni >1 %
- No Ni

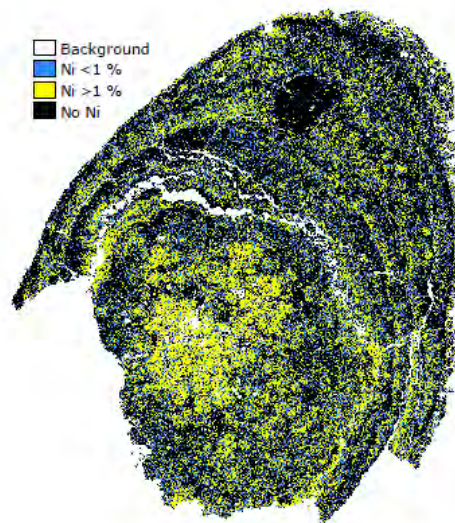


Figure 80: Ni plot of Nodule B104-1.

- Background
- Cu <1%
- Cu >1%
- No Cu

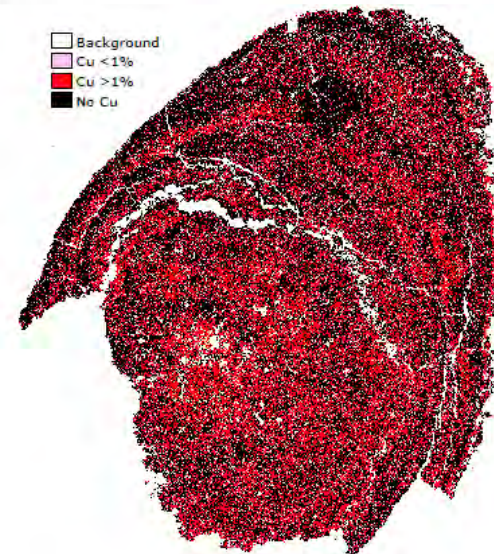


Figure 81: Cu plot of Nodule B104-1.

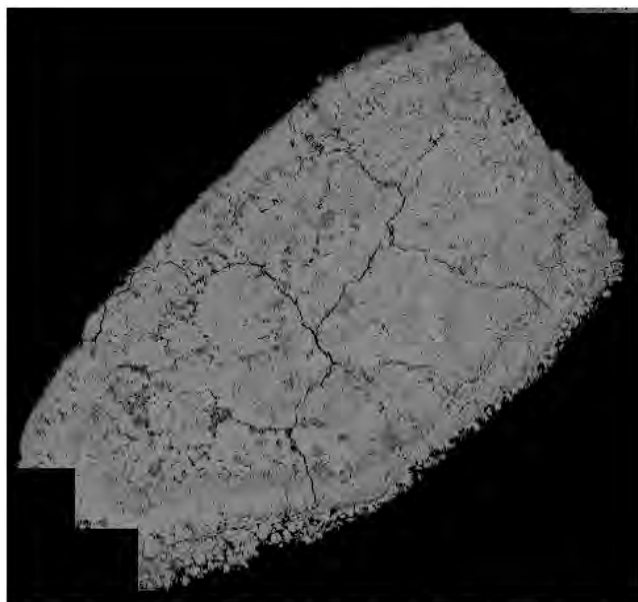


Figure 82: Backscattered electron image of Nodule B104-2.

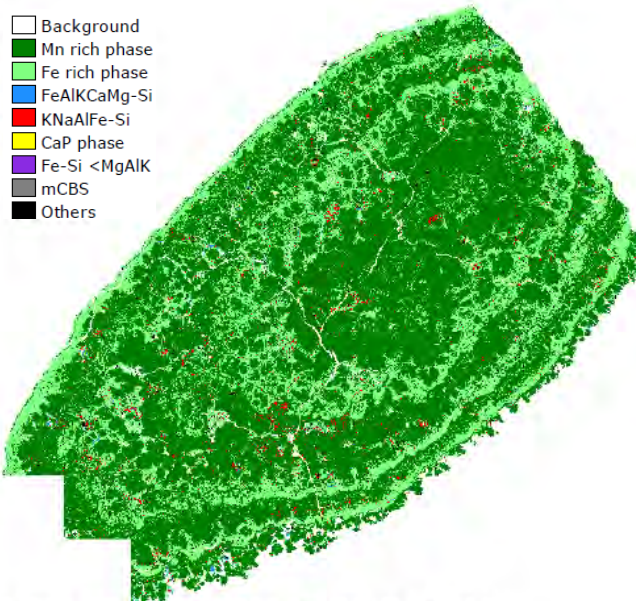


Figure 83: Mineral map of Nodule B104-2.

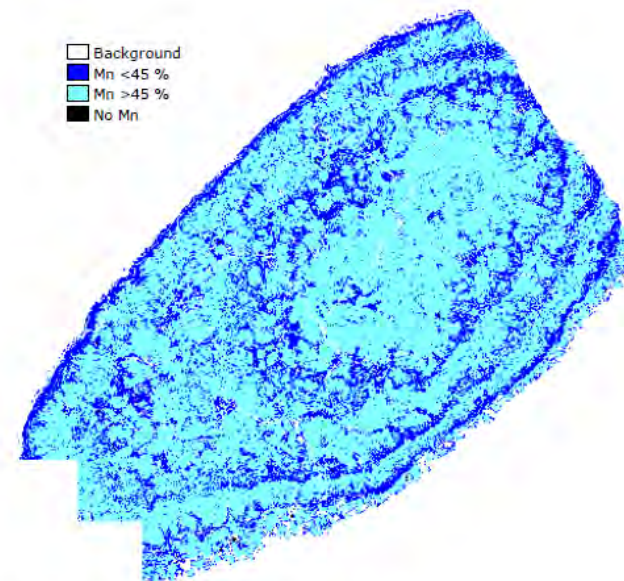


Figure 84: Mn plot of Nodule B104-2.

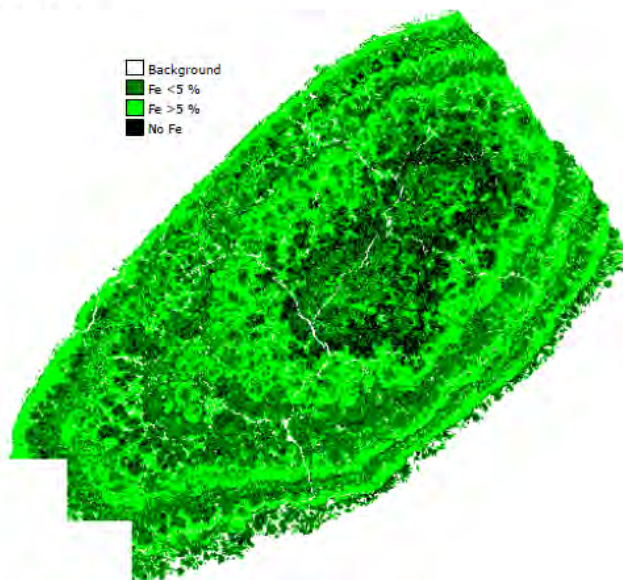


Figure 85: Fe plot of Nodule B104-2.

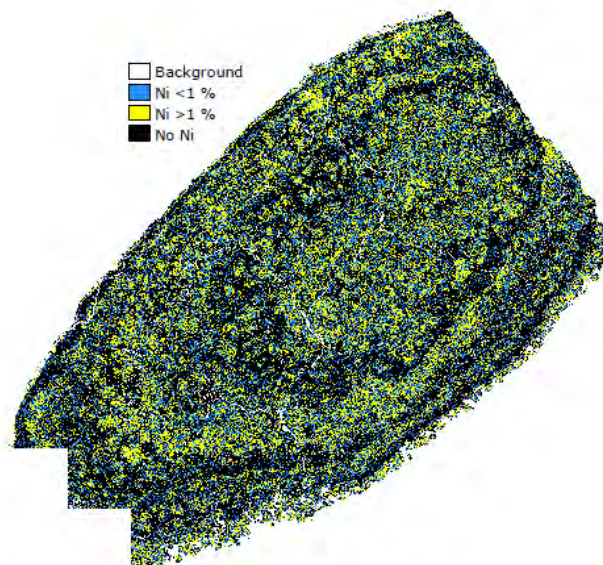


Figure 86: Ni plot of Nodule B104-2.

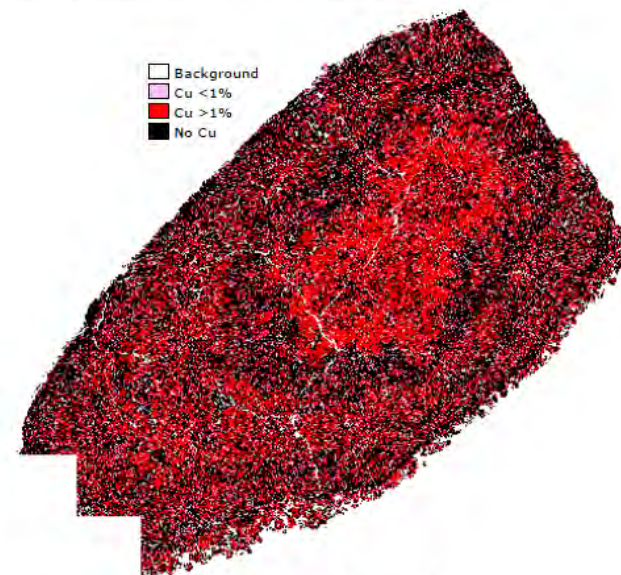


Figure 87: Cu plot of Nodule B104-2.



Figure 88: Backscattered electron image of Nodule B104-3.

- Background
- Mn rich phase
- Fe rich phase
- FeAlKCaMg-Si
- KNaAlFe-Si
- CaP phase
- Fe-Si <MgAlK
- mCBS
- Others

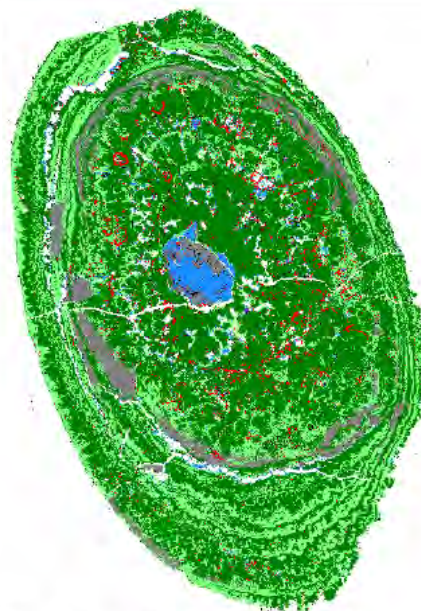


Figure 89: Mineral map of Nodule B104-3.

- Background
- Mn <45 %
- Mn >45 %
- No Mn

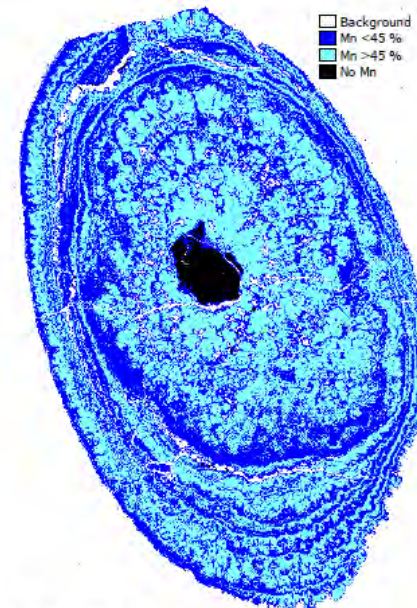


Figure 90: Mn plot of Nodule B104-3

- Background
- Fe <5 %
- Fe >5 %
- No Fe

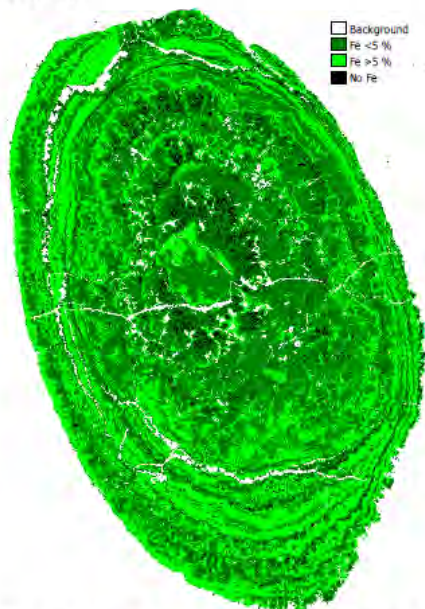


Figure 91: Fe plot of Nodule B104-3.

- Background
- Ni <1 %
- Ni >1 %
- No Ni

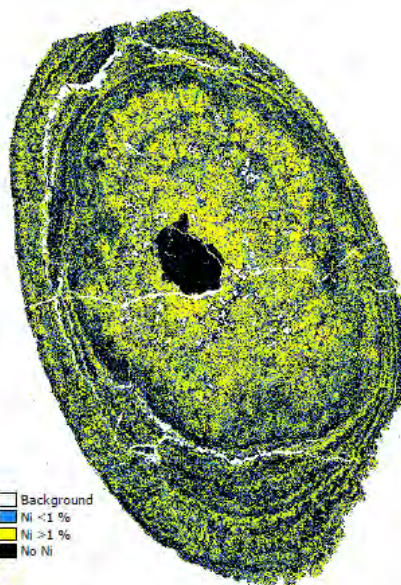


Figure 92: Ni plot of Nodule B104-3.

- Background
- Cu <1%
- Cu >1%
- No Cu



Figure 93: Cu plot of Nodule B104-3.

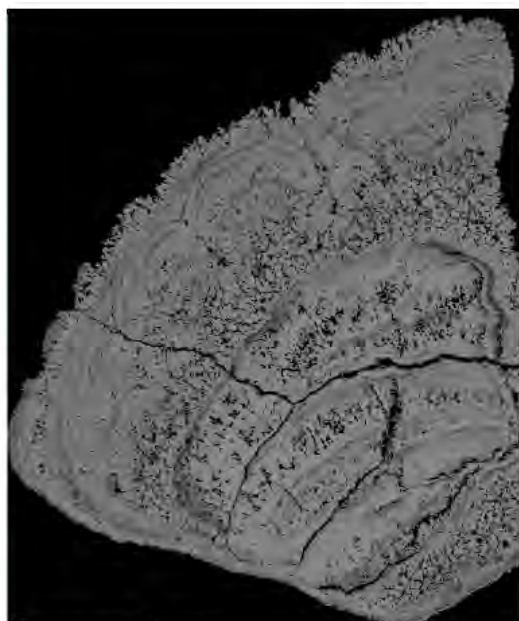


Figure 94: Backscattered electron image of Nodule B111-1.

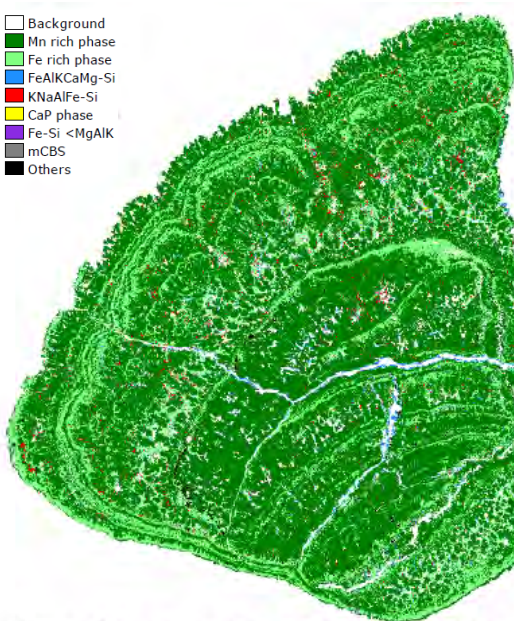


Figure 95: Mineral map of Nodule B111-1.

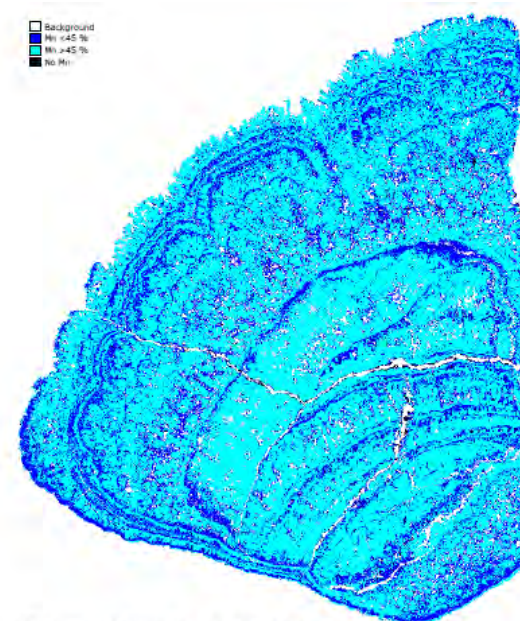


Figure 96: Mn plot of Nodule B111-1.

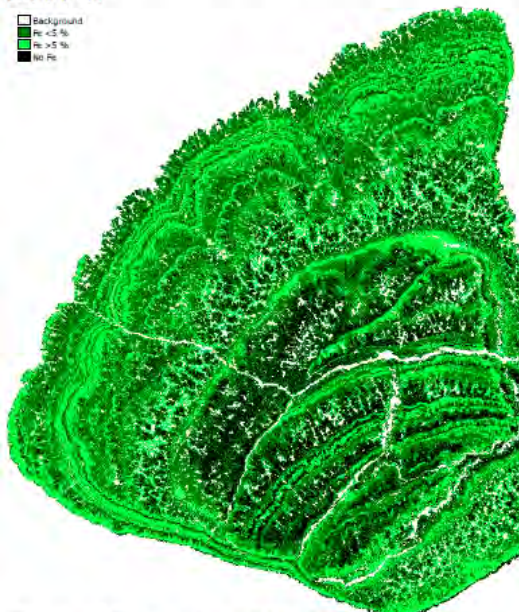


Figure 97: Fe plot of Nodule B111-1.

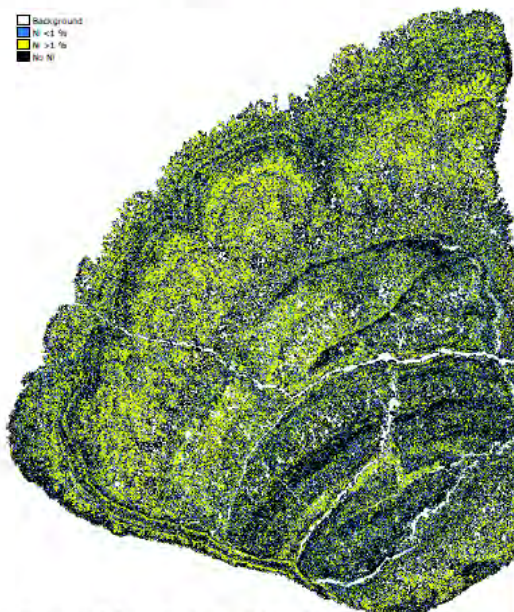


Figure 98: Ni plot of Nodule B111-1.

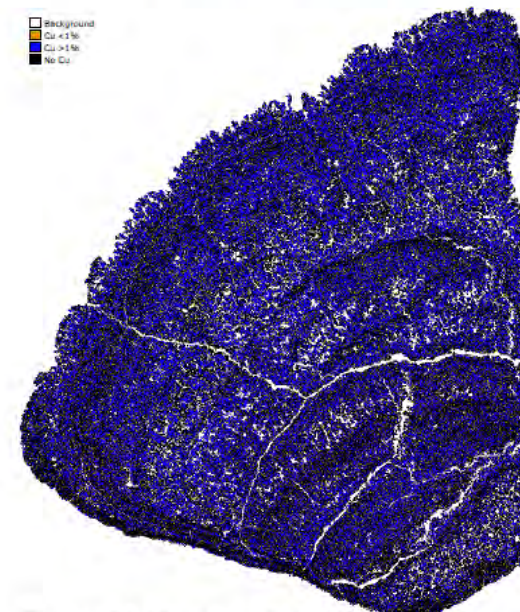


Figure 99: Cu plot of Nodule B111-1.

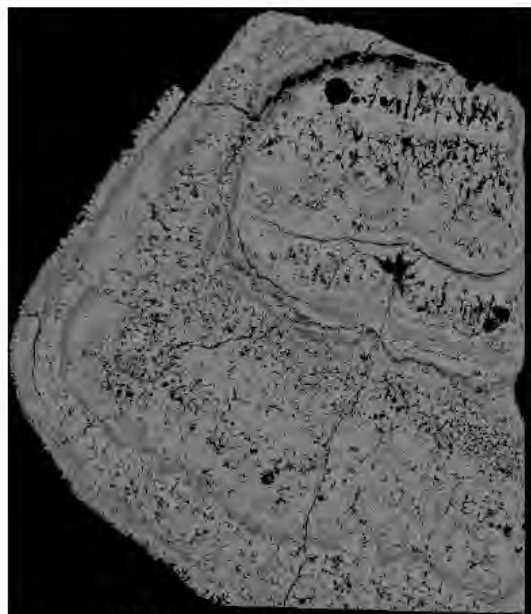


Figure 100: Backscattered electron image of Nodule B111-2.

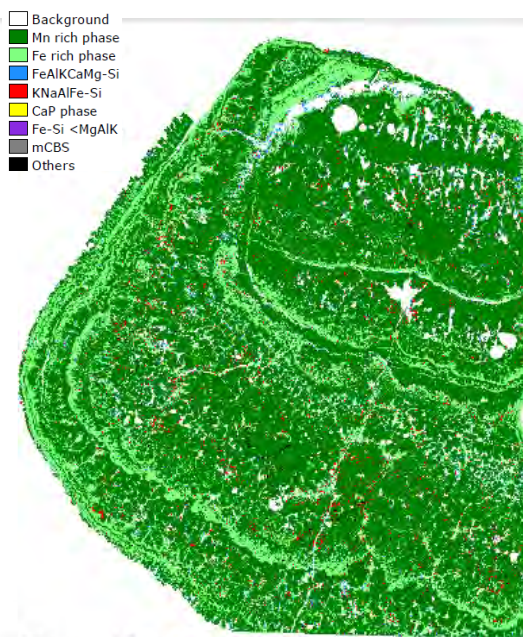


Figure 101: Mineral map of Nodule B111-2.

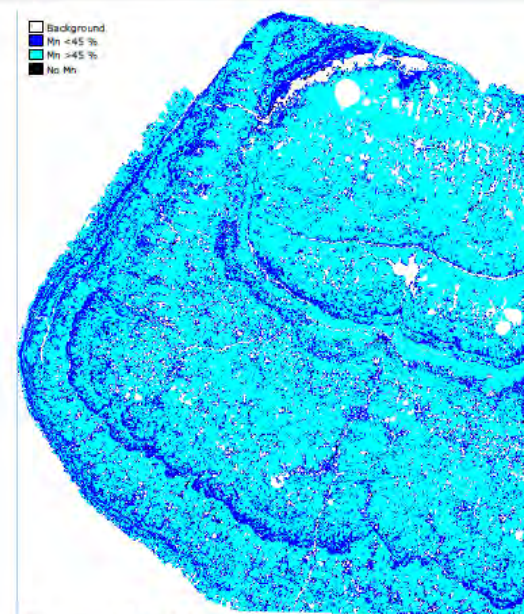


Figure 102: Mn plot of Nodule B111-2.

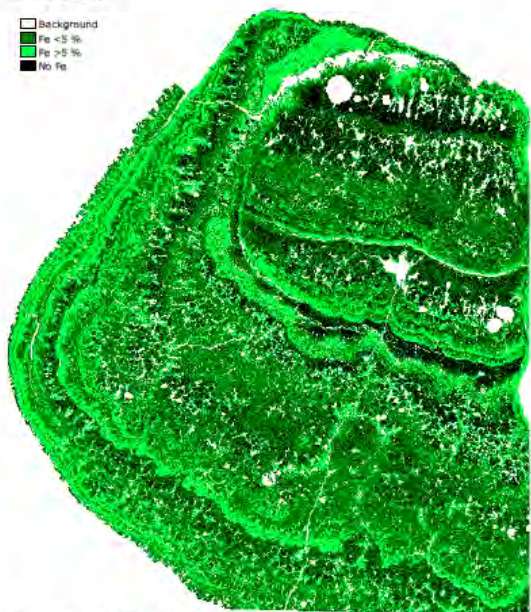


Figure 103: Fe plot of Nodule B111-2.

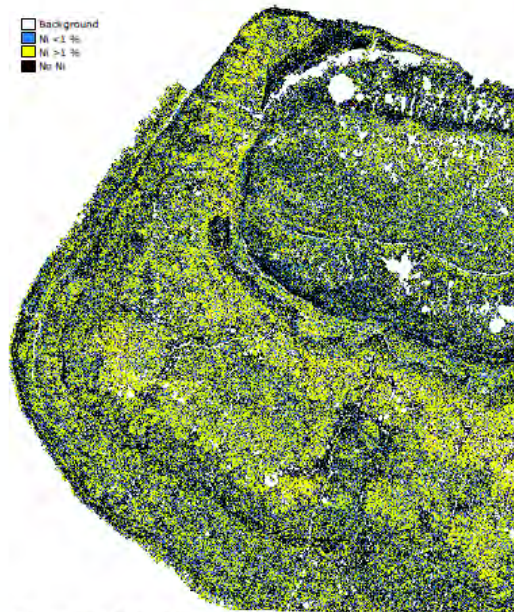


Figure 104: Ni plot of Nodule B111-2.

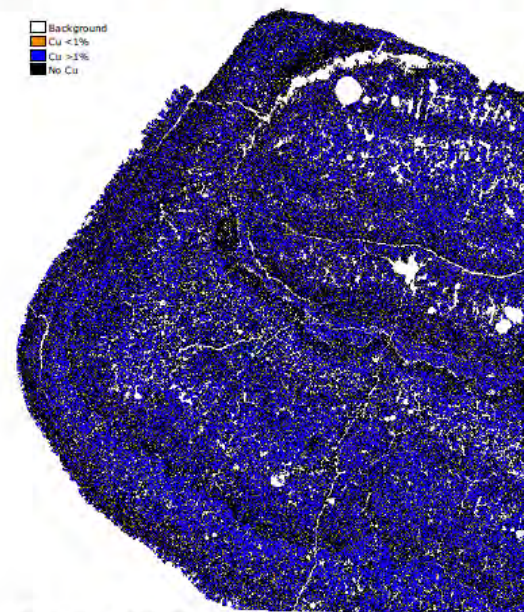


Figure 105: Cu plot of Nodule B111-2.

9.18 Appendix 4D: Box-core and dredge major element chemical analysis

https://www.researchgate.net/publication/350741114_0918_Appendix_4D_MajorElementChemistry?ev=project

9.19 Appendix 4E: Density measurements and calculations

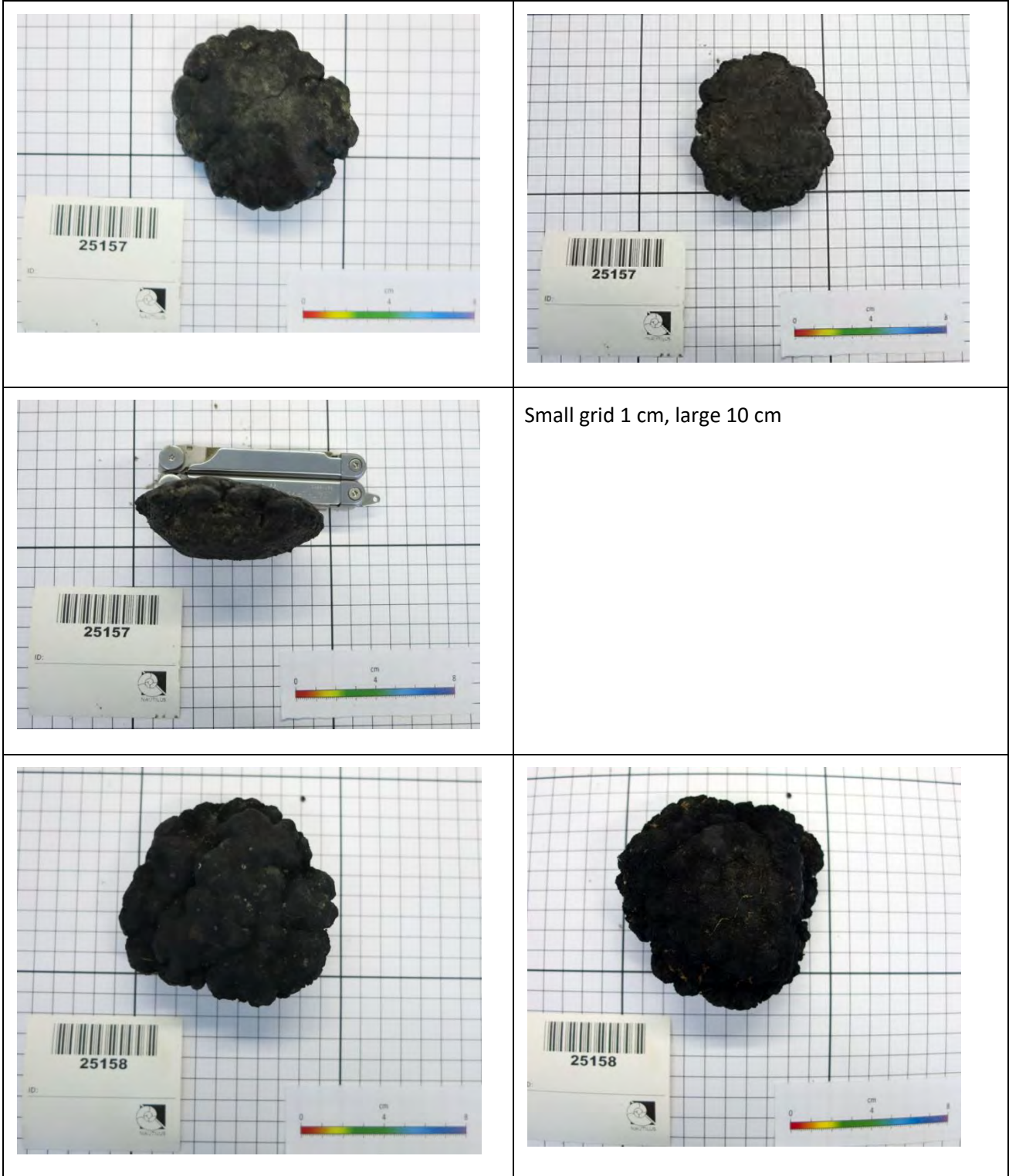
https://www.researchgate.net/publication/350741126_0919_Appendix_4E_Density_Measurements_Calculations?ev=project

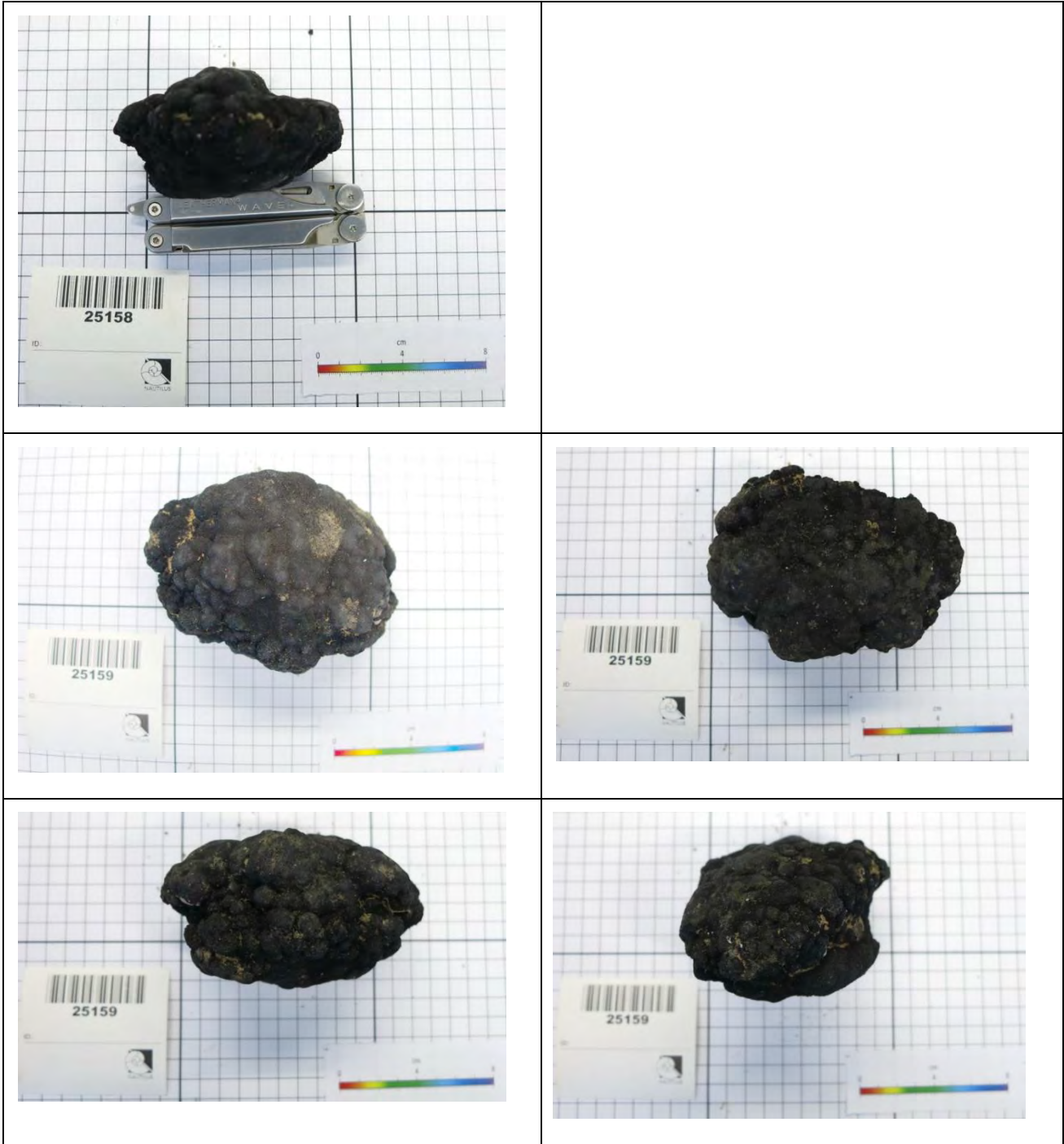
9.20 Appendix 4F: Sample moisture test results and calculations

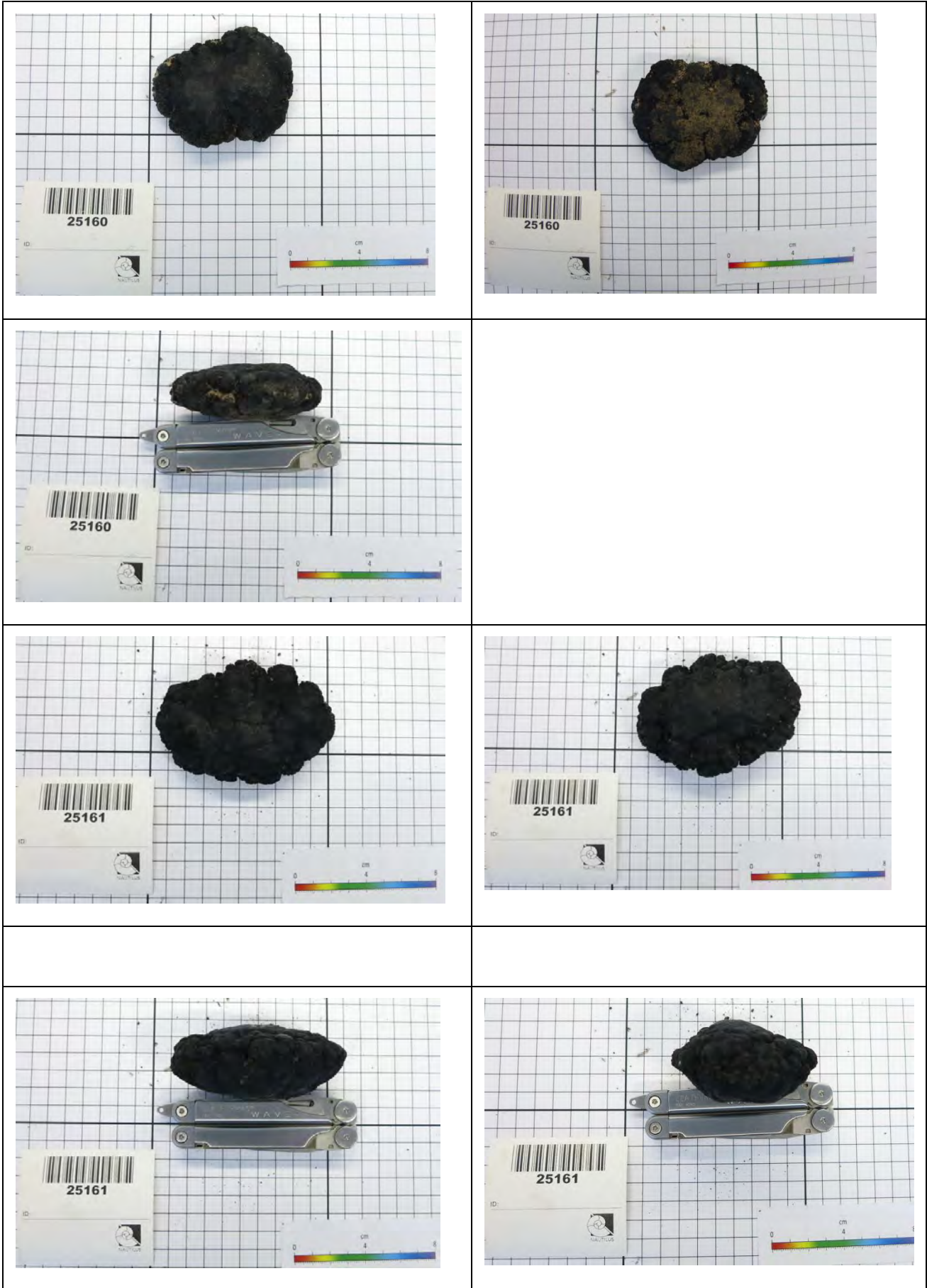
https://www.researchgate.net/publication/350740913_0920_Appendix_4F_SampleMoistureResults?ev=project

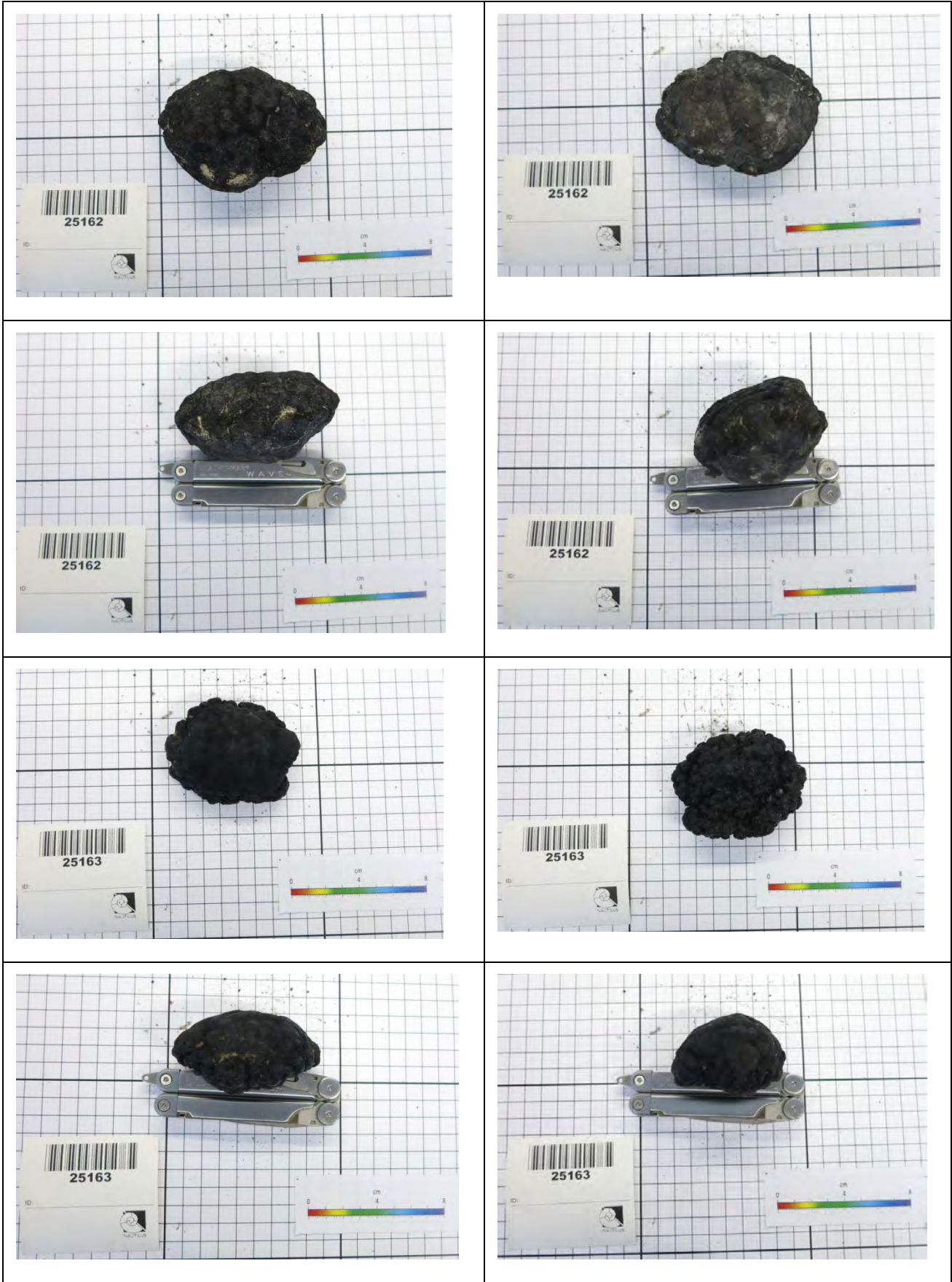
9.21 Appendix 4G: Photos of moisture determination samples

9.21.1 Batch 1









9.21.2 Batch 2



9.21.3 Batch 3





9.21.4 Longterm drying samples



CCZ15-D01 (28573)



CCZ15-D03 (28572)



CCZ17 D01 (26521)



CCZ17-D02/03 (26522)

9.22 Appendix 4H: Attrition fines test work results

https://www.researchgate.net/publication/350741136_0922_Appendix_4H_Attrition_Fines_Test_Work?ev=project

9.23 Appendix 6A: Other Publications

This appendix contains 11 publications as discussed in Chapter 6: Towards modifying factors

Publication	Title	Page numbers within this appendix)
(Yu and Parianos, 2021)	Empirical Application of Generalized Rayleigh Distribution for Mineral Resource Estimation of Seabed Polymetallic Nodules (in preparation, submitted to Minerals)	466 - 493
(Simon-Lledó et al., 2020)	Multi-scale variations in invertebrate and fish megafauna in the mid-eastern Clarion Clipperton Zone	494 - 508
(Simon-Lledó et al., 2019b)	Preliminary Observations of the Abyssal Megafauna of Kiribati	509 - 521
(Parianos et al., 2014a)	Decoupled seafloor mining system	522 - 529
(Parianos et al., 2014b)	A seafloor nodule concentrating system and method	530 - 541
(Berndt et al., 2014)	Seafloor haulage system	542 - 553
(Manocchio et al., 2020)	Polymetallic Nodule Concentrator: Lateral Conveyor – A Full-Scale Test (Appendices to this report not included)	554 - 583
(Yu et al., 2020)	Nautilus Nodule Concentrator: Lateral Conveyor - Numerical Simulation	584 - 608
(Xiao et al., 2019)	Model Test of Skip Lifting System for Deep-sea Mining	609 - 614
(Su et al., 2020b)	Thermodynamic and Experimental Study on Efficient Extraction of Valuable Metals from Polymetallic Nodules	615 - 628
(Su et al., 2021)	Alternative Resources for Producing Nickel Matte - Laterite Ores and Polymetallic Nodules (in preparation, submitted to Mineral Processing and Extractive Metallurgy Review)	629 - 642

Article

Empirical Application of Generalized Rayleigh Distribution for Mineral Resource Estimation of Seabed Polymetallic Nodules

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Abstract: An efficient empirical statistical method is developed to improve the process of mineral resource estimation of seabed polymetallic nodules and is applied to analyze the abundance of seabed polymetallic nodules in the Clarion Clipperton Zone (CCZ). The newly proposed method is based on three hypotheses as the foundation for a model of “idealized nodules”, which was validated by analyzing nodule samples collected from the seabed within the Tonga Offshore Mining Limited (TOML) exploration contract. Once validated, the “idealized nodule” model was used to deduce a set of empirical formulae for predicting the nodule resources, in terms of percentage coverage and abundance. The formulae were then applied to analyzing a total of 188 sets of nodule samples collected across the TOML areas, comprising box-core samples and towed camera images as well as other detailed box-core sample measurements from the literature. Numerical results for nodule abundance and coverage predictions were compared with field measurements, and unbiased agreement has been reached. The new method has the potential to achieve more accurate mineral resource estimation with reduced sample numbers and sizes. They may also have application in improving the efficiency of design and configuration of mining equipment.



Citation: Yu, G.; Parianos, J. Empirical Application of Generalized Rayleigh Distribution for Mineral Resource Estimation of Seabed Polymetallic Nodules. *Minerals* **2021**, *11*, 449. <https://doi.org/10.3390/min11050449>

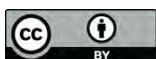
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Keywords: polymetallic nodules; mineral resource estimation; statistical analysis; Generalized Rayleigh Distribution; Clarion Clipperton Zone

1. Introduction

Polymetallic nodules are mineral particles found in many of the world's oceans [1]. A major deposit lies within the Clarion Clipperton Zone (CCZ) of the tropical North Pacific [2]. Nodules grow via precipitation in an organized manner in and on clay-ooze at the seabed [2] and they are often found with others of similar size and form [3–5]. Nodule “abundance” is the kilograms (usually wet) of nodules per square metre of seabed and is used to estimate tonnage of nodules in a mineral resource estimation (as the surrounding clay-ooze should be able to be disregarded at the first step of mining [4,6–10]). Interest in the deposit, from the perspectives of development, marine environment and regulation, has increased over the last 10 years [5,11].

The use of nodule long (or major) axis in predicting individual nodule weights has been long understood [12–15], even if application via seabed photographs is restricted to areas where the nodules are largely exposed in the host clay-ooze [4,16]. Ultimately, box-core samples are seen to be the most reliable source of abundance data [4], but their relatively high cost makes the use of seabed photographs appealing to workers trying to improve the confidence in abundance estimation [17]. Efforts to use percentage coverage to predict nodule abundance have so far not been effective [18,19].

The distribution of nodule long-axis lengths has been recognised to be often positively skewed (e.g., [4,15]), but such distributions are not known to have been used in the mineral resource estimation process.

In Section 2, three hypotheses are proposed as the basis for an idealized model of seabed polymetallic nodules. The hypotheses made for the “idealized nodule” model are

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In Section 2, three hypotheses are proposed as the basis for an idealized model of seabed polymetallic nodules. The hypotheses made for the “idealized nodule” model are based on analyses of nodule samples collected from the seabed at CCZ. One of the key hypotheses is based on numerical evidence that long axes of the seabed nodules follow the Generalized Rayleigh Distribution (GRD). Section 3 presents the mathematical characteristics of the GRD pertaining to the analysis of nodule samples. The traditional statistical methods for estimating the parameters of the sample distribution, and for performing the Goodness-of-fit test for GRD, are discussed. While they are found useful for analysing nodule samples, the traditional numerical procedure is too complex for practical applications.

In Section 4 based on the “idealized nodule” model discussed in Section 2, a simplified practical approach is developed to replace the complex numerical methods in Section 3. As a result, empirical relationships are derived to directly predict the parentage coverage and abundance of seabed nodules.

Section 5 shows the numerical results of testing the three hypotheses as the basis for “idealized nodule” model. Strong evidence is found that the three hypotheses are valid for the seabed nodule model. Section 6 shows the numerical results of testing the three hypotheses as the basis for “idealized nodule” model. Strong evidence is found, providing validation to the hypothesis of seabed nodules.

In Section 7, 188 samples of seabed polymetallic nodules from the CCZ are analysed using the empirical method developed in Section 4. The results of estimations in terms of percentage coverage and abundance are compared with the field measurements.

2. Three Hypotheses for an Idealized Model of Seabed Polymetallic Nodules

Polymetallic nodules from the CCZ are found in a wide range of forms [4], but within parts of the central and eastern CCZ covered by an exploration contract held by Tonga Offshore Mining Limited (TOML) they often form irregular slightly prolate spheroid-like forms ([4]; Figure 1). Growth around the horizontal axes (X and Y) is believed to be a function of horizontal space and mineral supply, and growth along the vertical axis is also a function of permissive layer of chemical conditions term the geochemically active layer [4]. Nodules have a very consistent density [4] and a relationship between the major horizontal axis and nodule weight (i.e., volume) has been long recognized [4,12,13].

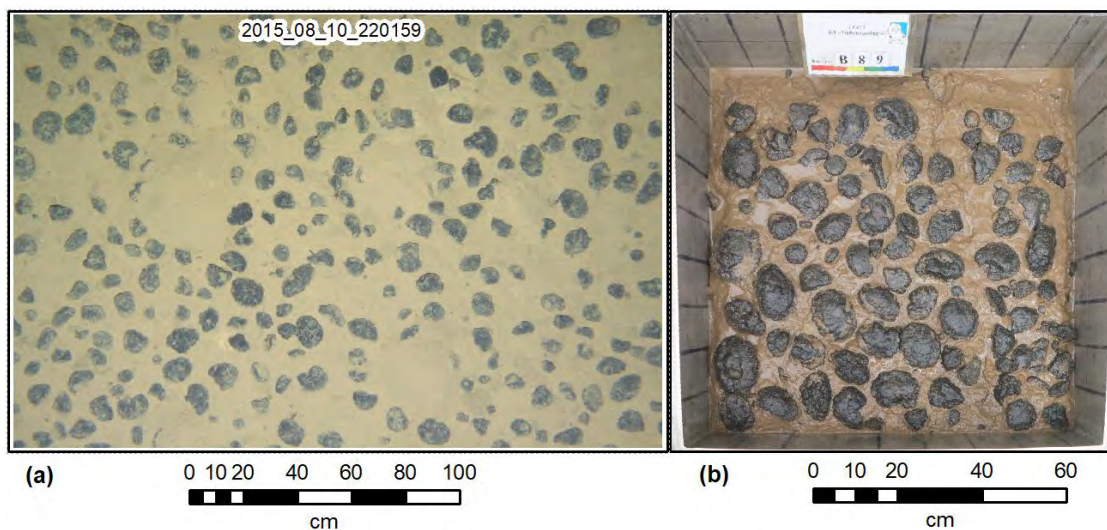


Figure 1. Example towed seabed photo (a) and box-core sample (b). Mounds of clay-ooze without nodules in the seabed photo are caused by bioturbation.

Based on the above observation, to allow mathematical modelling of seabed polymetallic nodules, the following three somewhat severe fundamental hypotheses are constructed:

1. Each nodules piece is of ellipsoidal shape (e.g., in Figure 2a,b), which is defined by its three axes X_i , Y_i and Z_i , where $i = 1, 2, 3 \dots N$, with N being the number of nodules. Here X_i is the long or major axis, which is usually in the horizontal plane while Y_i and Z_i are the two typically shorter minor axes in the horizontal and vertical planes.

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2. Within a certain boundary (domain) on the seabed, the ellipsoidal nodules are similar in shape, i.e., the ratio between two minor axes and the major axis, $x_1 = \frac{Y_i}{X_i}$ and $x_2 = \frac{Z_i}{X_i}$ are constant.
3. Within a certain boundary (domain) on the seabed, the long axis of nodule X_i follows a Generalized Rayleigh Distribution (GRD), which is defined by a pair of parameters α and β (See Section 3).

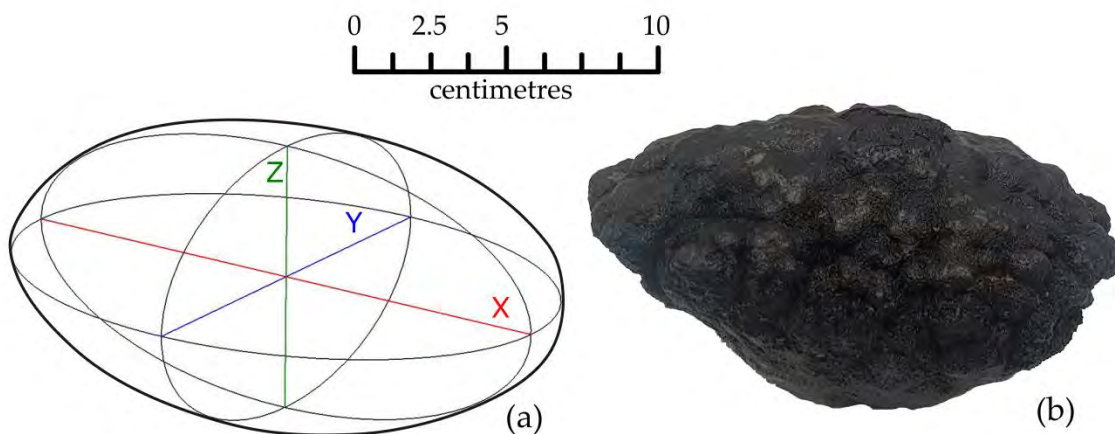


Figure 2. An idealized nodule of ellipsoidal shape (a) and an example from the TOML C1 area (b).

The above idealization is supported by analysis of nodule data and they were found accurate to certain degree. Specifically, the hypothesis 1 and 2 above will be justified using regression analysis of nodule dimensions and weights of seabed nodules samples in Section 5.1, while the hypothesis 3 will be validated by Anderson-Darling “Goodness-of-Fit” tests in Section 5.2 using nodule samples collected from TOML areas.

3. Generalized Rayleigh Distribution (GRD) and the Traditional Method

The Rayleigh distribution has been widely used to model phenomena in various technical fields. For instance, in the field of oceanography, Longuet-Higgins [20] showed the heights of narrow-banded random ocean waves follows the Rayleigh distribution. Generalized Rayleigh Distributions (GRD), a family of two-parameter variations, have also been proposed although their practical application is limited. For a random variable X following the GRD, its probability density function (PDF) $f(x)$ is in the form:

$$f(x) = 2\alpha\beta^2 x e^{-(\beta x)^2} [1 - e^{-(\beta x)^2}]^{\alpha-1}, x \geq 0, \quad (1)$$

where $\alpha \geq 0$ and $\beta \geq 0$ are shape and scale parameters, respectively.

The cumulative distribution function (CDF) $F(x)$ is given by:

$$F(x) = \left[1 - e^{-(\beta x)^2} \right]^\alpha, x > 0. \quad (2)$$

Figure 3 shows the PDF of Generalized Rayleigh Distribution for various values of parameters α and β . For a typical statistical analysis of seabed polymetallic nodules, the parameter range is $\alpha \geq 1$.

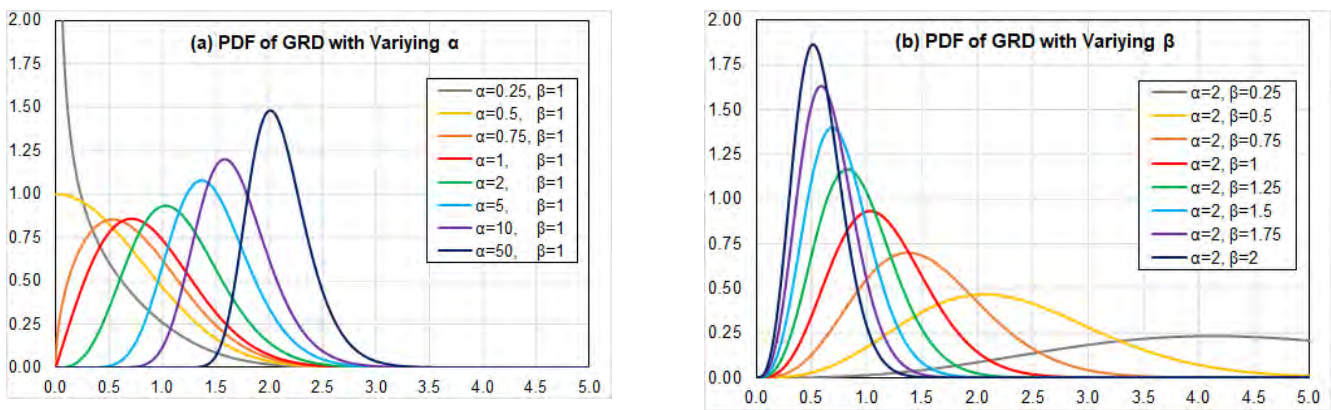


Figure 3. PDF of Generalized Rayleigh Distribution for Varying Parameters α (a) and β (b).

3.1. Mean and Standard Deviation of the Generalized Rayleigh Distribution (GRD)

As derived in Appendix A (Equations (A9) and (A15)), the mean μ and the standard deviation σ of the Generalized Rayleigh Distribution can be written as:

$$\begin{cases} \mu = \frac{\alpha}{\beta} \frac{F_1(\alpha)}{H_1(\alpha)} \\ \sigma = \mu \sqrt{\frac{F_2(\alpha)}{H_1(\alpha)}} \end{cases} \quad (3)$$

Where:
where:

$$\begin{cases} F_1(\alpha) = \int_0^\infty \int_0^\infty z e^{-z} [1 - e^{-z}]^{\alpha-1} dz \\ F_2(\alpha) = \int_0^\infty \int_0^\infty z^2 e^{-z} [1 - e^{-z}]^{\alpha-1} dz \\ F_2^G(\alpha) = \int_0^\infty \frac{F_2(\alpha)}{z^2 e^{-z} [1 - e^{-z}]^{\alpha-1}} dz \end{cases} \quad (4)$$

Formally, Equation (3) can be used to estimate α and β when μ and σ are known. However, due to the complexity of functions $F_1(\alpha)$ and $F_2(\alpha)$ in Equation (4), the solution process is rather tedious. Due to the complexity in evaluating $F_1(\alpha)$, $F_2(\alpha)$, an empirical method is developed below in Section 4 to simplify the solution procedure for practical applications. Formally, Equation (3) is used to estimate the solution procedure for practical applications. However, due to the complexity of functions $F_1(\alpha)$ and $F_2(\alpha)$ in Equation (4), the solution process is rather tedious. Due to the complexity in evaluating $F_1(\alpha)$, $F_2(\alpha)$, an empirical method is developed below in Section 4 to simplify the solution procedure for practical applications.

3.2. Test of Goodness of Fit of Generalized Rayleigh Distribution

3.2.1. Parameter Estimation by Maximum Likelihood Estimation (MLE)

For a random sample X_1, X_2, \dots, X_n of size n , following the Generalized Rayleigh Distribution (GRD), to determine the two parameters α and β , defining the GRD, the Maximum Likelihood Estimation (MLE) likelihood function, gives the following a pair of equations (Abd-Elfattah [21]):

$$\begin{cases} \frac{\sum_{i=1}^n x_i^2 e^{-\beta^2 x_i^2} / (1 - e^{-\beta^2 x_i^2})}{\sum_{i=1}^n \ln(1 - e^{-\beta^2 x_i^2})} = \frac{1}{\beta^2} \\ \frac{\sum_{i=1}^n x_i^2 / (1 - e^{-\beta^2 x_i^2})}{n} = \frac{1}{\beta^2} \end{cases} \quad (5)$$

In a typical solution process for α and β , Equation (5) is first solved iteratively by the Newton-Raphson Method to yield β , and Equation (6) is then used to calculate α . It is obvious that the solution process for Equation (6) is quite tedious. An empirical alternative is, therefore, devised in Section 4 to simplify the process for practical application. In a typical solution process for α and β , Equation (5) is first solved iteratively by the Newton-Raphson Method to yield β , and Equation (6) is then used to calculate α . It is obvious that the solution process for Equation (6) is quite tedious. An empirical alternative is, therefore, devised in Section 4 below to simplify the process for practical application.

3.2.2. The Anderson–Darling Test Statistics

Once the parameters α and β are estimated as above, it is important to test whether they will yield a Generalized Rayleigh Distribution which gives a “good-fit” for the sample. For computational purpose, the Anderson–Darling (AD) test statistics A_n^2 and V_n^2 can be written as:

$$\begin{cases} A_n^2 = -n - \frac{1}{n} \sum_{i=1}^n (2i - 1) \{ \ln[z_i + \ln(1 - z_{n+1-i})] \} \\ V_n^2 = \frac{n}{2} - 2 \sum_{i=1}^n z_i - \sum_{i=1}^n \left[2 - \frac{2i-1}{n} \right] \ln(1 - z_i) \end{cases} \quad (7)$$

Here $z_i = F(x_i)$, where $F(x_i)$ is the empirical Probability Density Function (PDF), calculated using Equation (2) above, and arranged into ascending order.

3.2.3. The Test Criteria for Hypothesis

The value of A_n^2 and V_n^2 calculated above are then compared with their corresponding critical values y_Γ and u_Γ , respectively. If:

$$\begin{cases} A_n^2 < y_\Gamma \\ V_n^2 < u_\Gamma \end{cases} , \quad (8)$$

the null hypothesis that sample data follow generalized Rayleigh distribution, is accepted at the particular significance level Γ (or at $1 - \Gamma$ confidence level). The critical values y_Γ and u_Γ are simulated by the Monte Carlo Method, as discussed in Appendix B.

4. A New Empirical Method and Its Application to Nodule Resources

As shown above in Section 3, the traditional formulation can be used for (1) analysing whether a numerical sample follows the Generalized Rayleigh Distribution in a statistically significant way, and (2) for, if it does, estimating the parameters which defines a GRD yielding the best fit to the sample. However, the complexity of the numerical process described about in Section 3, makes it difficult to be applied in practice. In this Section, we introduce a simplified numerical procedure for predicting the mineral resource of seabed nodules.

4.1. Empirical Estimation of Parameters of the Generalized Rayleigh Distribution

As shown in Section 3.2.1, Equations (3) and (4) can formally be used to estimate α and β when μ and σ are known. To simplify the calculation of $F_1(\alpha)$ and $F_2(\alpha)$, using the technique of nonlinear regression, it can be shown, for the interested range of $1 \leq \alpha \leq 9$, the following empirical formulae:

$$\begin{cases} F_1(\alpha) = \frac{1.26364}{(\alpha + 0.51265)^{0.85786}} \\ F_2(\alpha) = \frac{1.73929}{(\alpha + 1.11917)^{0.73864}} \\ G(\alpha) = \frac{0.19249}{(\alpha - 0.41497)^{0.67379}} \end{cases} , \text{ for } 1 \leq \alpha \leq 9 \quad (9)$$

are accurate to an accuracy of 10^{-4} (See Figure 4).

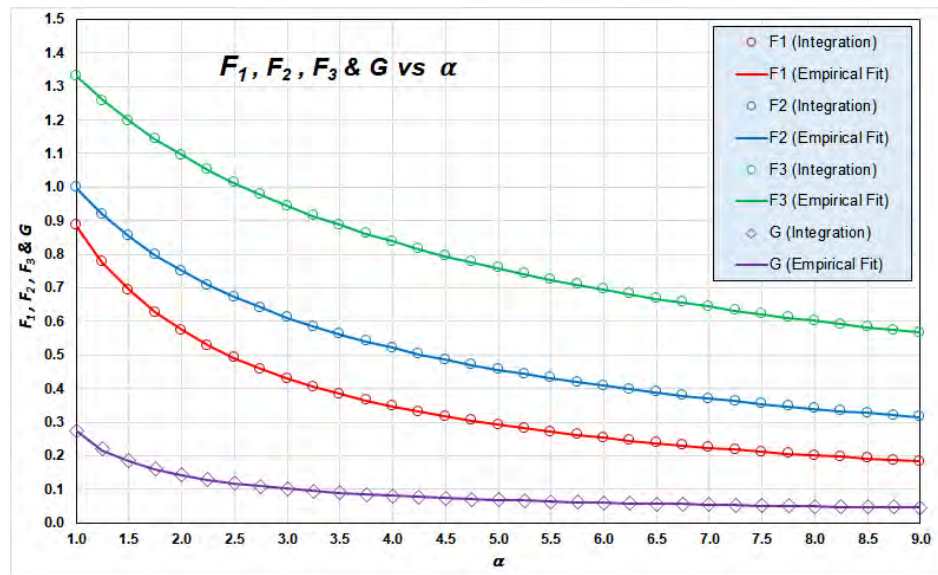


Figure 4. $F_1(\alpha)$, $F_2(\alpha)$, $F_3(\alpha)$ and $G(\alpha)$ as functions of α : Numerical Integration vs. Empirical Formulas.

Additionally, included in Figure 4 is $F_3(\alpha)$, which will be discussed further in Section 4.2 below. The empirical form of $F_3(\alpha)$ is:

$$F_3(\alpha) = \frac{F_3(\alpha) \cdot 2.48274}{(\alpha + 1.71977)^{0.62304}} \quad (10)$$

Combining Equations (9) and (10) it is straightforward to derive:

$$\begin{cases} \alpha = 0.41497 + 0.08669 \left(\frac{\mu}{\sigma}\right)^{2.96828} \\ \beta = \frac{1.26364 \alpha}{(\alpha + 0.51265)^{0.85786}} \left(\frac{1}{\mu}\right) \end{cases} \quad (11)$$

For a random sample X_1, X_2, \dots, X_n of size n , the mean μ and standard deviation σ are first estimated from the sample and then the two formulae in Equation (11) can be used to estimate parameters α and β .

It is evident from the first equation of Equation (11) that shape parameter α is determined by the ratio of μ and σ (in effect the reciprocal of the coefficient of variation or signal-to-noise ratio). The scale parameter β , on the other hand, is related to the mean μ . This is consistent with the observation in Figure 3. It can be posited that geologically these two parameters may in turn relate to the stability and thickness of the geochemically active layer in which the nodules grow, as described in [4].

4.2. Resource Estimation for Seabed Polymetallic Nodules Using Coverage and Abundance

To estimate the percentage coverage and abundance of seabed polymetallic nodules using the measurements of their long axes, the first two hypothesis, as in Section 2 above, are applied:

1. The nodule is assumed to be in an idealized ellipsoid shape.
2. Nodules within a certain boundary are assumed to be "similar" in shape, the ratios between the lengths of the two minor axes and the major axis (denoted by ϵ_1 and ϵ_2) are constant.

4.2.1. Prediction of Nodule Coverage: Idealized Nodules

Assuming X_1, X_2, \dots, X_N are samples of long axes of ellipsoid nodules, with N being the number of nodules in the photo, the total area S_c being covered by nodules can be calculated as the summation of the elliptical projections of nodules S_i in the photo image:

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$$S_c = \sum_{i=1}^N S_i = \sum_{i=1}^N \frac{\pi}{4} X_i Y_i \tag{12}$$

where $Y_i = \varepsilon_1 X_i$ being the shorter axes ($\varepsilon_1 \leq 1$). Equation (12) can then be re-arranged as:

$$S_c = \sum_{i=1}^N \frac{\pi}{4} X_i Y_i = \frac{\pi}{4} \sum_{i=1}^N X_i (\varepsilon_1 X_i) = \frac{\pi \varepsilon_1}{4} \sum_{i=1}^N X_i^2 \tag{13}$$

where $\overline{X^2}$ indicating the mean of X_i^2 . Using Equation (A8) in Appendix A and taking $m = 2$, Equation (13) becomes:

$$S_c = \frac{\pi \varepsilon_1}{4} N \overline{X^2} = \frac{\pi \varepsilon_1}{4} N \frac{\alpha}{\beta^2} F_2(\alpha) \tag{14}$$

Assuming S_p is the total area of the photo and using Equation (9), the nodule percentage coverage C_N becomes:

$$C_N = \frac{S_c}{S_p} = \frac{\pi \varepsilon_1 N}{4 S_p} \frac{\alpha}{\beta^2} F_2(\alpha) = \frac{\varepsilon_1 N}{S_p} \frac{1.36603 \alpha}{\beta^2 (\alpha + 1.11917)^{0.73864}} \tag{15}$$

4.2.2. Prediction Nodule Abundance I: Based on “Idealized Nodule” Model

Similarly, the total Weight W_a of nodules in the photo can be calculated as the summation of the weights of nodules W_i in the photo:

$$W_a = \sum_{i=1}^N W_i = \sum_{i=1}^N \frac{\pi}{6} \rho X_i Y_i Z_i \tag{16}$$

Assuming the two minor axes Y_i and Z_i are related to the major axis X_i by $Y_i = \varepsilon_1 X_i$ and $Z_i = \varepsilon_2 X_i$, Equation (16) can be re-arranged as:

$$W_a = \sum_{i=1}^N \frac{\pi}{6} \rho X_i Y_i Z_i = \frac{\pi}{6} \rho \sum_{i=1}^N X_i (\varepsilon_1 X_i) (\varepsilon_2 X_i) = \frac{\pi \rho \varepsilon_1 \varepsilon_2}{6} \sum_{i=1}^N X_i^3 = \frac{\pi \rho \varepsilon_1 \varepsilon_2}{6} N \overline{X^3} \tag{17}$$

where $\overline{X^3}$ indicating the mean value of X_i^3 . Using Equation (A8) in Appendix A and taking $m = 3$, Equation (17) becomes:

$$W_a = \frac{\pi \rho \varepsilon_1 \varepsilon_2}{6} N \overline{X^3} = \frac{\pi \rho \varepsilon_1 \varepsilon_2}{6} N \frac{\alpha}{\beta^3} F_3(\alpha) \tag{18}$$

Assuming S_p is the area of the photo and using Equation (10), the nodule abundance A_N becomes:

$$A_N = \frac{W_a}{S_p} = \frac{\pi \rho \varepsilon_1 \varepsilon_2 N}{6 S_p} \frac{\alpha}{\beta^3} F_3(\alpha) = \frac{\rho \varepsilon_1 \varepsilon_2 N}{S_p} \frac{1.29996 \alpha}{\beta^3 (\alpha + 1.71977)^{0.62304}} \tag{19}$$

4.2.3. Prediction Nodule Abundance II: With Empirical Long-Axis-Weight Relationship

According to [4,13] and Case 4 in Section 5.1 below, the weight of the nodule is correlated to its long axis by:

$$\log_{10} W_i = k \log_{10} X_i + b \tag{20}$$

where k and b are constants and k is usually smaller and close to 3.0 (See discussion in Section 5.1). Equation (20) can be re-arranged as:

$$W_i = 10^b X_i^k \quad (21)$$

Then, the total weight W_a of nodules in the photo can be calculated by adding the weights of nodules W_i in the photo:

$$W_a = \sum_{i=1}^N W_i = \sum_{i=1}^N 10^b X_i^k = 10^b \sum_{i=1}^N X_i^k \quad (22)$$

Using Equation (A8) in Appendix A and taking $m = k$, Equation (22) becomes:

$$W_a = 10^b \sum_{i=1}^n X_i^k = 10^b N \overline{X^k} = 10^b N \frac{\alpha}{\beta^k} F_k(\alpha) \quad (23)$$

$F_k(\alpha)$, with $2 < k \leq 3$, can be approximated by interpolating $F_2(\alpha)$ and $F_3(\alpha)$:

$$F_k(\alpha) = [F_3(\alpha) - F_2(\alpha)] k + [3F_2(\alpha) - 2F_3(\alpha)] \quad (24)$$

Assuming S_p is the area of the photo and using Equation (24), the nodule abundance A_N becomes:

$$\begin{aligned} A_N &= \frac{W_a}{S_p} = \frac{10^b N}{S_p} \frac{\alpha}{\beta^k} F_k(\alpha) \\ &= \frac{10^b N}{S_p} \frac{\alpha}{\beta^k} \{ [F_3(\alpha) - F_2(\alpha)] k + [3F_2(\alpha) - 2F_3(\alpha)] \} \end{aligned} \quad (25)$$

4.2.4. Relation between Nodule Percentage Coverage and Abundance

The abundance A_N are related to the percentage coverage C_N by dividing Equation (19) by Equation (15):

$$\frac{A_N}{C_N} = \frac{2}{3} \frac{\rho \varepsilon_2}{\beta} \frac{F_3(\alpha)}{F_2(\alpha)} \quad (26)$$

Eliminating β using the first equation of Equation (3), Equation (26) above becomes:

$$\frac{A_N}{C_N} = \frac{2}{3} \rho \varepsilon_2 \mu \frac{F_3(\alpha)}{\alpha F_1(\alpha) F_2(\alpha)} \quad (27)$$

Using the technique of nonlinear regression, Equation (27) can be rewritten into the form:

$$\frac{A_N}{C_N} = \rho \varepsilon_2 \mu \frac{0.70834(\alpha + 0.41373)^{0.99261}}{\alpha} \quad (28)$$

For the range of $1 < \alpha < 4$, of interest to nodules, Equation (28) can be further approximated, within 0.2% error, by:

$$\frac{A_N}{C_N} \approx \rho \varepsilon_2 \mu \left[1 - 0.3 \left(1 - \frac{1}{\alpha} \right) \right] \quad (29)$$

The above formulation, based on the "Idealized Nodule" model, provides two alternative ways to estimate the nodule resources:

1. Equations (15) and (19) can be used independently to calculate the nodule percentage coverage C_N and the abundance A_N , respectively.
2. If an estimation of the C_N is already estimated (e.g., using digitization technique from seabed imagery), then Equation (28) or Equation (29) can be used to compute A_N .

5. Test of Hypotheses of the Idealized Nodule Model

The three fundamental hypotheses that define the “idealized nodule” in Section 2 find considerable support from numerical measurements of samples of seabed nodule. 9 of 28

5.1. Test of Hypotheses 1 and 2: Linear Regression Analyses on Nodule Dimensions and Weights

In order to examine the validity of the first two hypotheses for the “idealized nodules”, linear regression analyses were carried out on the first published data set for the “idealized nodules”, volume and weight of the fabric-covered sea (BGR East and GSR Central Regions) in CCZ [14]. Specifically, the following cases of linear regressions were carried between:

1. Case 1: Nodule long axis and its horizontal minor axis;
2. Case 2: Nodule long axis and its vertical minor axis;
3. Case 3: Nodule long axis and its vertical minor axis;
4. Case 4: Nodule weight and its volume;
5. Case 5: Nodule weight and its weight.

The numerical results are shown in Figure 5 (for BGR East Region) and Figure 6 (for GSR Central Region), with charts (a) to (d) representing Cases 1 to 4, respectively, and are also summarized in Table 1. The linear regression was performed for Cases 1 to 3 with intercept forced be zero to match the fact that the two variables vanish at the origin.

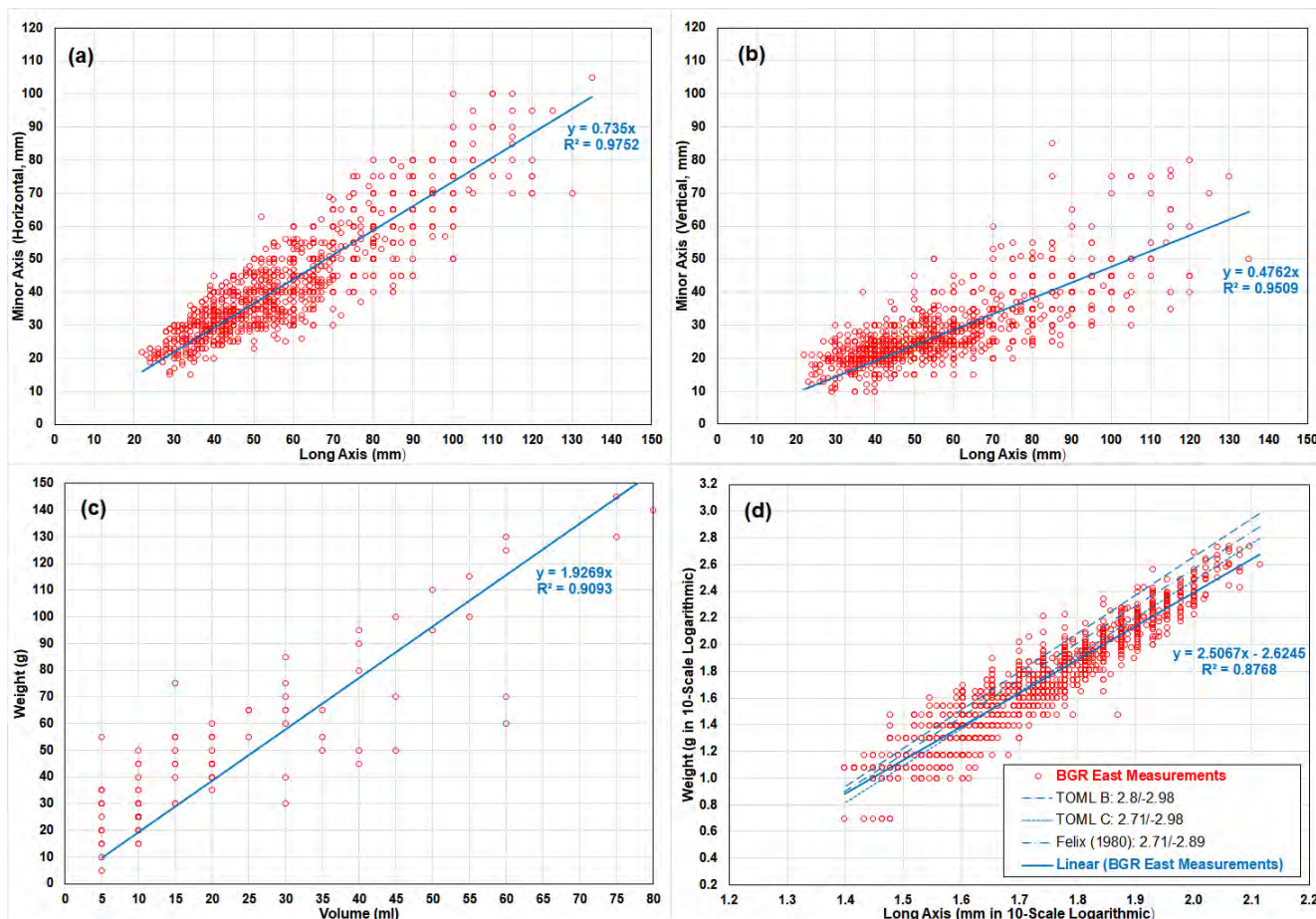


Figure 5. Linear Regression between Nodule Dimensions and Weights for BGR East Region. Data source [14]. Note in (d) the legend shows the slopes and intercepts of the linear regressions of the data of Felix [13] and TOML [4], where the intercepts are converted from cm to mm (in logarithmic scale).

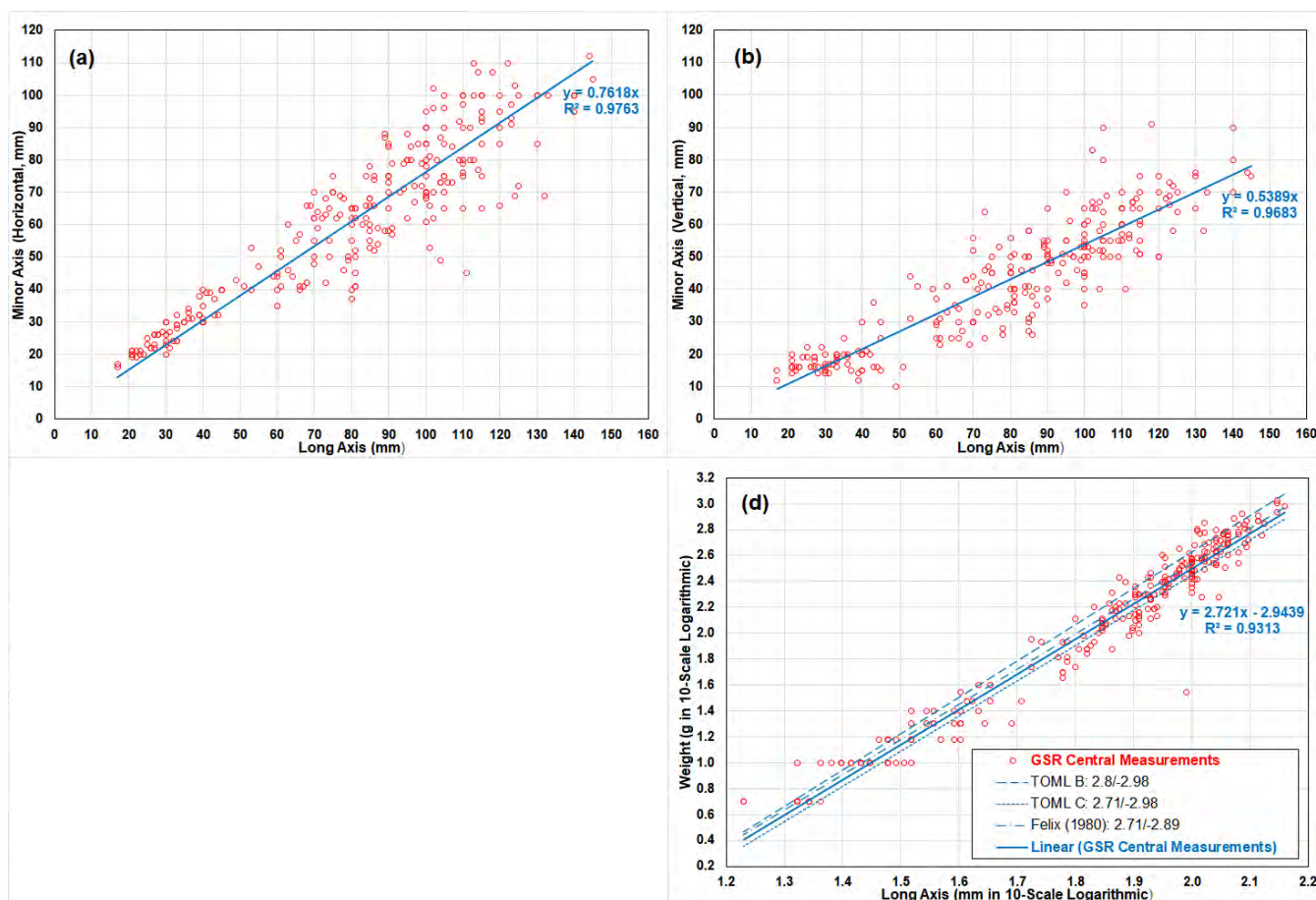


Figure 6. Linear Regression between Nodule Dimensions and Weights for GSR Central Region. Data source [14]. Note in (d) the legend shows the slopes and intercepts of the linear regressions of the data of Felix [13] and TOML [4], where the intercepts are converted from cm to mm (in logarithmic scale).

Table 1. Results of Linear Regression for Nodule Dimensions and Weights.

Case	Regression Parameters	Regions	Sample Size	Estimated Slope	Estimated Intercept	Coefficient of Determination (R ²)
1	Minor Axis Y (Horizontal, mm)	BGR East	1376	0.7350	0 (Forced)	97.52%
1	Minor Axis Y (Horizontal, mm)	GSR Central	259	0.7618	0 (Forced)	97.87%
2	Minor Axis Z (Vertical, mm)	BGR East	1376	0.4768	0 (Forced)	95.09%
2	Minor Axis Z (Vertical, mm)	GSR Central	259	0.5389	0 (Forced)	96.83%
3	Weight (g)	BGR East	99	1.9269	0 (Forced)	90.93%
3	Weight (g)	GSR Central	259	0.5389	0 (Forced)	96.83%
3	Weight (g)	BGR East	1376	1.9269	0 (Forced)	90.93%
4	Weight (Logarithmic, g)	BGR East	1376	2.5067	-2.6245	87.68%
4	Weight (Logarithmic, g)	GSR Central	259	2.7210	-2.9439	93.13%

The results from Cases 1 and 2 show the two minor axes are correlated to the long axis in statistically significant ways. With $R^2 > 95\%$, a great majority (>95%) of the data points supports the hypothesis that, with a certain boundary, the ratios between the length of the major axes X and the lengths of the horizontal and the vertical minor axes Y and Z can be considered as constants. It is also noted the ratios vary between regions. The result from the 3rd Case indicates a nodule density of 1.93 g/cm^3 although it is only supported by a small sample. The Case 4 indicates the nodule weight is strongly correlated with the length of the major axes X and the lengths of the horizontal and the vertical minor axes Y and Z can be considered as constants. It is also noted the ratios vary between regions. The result from the 3rd Case indicates a nodule density of 1.93 g/cm^3 although it is only supported

by a small sample. The Case 4 indicates the nodule weight is strongly correlated with the 2.5056th and 2.7210th power of the long axes, supported by about 88% and 93% of the data points from the two regions, respectively. It is worthwhile to notice, for “idealized nodules”, the nodule weight is proportional exactly to the cubic (the 3rd power) of its long axis.

While the above results give broad, yet strong support to the first two hypotheses for “idealized nodules” in Section 2 (these being on ellipsoid form and similarity of form within a domain), we use additional analysis in Section 2 to validate the 3rd hypothesis regarding a GRD distribution.

5.2. Test of Hypotheses 3: Goodness-of-Fit Test of Generalized Rayleigh Distribution for Nodule Long Axes

In this Section, the traditional Anderson-Darling “Goodness-of-Fit” tests, as outlined in Section 3, are carried out to check the validity of the 3rd hypothesis for the “idealized nodules”. It is to check whether the long axes of seabed nodules follow the Generalized Rayleigh Distribution (GRD) in a statistically significant way. A total of 9 samples (5 towed photos and 4 washed samples) of nodule long axes were analysed. While Table 2 shows the key statistical properties of the 9 data sets, Table 3 presents the results of “Goodness-of-Fit” tests.

Table 2. Summary of 9 Sets of Samples of Nodule Long Axes used for Goodness-of-Fit Test.

No	Sample ID	TOML Area	Type	Sample Size	Mean	Standard Deviation
1	2015_08_10_172643	B	Towed Photo	336	3.091	2.512
2	2015_08_10_220159	B	Towed Photo	153	7.767	2.387
3	2015_08_11_121357	B	Towed Photo	403	5.978	1.732
4	2015_08_29_131349	C	Towed Photo	440	5.425	1.995
5	2015_09_02_185307	C	Towed Photo	113	3.827	1.270
6	CCZ15-B51	D	Washed Sample	67	7.486	2.404
7	CCZ15-B102	F	Washed Sample	278	4.318	1.705
8	CCZ15-B106	F	Washed Sample	559	3.681	1.298
9	CCZ15-B110	F	Washed Sample	135	6.910	2.602

Table 3. Results of Goodness-of-Fit Test for 9 Sets of Samples of Nodule Long Axes.

No	Sample ID	α	β	A_n^2	y_Γ	V_n^2	u_Γ	Conclusions
1	2015_08_10_172643	0.623	0.211	9.957	0.833	5.436	0.43	Generalized Rayleigh Dist. at 5% Level of Significance
2	2015_08_10_220159	2.714	0.162	0.66	0.784	0.257	0.414	
3	2015_08_11_121357	3.598	0.226	0.69	0.770	0.226	0.410	
4	2015_08_29_131349	1.965	0.210	0.541	0.777	0.305	0.408	
5	2015_09_02_185307	2.690	0.327	0.159	0.789	0.076	0.419	
6	CCZ15-B51	1.701	0.144	0.376	0.804	0.200	0.423	Not Generalized Rayleigh
7	CCZ15-B102	1.396	0.243	1.435	0.790	0.605	0.412	
8	CCZ15-B106	2.410	0.321	0.738	0.778	0.314	0.410	Generalized Rayleigh Dist. at 5% Level of Significance
9	CCZ15-B110	1.890	0.171	0.361	0.791	0.192	0.418	

For each set of data in Table 3, α and β are solved iteratively by Equations (5) and (6), using the MLE method described in Section 3.2.1. The Anderson–Darling (AD) test statistics A_n^2 and V_n^2 are then calculated by Equation (7) and they are in turn compared with their critical values y_Γ and u_Γ , which are computed by the Monte Carlo Simulation in

Appendix B. According to the test criteria in Equation (8), among the 9 sets of samples, 7 of them have passed the AD tests at 95% confidence level. It indicates a high probability that the samples of long axes of polymetallic nodules do follow Generalized Rayleigh Distribution although more AD tests need to be carried out for more samples to check the generality. This conclusion may be conditional (e.g., by geological domain), and more research is needed to identify the conditions.

Figures 7 and 8 show the visual comparison of distribution of nodule long axes from raw data, computed by the traditional method, and by the new empirical method. Probability density functions (PDF) and cumulative distribution functions (CDF) are plotted in Figures 7 and 8, respectively, using Sample ID: 2015_08_29_131349 as an example. For the raw data, a bin size of 0.25 was selected to create a histogram of the sample of long axis, and the PDF and the CDF are then computed. The dark blue line shows the raw counts of the original data set, with the light blue line showing the smoothed data using the Savitzky-Golay filter [22] for the PDF in Figure 7. The green line shows PDF and CDF based on parameters α and β calculated iteratively by MLE method described in Section 3.2.1 above. The red line shows PDF and CDF based on parameters α and β calculated by the empirical formulas in Equation (11). The empirical formulas, while much more straightforward to use, do give reasonably accurate results for the statistical distributions in practical applications.

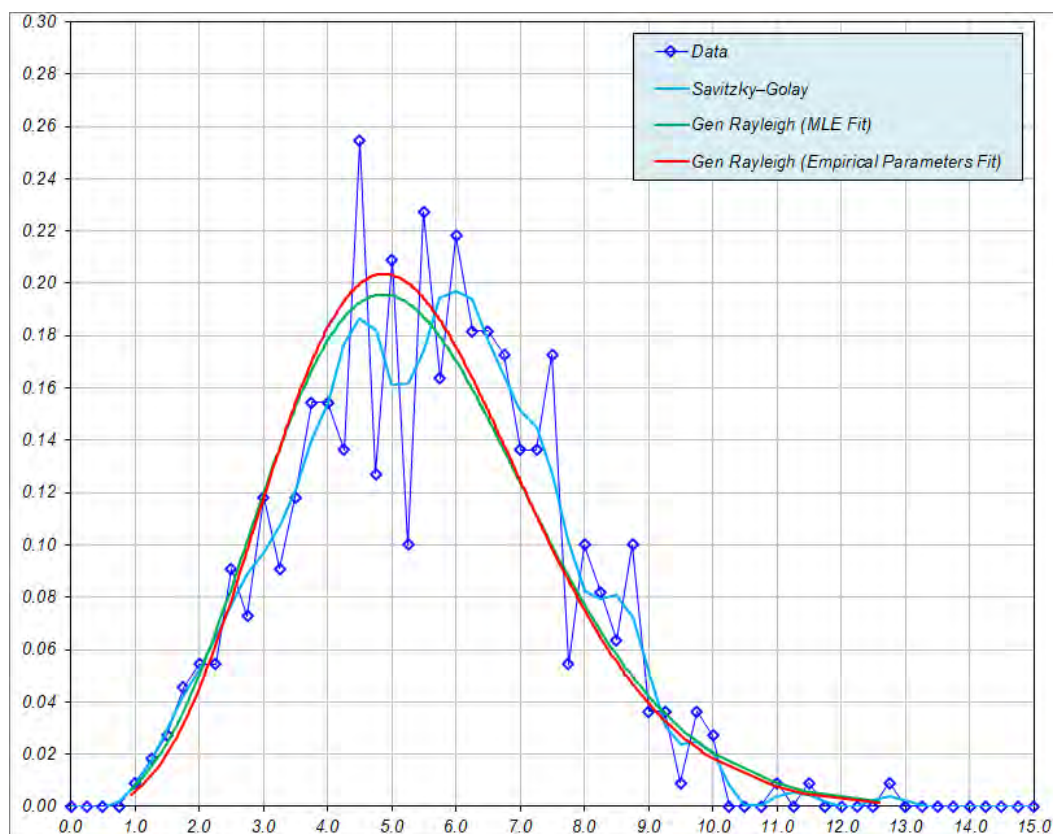


Figure 7. Probability Density Function (PDF) of the example towed seabed photograph (2015_08_29_131349 in Tables 2 and 3).

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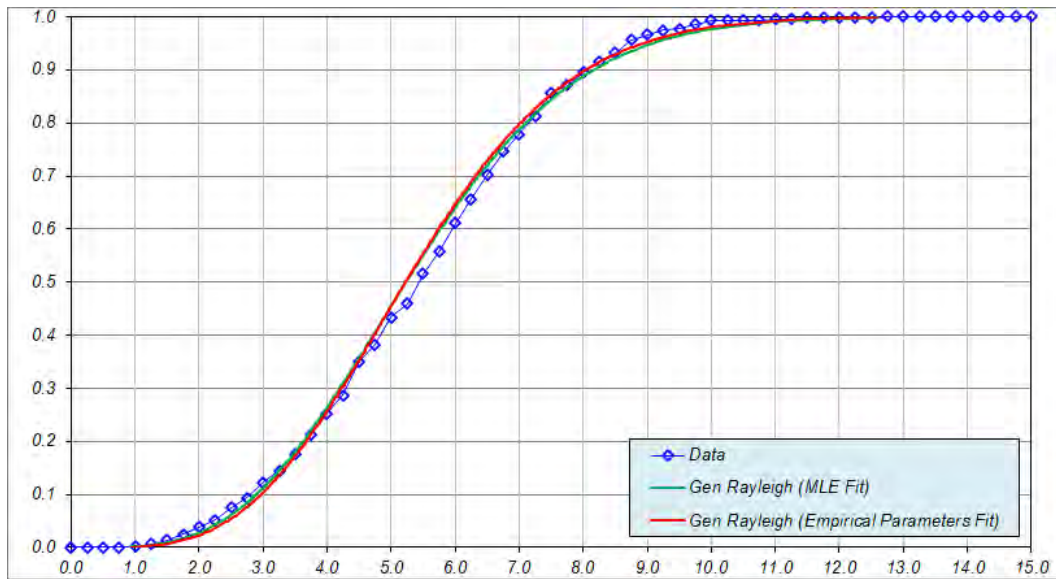


Figure 8. Cumulative Distribution Function (CDF) of the example towed seabed photograph (2015_08_29_131349 in Tables 2 and 3).
Figure 8. Cumulative Distribution Function (CDF) of the example towed seabed photograph (2015_08_29_131349 in Tables 2 and 3).

5.3. Comments on the Level of Support
 5.3. Comments on the Level of Support

Significantly, the Linear Regression Analysis in Section 5.1 and the Goodness-of-Fit Test in Section 5.2 do support the three seemingly drastic fundamental hypotheses made in Section 2 for “idealized nodules”. However, more analyses are needed to check the generality. Nonetheless, as the hypotheses have been validated, the empirical method developed in Section 4 can be used for nodule resource prediction in the next Section.

Possible reasons for achieving the statistically significant validations, include that the samples are located within a particular growth domain (the CCZ), and that the conditions of growth within this domain are remarkably consistent as nodules grow in effect from the ocean’s epibenthos, and slowly enough to “average out” short term (millennia scale) variances in growth conditions.

6. Numerical Results of Nodule Resource Prediction Using the New Empirical Method

Once newly proposed “idealized nodules” model has been validated in the previous Section, the empirical formulation as developed in Section 3, particularly the Equation (19) for Equation (23) for nodule abundance N are applied to a total of 188 samples of seabed polymetallic nodule collected in 2015 as part of the TOML CCZ15 marine expedition. The dataset thus towed photo sample datasets (long-axis abundance estimate) between the TOML B and G areas (~300 km apart). The dataset is limited in that

The 188 samples of seabed polymetallic nodules used for the empirical analyses can be grouped in three datasets:

1. Dataset 1: regional scale box-core sample dataset (physical weights). This involves some 2000 km of longitude and 700 km of latitude. The dataset thus allows for a general relationship for a general relationship between contract areas (TOML B, C, D, F; Figure 9) spanning some 2000 km of longitude and 700 km of latitude. The physical weights of two distinct facies types but only within the TOML F area (~200 × 200 km). Type 1 nodules are smaller and often densely packed, type 2 nodules are significantly larger and more variable (cf. [5]). The dataset thus allows for differences in nodule types from an area where the distinction between type is simple and straightforward.
2. Dataset 2: local scale box-core sample dataset (physical weights). This involves some 200 km of longitude and 700 km of latitude. The dataset thus allows for a general relationship between contract areas (TOML B, C, D, F; Figure 9) spanning some 2000 km of longitude and 700 km of latitude. The physical weights of two distinct facies types but only within the TOML F area (~200 × 200 km). Type 1 nodules are smaller and often densely packed, type 2 nodules are significantly larger and more variable (cf. [5]). The dataset thus allows for differences in nodule types from an area where the distinction between type is simple and straightforward.
3. Dataset 3: local scale towed photo sample datasets (long-axis abundance estimate) between the TOML B and G areas (~300 km apart). The dataset is limited in that

- Dataset 3: two local scale towed photo sample datasets (long-axis abundance estimate) between the TOML B and C areas (~300 km apart). The dataset is limited in that actual nodule weights cannot be compared, but it allows for larger datasets from two distinctly different areas to be compared.

Coverage was also measured for datasets 2 and 3 from seabed photographs (box-core mounted and towed, respectively) using Image J software. Dataset 1 was not able to be measured due to a lack of images (the box-core camera had frequently malfunctioned).

A summary of the datasets used for analysis is shown in Table 4 and Figure 9.

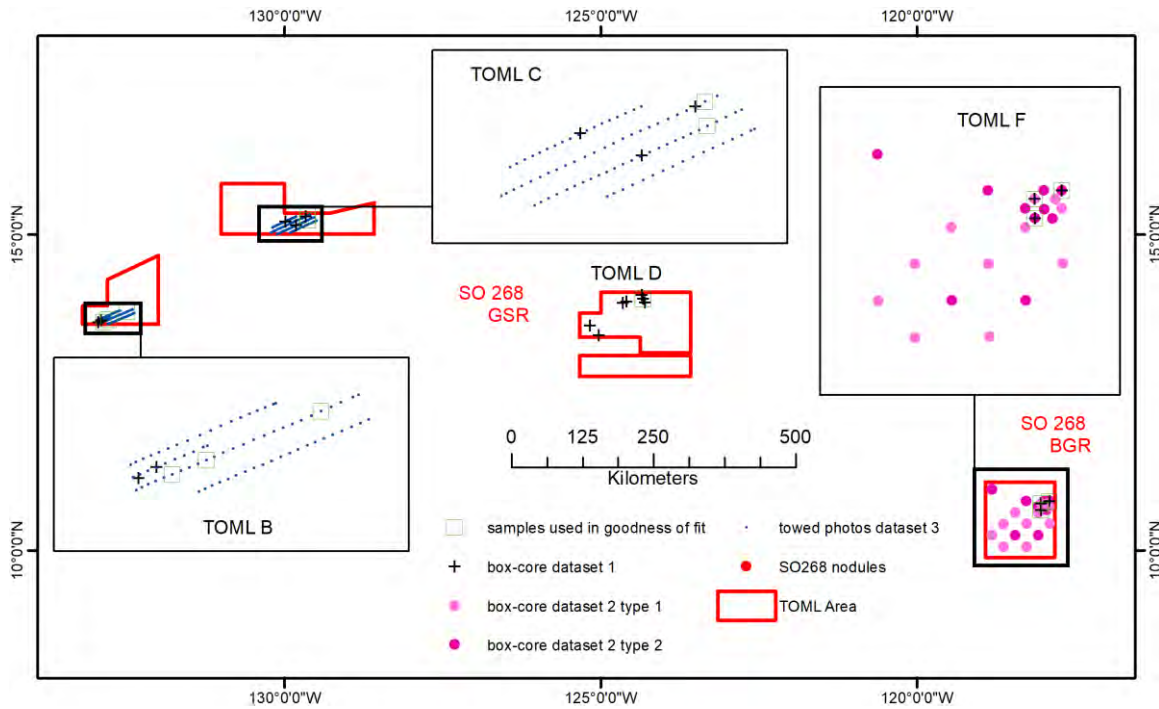


Figure 9. Sample datasets locations.

Table 4. Summary of 188 Sample Sets of Nodule Long Axes to be Analysed.

Data-Set	TOML Areas	Number of Samples	Comparative Data Type	Range of Measured Abundances	Range of Mean Long Axes*	Range of Coefficient of Variation*
1	B, C, D, F	2, 3, 7, 3	Washed sample weights	3.2 to 25.7 kg/m ²	2.2 to 7.6 cm	0.23 to 0.86
2	F	11 for Type 1 9 for Type 2	Washed sample weights	1.2 to 21.3 3.3 to 29.1	2.2 to 3.9 2.6 to 9.2	0.28 to 0.45 0.28 to 0.72
3	B	68	Long axis estimates on individual nodule images	0.03 to 31	1.6 to 7.8	0.24 to 0.96
3	C	85	Long axis estimates on individual nodule images	0.01 to 18	1.5 to 6.1	0.25 to 0.83

* For datasets 1 and 2 long axes measured from grid photos of the nodules after collection, separation from the host clay-ooze and washing. For dataset 3 long axes measured from photos of the seabed as detailed in [4].

6.2. Prediction of Abundance of Seabed Nodules

The accuracy of abundance prediction made by the new empirical method, particularly Equation (19) or Equation (25), Figures 10–12 show the ratio between the abundance prediction and the actual long-axis measurements (for datasets 1 and 2) or the available estimate from a long-axis measurement (for dataset 3). In the Figures, the ratios are plotted against the mean long axes of each sample. For each dataset, three charts are presented against abundance calculated directly by the empirical formula Equation (19), which is strictly based on the three hypotheses for idealized

1. nodule shape (19), ratio is based on the calculated by the empirical formula Equation (19), which is strictly based on the three hypotheses for idealized

- nodule model in Section 2. The axis ratios ε_1 and ε_2 used in the formula are extracted from the analyses of BGR East and GSR Central data (Table 1 in Section 5.1);
2. Chart (b) showing the ratios in Chart (a) corrected by a “linear adjustment”. Each individual ratio in Chart (a) is factored/divided by the result of linear regression of the ratios, and the corrected results are shown in Chart (b); and
 3. Chart (c) showing ratios based on abundance calculated by the empirical formula Equation (19), incorporating the long-axis-weight relationship observed by several researchers (e.g., Felix [13]), which indicates the nodule weight is coorelated to the 2.7–2.8th power of its long-axis (noting for “idealized nodule”, it is the 3rd power).

Figure 10 shows the results for Dataset 1, which is collected across the TOML areas. It is observed that empirical formula Equation (19), which is strictly based on the three hypotheses for idealized nodule model in Section 2, gives a slight bias of over-predicting the abundance for larger nodules. Unbiased prediction can be achieved once either the “linear adjustment” or the long-axis-weight relationships are applied.

Figure 11 depicting Dataset 2 shows that nodule types can have an influence in the prediction. While empirical formula Equation (19) results in a similar bias to that seen for Dataset 1, facies specific “linear adjustment” results in unbiased estimates with slightly higher levels of scatter. Use of empirical formula Equation (25) based on the coefficients of [13] works better for Type 1 nodules than for Type 2, suggesting that different coefficients may work better.

Figure 12 with Dataset 3 shows that the accuracy of prediction made by empirical formula Equation (19) may vary for nodules between different areas. In effect the nodules from TOML B1 appear to deviate more from the “idealized nodules” per Section 2 than the nodules from TOML C1. This may be due to the fact that the TOML B1 nodules are likely older and more often formed from multiple generations of growth (i.e., fragments of nodules with younger concentric growth phases). This could predispose them to be more equant in shape. Again, the linear adjustment addresses the size-bias seen in the direct application of Equation (19). Application of Equation (25) gives broadly similarly agreeable results in (c) as those with “linear correction” in (b).

The slight biases of over-estimation of abundance for larger nodules reveals a limitation of the empirical formula Equation (19), which is directly based on the three fundamental hypotheses for the “idealized nodules”. While the first two hypothesis state that the nodules are in ellipsoidal shape and they are “similar” in shape, in reality, it is obvious that the nodule shapes are complex and for nodules of various sizes, the ratios between the minor axes and the long one may vary with nodule size. However, this bias seems much less severe while empirical formula Equation (25) is applied, which is based on an empirical relationship between the nodule long axis and its weight (e.g., Felix [13]).

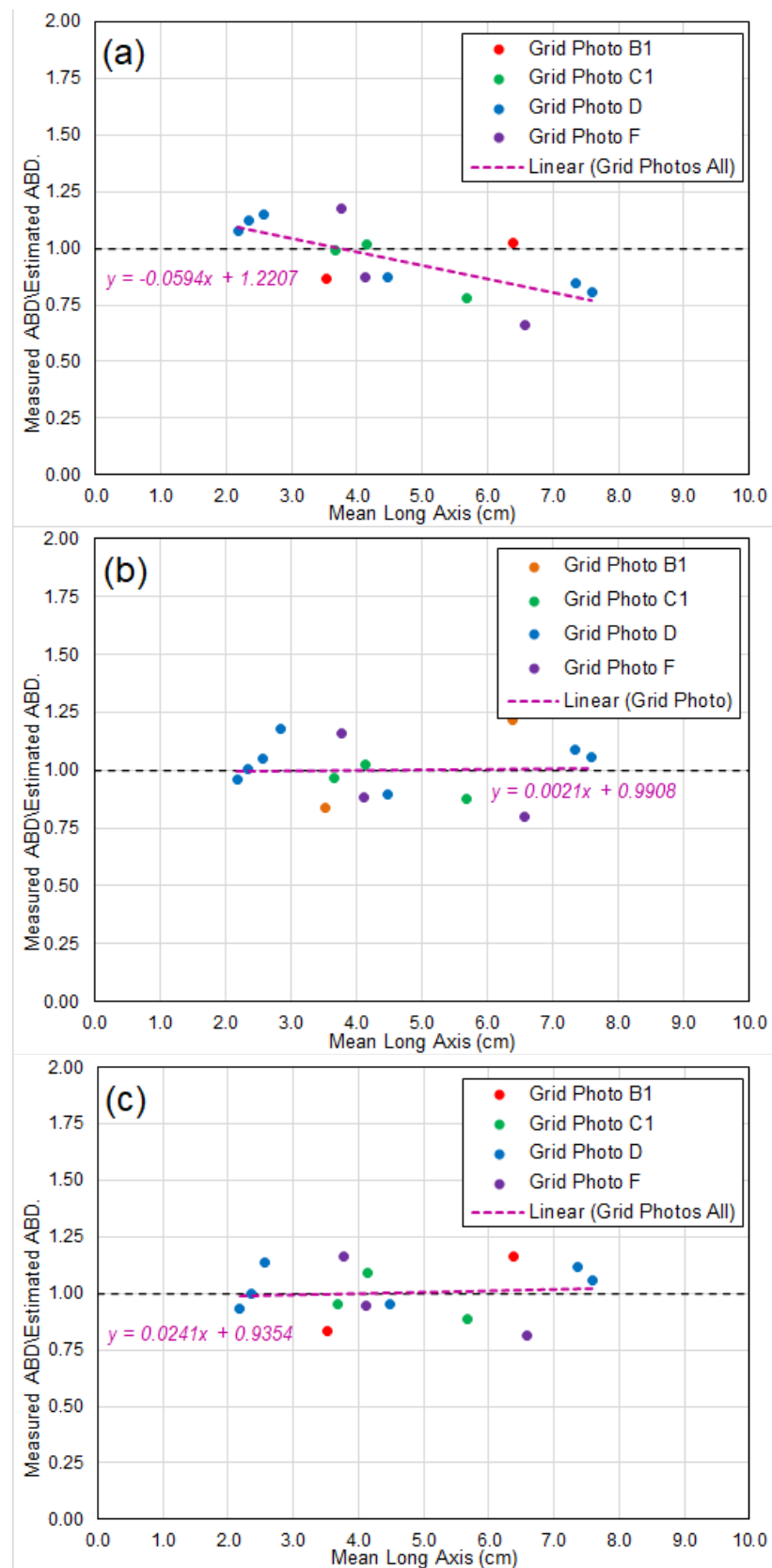


Figure 10. Comparisons of the measured Abundances and the predicted ones by the new empirical method with Dataset 1: (a) by empirical formula Equation (19); (b) by empirical formula Equation (19) with a linear adjustment; (c) by empirical formula Equation (25).

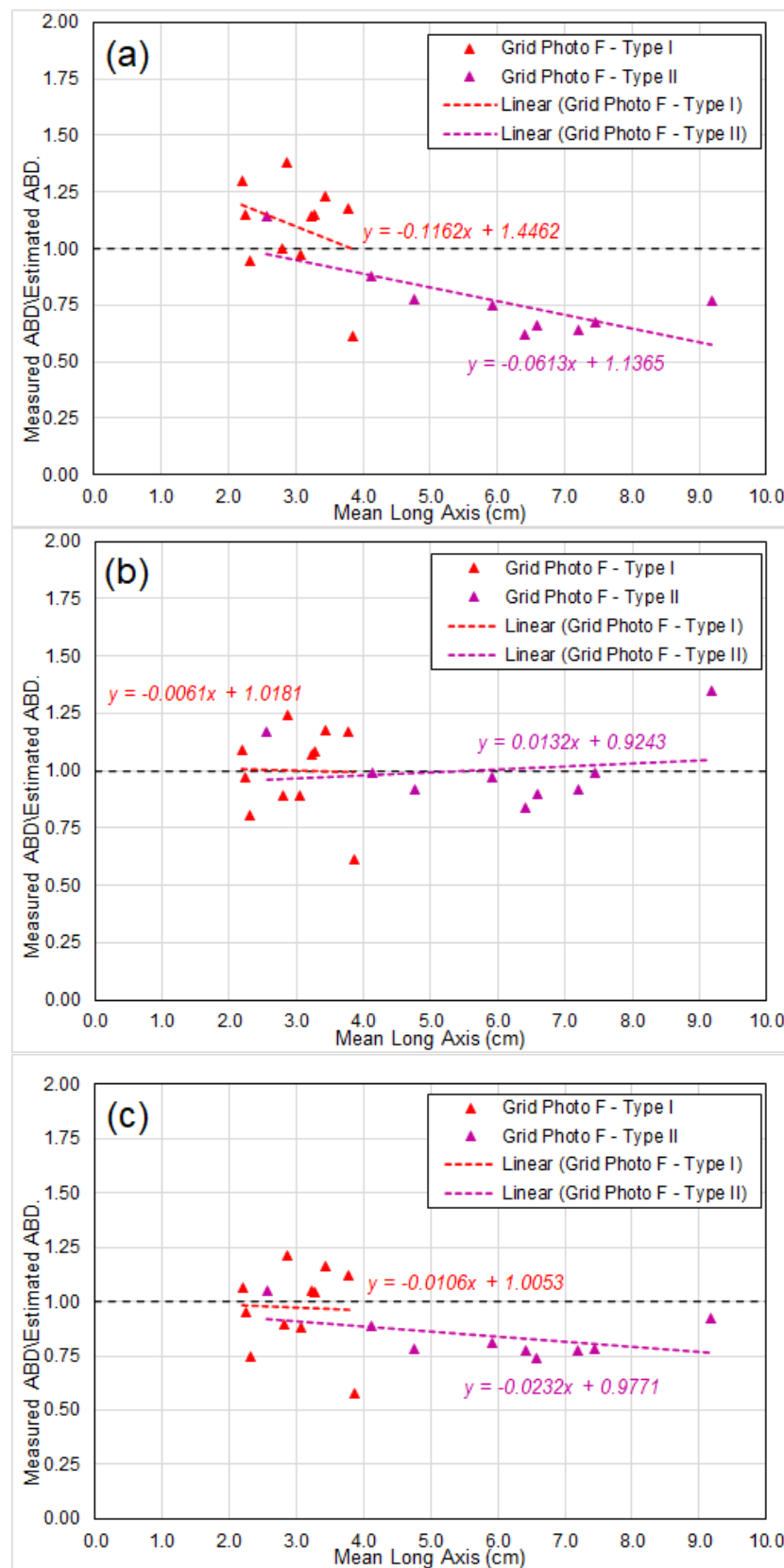


Figure 11. Comparisons of the measured Abundances and the predicted ones by the new empirical method with Dataset 2: (a) by empirical formula Equation (19); (b) by empirical formula Equation (19) with a linear adjustment; (c) by empirical formula Equation (25).

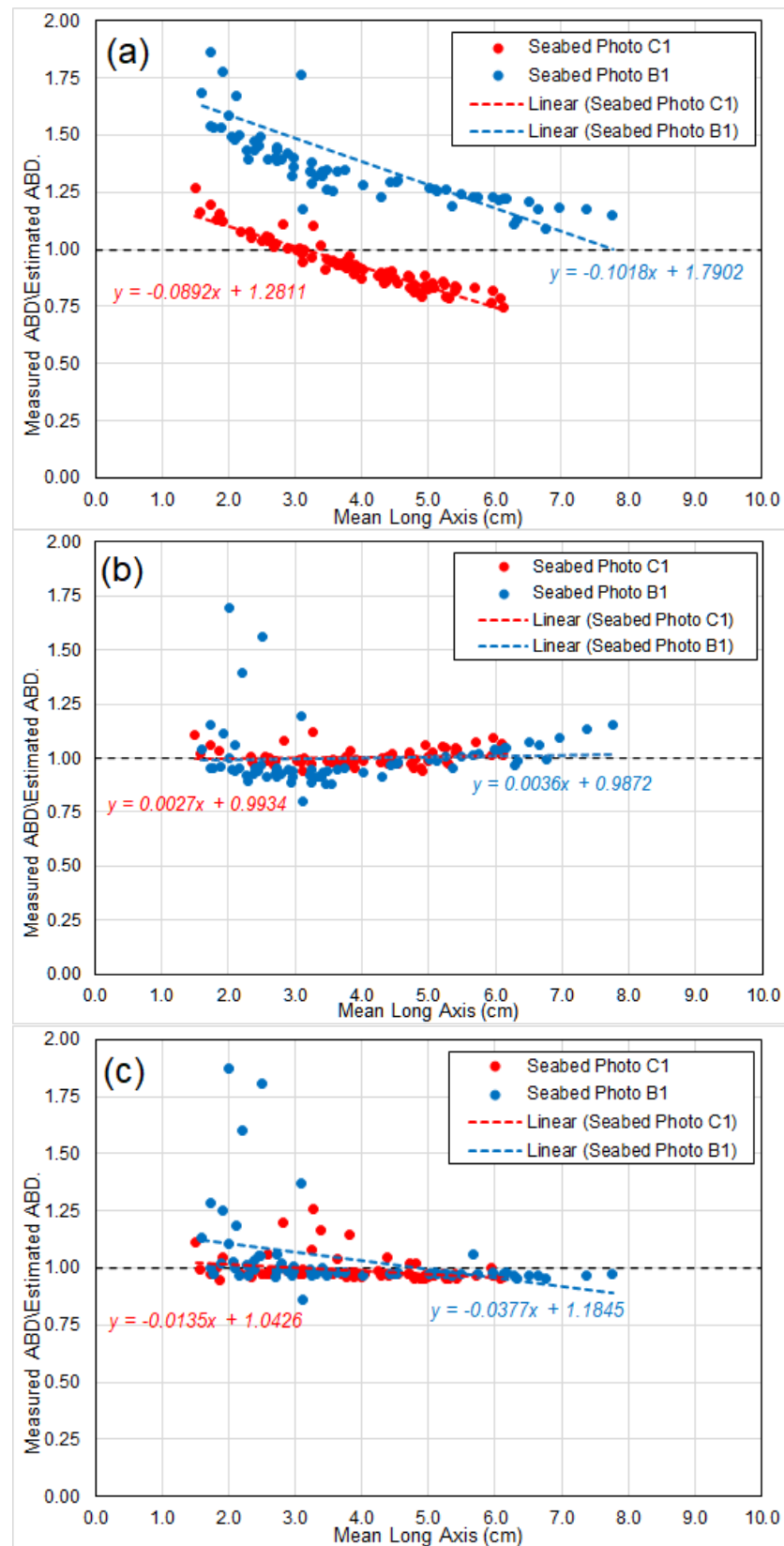


Figure 12. Comparisons of the measured Abundances and the predicted ones by the new empirical method with Dataset 3: (a) by empirical formula Equation (19); (b) by empirical formula Equation (19) with a linear adjustment; (c) by empirical formula Equation (25).

Estimates of coverage using the new empirical method show mixed but encouraging results when compared with field measurements from three areas (Figure 13). Dataset 2

Estimates of coverage using the new empirical method show mixed but encouraging results when compared with field measurements from three areas (Figure 13). Dataset 2 from TOML F shows a systematic bias independent of nodule facies types. In contrast, Dataset 3 from TOML B and C do not display any appreciable bias. This is likely related to the degree of clay-ooze sediment cover between the areas (Figure 14).

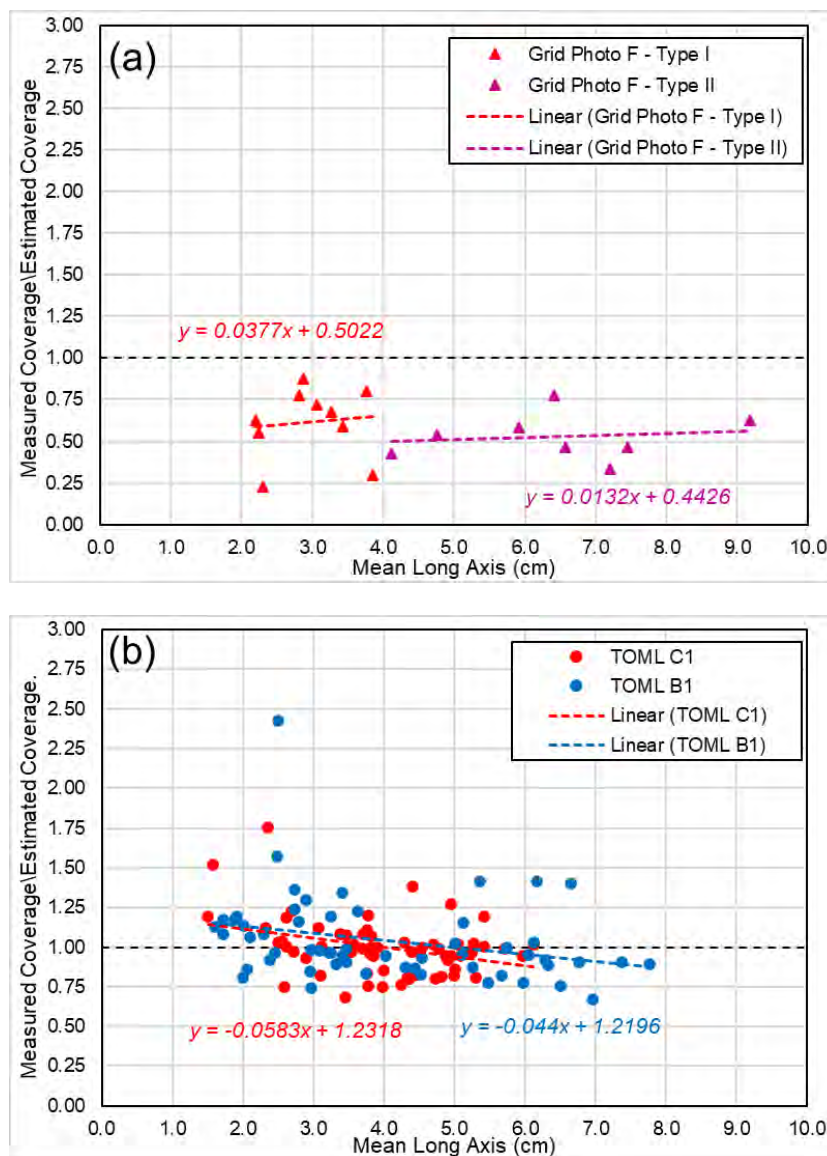


Figure 13. Comparisons of the measured Percentage Coverage and the predicted ones by the new empirical method for Datasets 2 in (a) and Dataset 3 in (b) with predictions by empirical formula Equation (15).

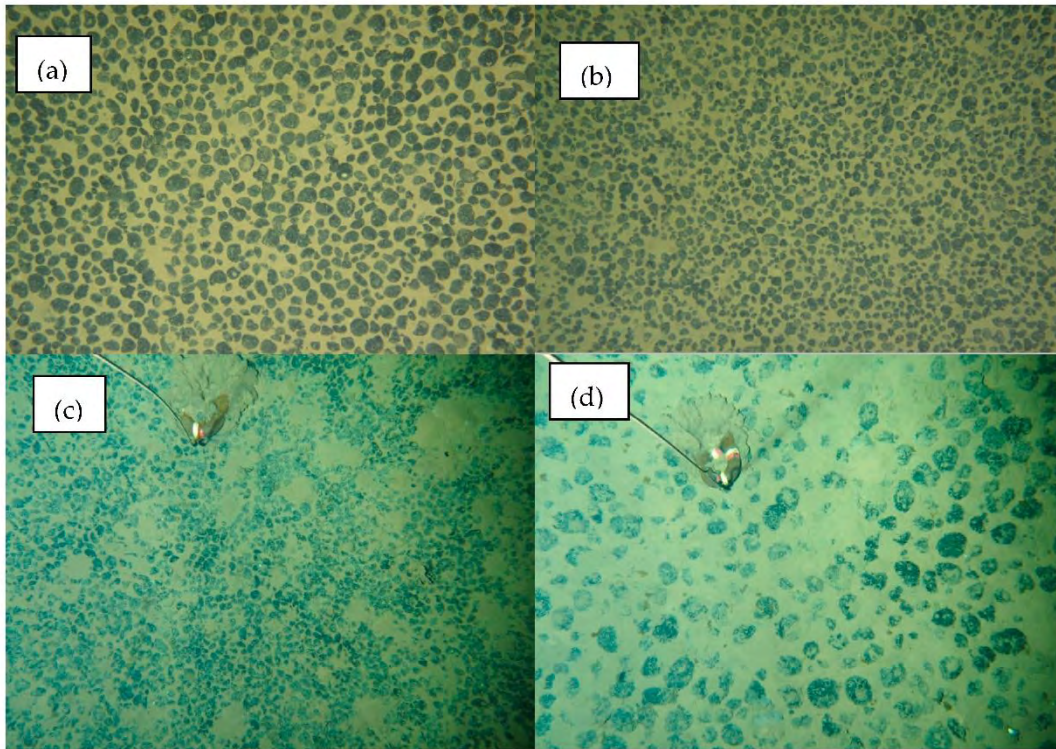


Figure 14. Seabed photos from TOML B, C and F: (a) TOML B, CCZ15-F02: 2015_08_17_032745 (b) F05: 2015_08_29_071000 (c) TOML F type 1 nodules CCZ15-B105 (d) TOML F type 2 nodules CCZ15-B99. Images in (a) and (b) are 2.4 × 4.6 m in area. Trigger weight in images (c) and (d) is 28 × 16 cm long.

7. Conclusions

It is concluded that:
 It is concluded that:

1. There is statistically significant evidence that the forms of CCZ polymetallic nodules resemble an idealized nodule model based on three hypotheses: (1) broadly ellipsoidal shape, (2) similar forms between nodules in a given area and (3) the nodule long axes follow a two-parameter Generalized Rayleigh Distribution (GRD). These three hypotheses were tested using field measurements from available nodule samples collected from CCZ. Numerical evidence supports the three hypotheses, possibly due to the relatively stable seabed environment and the long growth period of the nodules removing short-term transient effects.
2. The distribution of nodules sizes and associated parameters can be estimated using empirical formulae. Specifically, explicit empirical formulae have been derived for direct calculation of GRD parameter α and β (Equation (11)), for percentage coverage C_N (Equation (15)) and for abundance A_N (Equation (19)) or Equation (25)). These formulae are found to be sufficiently accurate for mineral resource estimation and are much easier to use than the traditional analytical methods for GRD.
3. The direct application of the formula for A_N does display a slight bias of overestimating the abundance for larger nodules. However, “unbiased accurate” prediction of nodules abundance can be achieved by applying either a “linear adjustment” or the TOML linear weight relationship.
4. For both of the TOML areas the system is consistent. This may be related to the degree of clay or silt in the mud and the mineral composition of this silt. Further related to this will be needed to better understand the general behavior of nodules in other regions. Further evidence and analysis is needed to better understand the general behavior and its derived formulae. Such analysis is needed in any event to calibrate the model in other areas.

5. The new empirical method with derived explicit formulae has shown the potential of achieving more accurate mineral resource estimation with reduced sample numbers and sizes. The new understanding of the nodule size distribution can likely also improve the efficiency of design and configuration of mining equipment with limitations regarding particle size.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Functions $F_1(\alpha)$, $F_2(\alpha)$ and $F_3(\alpha)$

For a random sample X_1, X_2, \dots, X_N of size N , following the Generalized Rayleigh Distribution (GRD) with its probability density function (PDF) $f(x)$ in the form of:

$$f(x) = 2\alpha\beta^2 x e^{-(\beta x)^2} [1 - e^{-(\beta x)^2}]^{\alpha-1}, \quad x > 0, \quad (\text{A1})$$

and its mean value \bar{X} or μ can be expressed in the integral form below:

$$\bar{X} = \mu = \frac{1}{N} \sum_{i=1}^N X_i = \int_0^{\infty} x f(x) dx = 2\alpha\beta^2 \int_0^{\infty} x^2 e^{-(\beta x)^2} [1 - e^{-(\beta x)^2}]^{\alpha-1} dx \quad (\text{A2})$$

Similarly, the means of square and cubic \bar{X}^2 and \bar{X}^3 be written, respectively, as:

$$\bar{X}^2 = \frac{1}{N} \sum_{i=1}^N X_i^2 = \int_0^{\infty} x^2 f(x) dx = 2\alpha\beta^2 \int_0^{\infty} x^3 e^{-(\beta x)^2} [1 - e^{-(\beta x)^2}]^{\alpha-1} dx \quad (\text{A3})$$

And:

$$\bar{X}^3 = \frac{1}{N} \sum_{i=1}^N X_i^3 = \int_0^{\infty} x^3 f(x) dx = 2\alpha\beta^2 \int_0^{\infty} x^4 e^{-(\beta x)^2} [1 - e^{-(\beta x)^2}]^{\alpha-1} dx \quad (\text{A4})$$

Equations (A3) and (A4) can then be combined formally as below:

$$\bar{X}^m = \frac{1}{N} \sum_{i=1}^N X_i^m = \int_0^{\infty} x^m f(x) dx \quad (\text{A5})$$

Assuming $z = (\beta x)^2$ and $dz = 2\beta^2 x dx$, Equation (A5) becomes:

$$\begin{aligned} \overline{X^m} &= 2\alpha\beta^2 \int_0^\infty x^{m+1} e^{-(\beta x)^2} [1 - e^{-(\beta x)^2}]^{\alpha-1} dx \\ &= \alpha \int_0^\infty \frac{z^{\frac{m}{2}}}{\beta^m} e^{-z} [1 - e^{-z}]^{\alpha-1} dz = \frac{\alpha}{\beta^m} \int_0^\infty z^{\frac{m}{2}} e^{-z} [1 - e^{-z}]^{\alpha-1} dz \end{aligned} \tag{A6}$$

Further defining:

$$F_m(\alpha) = \int_0^\infty z^{\frac{m}{2}} e^{-z} [1 - e^{-z}]^{\alpha-1} dz, \text{ where } m = 1, 2, 3, \tag{A7}$$

Equation (A6) can be written as:

$$\overline{X^m} = \frac{\alpha}{\beta^m} F_m(\alpha) \tag{A8}$$

From Equation (A8), when $m = 1$, the mean μ of the sample is:

$$\mu = \frac{\alpha}{\beta} F_1(\alpha) \tag{A9}$$

The variance σ^2 of the Generalized Rayleigh Distribution can be calculated as:

$$\begin{aligned} \sigma^2 &= \int_0^\infty (x - \mu)^2 f(x) dx = \int_0^\infty (x^2 - 2\mu x + \mu^2) f(x) dx \\ &= \int_0^\infty x^2 f(x) dx - 2\mu \int_0^\infty x f(x) dx + \mu^2 \int_0^\infty f(x) dx \\ &= \int_0^\infty x^2 f(x) dx - 2\mu\mu + \mu^2 = \int_0^\infty x^2 f(x) dx - \mu^2 \end{aligned} \tag{A10}$$

or

$$\sigma^2 + \mu^2 = \int_0^\infty x^2 f(x) dx = \overline{X^2} = \frac{\alpha}{\beta^2} F_2(\alpha) \tag{A11}$$

Combining Equation (A9) and (A11) gives:

$$\frac{\sigma^2 + \mu^2}{\mu^2} = \frac{\frac{\alpha}{\beta^2} F_2(\alpha)}{\frac{\alpha^2}{\beta^2} [F_1(\alpha)]^2} = \frac{F_2(\alpha)}{\alpha [F_1(\alpha)]^2} \tag{A12}$$

Defining:

$$G(\alpha) = \frac{F_2(\alpha)}{\alpha [F_1(\alpha)]^2} - 1 \tag{A13}$$

Equation (A12) can be rewritten as:

$$\frac{\sigma^2}{\mu^2} = G(\alpha) \tag{A14}$$

Or:

$$\sigma = \mu \sqrt{G(\alpha)} \tag{A15}$$

From Equation (A7), functions $F_1(\alpha)$, $F_2(\alpha)$ and $F_3(\alpha)$ can be expressed as:

$$F_m(\alpha) = \int_0^\infty z^{\frac{m}{2}} e^{-z} [1 - e^{-z}]^{\alpha-1} dz, \text{ where } m = 1, 2, 3 \tag{A16}$$

By using generalized Binomial Theorem, Equation (A16) gives:

$$\begin{aligned}
 F_m(\alpha) &= \int_0^\infty z^{\frac{m}{2}} e^{-z} \left[\sum_{k=0}^\infty \binom{\alpha-1}{k} 1^{[(\alpha-1)-k]} (-e^{-z})^k \right] dz \\
 &= \sum_{k=0}^\infty \binom{\alpha-1}{k} \int_0^\infty z^{\frac{m}{2}} e^{-z} [(-e^{-z})^k] dz \\
 &= \sum_{k=0}^\infty \binom{\alpha-1}{k} (-1)^k \int_0^\infty z^{\frac{m}{2}} e^{-(k+1)z} dz
 \end{aligned}
 \tag{A17}$$

Assuming $y = (k + 1)z$, the integral in Equation (A16) becomes:

$$\begin{aligned}
 \int_0^\infty z^{\frac{m}{2}} e^{-(k+1)z} dz &= \int_0^\infty \left(\frac{y}{k+1} \right)^{\frac{m}{2}} e^{-y} d\left(\frac{y}{k+1} \right) \\
 &= \frac{1}{(k+1)^{\frac{m}{2}+1}} \int_0^\infty y^{\frac{m}{2}} e^{-y} dy = \frac{1}{(k+1)^{\frac{m}{2}+1}} \Gamma\left(\frac{m}{2} + 1\right)
 \end{aligned}
 \tag{A18}$$

where $\Gamma\left(\frac{m}{2} + 1\right)$ is the Gamma function. Inserting Equation (A18) into Equation (A17) gives:

$$\begin{aligned}
 F_m(\alpha) &= \sum_{k=0}^\infty \binom{\alpha-1}{k} (-1)^k \frac{\Gamma\left(\frac{m}{2} + 1\right)}{(k+1)^{\frac{m}{2}+1}} \\
 &= \Gamma\left(\frac{m}{2} + 1\right) \sum_{k=0}^\infty \frac{(\alpha-1)!}{k!(\alpha-1-k)!} \frac{(-1)^k}{(k+1)^{\frac{m}{2}+1}} \\
 &= \Gamma\left(\frac{m}{2} + 1\right) \sum_{k=0}^\infty \frac{(\alpha-1)(\alpha-2)\dots[(\alpha-1-k)+1]}{(k+1)!} \frac{(-1)^k}{(k+1)^{\frac{m}{2}}} \\
 &= \Gamma\left(\frac{m}{2} + 1\right) \sum_{k=0}^\infty (-1)^k \frac{(\alpha-1)(\alpha-2)\dots(\alpha-k)}{(k+1)!(k+1)^{\frac{m}{2}}}
 \end{aligned}
 \tag{A19}$$

Noting for $\Gamma\left(\frac{m}{2} + 1\right)$ with $m = 1, 2$ and 3 ,

$$\Gamma\left(\frac{1}{2} + 1\right) = \Gamma\left(\frac{3}{2}\right) = \frac{\sqrt{\pi}}{2}, \quad \Gamma\left(\frac{2}{2} + 1\right) = \Gamma(2) = 1 \text{ and } \Gamma\left(\frac{3}{2} + 1\right) = \Gamma\left(\frac{5}{2}\right) = \frac{3}{4}\sqrt{\pi}
 \tag{A20}$$

respectively, $F_1(\alpha)$, $F_2(\alpha)$ and $F_3(\alpha)$ can then be expressed by the infinite series as:

$$\begin{aligned}
 F_1(\alpha) &= \frac{\sqrt{\pi}}{2} \sum_{k=0}^\infty (-1)^k \frac{(\alpha-1)(\alpha-2)\dots(\alpha-k)}{(k+1)! \sqrt{k+1}} \\
 &= \frac{\sqrt{\pi}}{2} \left[1 - \frac{(\alpha-1)}{\sqrt{2} * 2!} + \frac{(\alpha-1)(\alpha-2)}{\sqrt{3} * 3!} - \frac{(\alpha-1)(\alpha-2)(\alpha-3)}{\sqrt{4} * 4!} + \dots \right]
 \end{aligned}
 \tag{A21}$$

And:

$$\begin{aligned}
 F_2(\alpha) &= \sum_{k=0}^\infty (-1)^k \frac{(\alpha-1)(\alpha-2)\dots(\alpha-k)}{(k+1)! (k+1)} \\
 &= \left[1 - \frac{(\alpha-1)}{2 * 2!} + \frac{(\alpha-1)(\alpha-2)}{3 * 3!} - \frac{(\alpha-1)(\alpha-2)(\alpha-3)}{4 * 4!} + \dots \right]
 \end{aligned}
 \tag{A22}$$

And:

$$\begin{aligned}
 F_3(\alpha) &= \frac{3}{4}\sqrt{\pi} \sum_{k=0}^\infty (-1)^k \frac{(\alpha-1)(\alpha-2)\dots(\alpha-k)}{(k+1)! (k+1)^{\frac{3}{2}}} \\
 &= \frac{3}{4}\sqrt{\pi} \left[1 - \frac{(\alpha-1)}{2\sqrt{2} * 2!} + \frac{(\alpha-1)(\alpha-2)}{3\sqrt{3} * 3!} - \frac{(\alpha-1)(\alpha-2)(\alpha-3)}{4\sqrt{4} * 4!} + \dots \right]
 \end{aligned}
 \tag{A23}$$

The above infinite series are particularly useful for calculating $F_1(\alpha)$, $F_2(\alpha)$ and $F_3(\alpha)$ when α is an integer. In this case, $(\alpha + 1)$ -th terms onwards are all zero, and only the first α terms need to be included in the calculation.

Appendix B. Computation of Critical Values for Goodness-of-Fit Test of Generalized Rayleigh Distribution by Monte Carlo Simulations

The critical values y_Γ and u_Γ of the test statistics A_n^2 and V_n^2 can be computed as their percentage points using Monte Carlo simulations. Given the parameters α and β and sample size n , the numerical procedure consists of the following steps:

1. A set of random numbers of size n is generated in the interval $(0, 1)$ as values of cumulative distribution function (CDF). Equation (2) is used to back-calculate a sample X_1, X_2, \dots, X_n of size n for given α and β .
2. For a sample X_1, X_2, \dots, X_n , Equations (5) and (6), based on MLE method, are solved iteratively to estimate parameters $\hat{\alpha}$ and $\hat{\beta}$.
3. Parameters $\hat{\alpha}$ and $\hat{\beta}$ are used in Equation (2) to calculate $z_i = F(x_i)$, with values in ascending order.
4. Equation (7) is used to calculate test statistics A_n^2 and V_n^2 , using values of z_i calculated in step 3.
5. Steps 1. to 4. above are repeated to generate a sample for A_n^2 and V_n^2 .
6. The percentiles of A_n^2 and V_n^2 are calculated as critical values. The $(1 - \Gamma)$ th percentile is taken as the critical value for the level of significance of Γ .

For a set of critical value for given parameters α and β and sample size n , 250,000 Monte Carlo simulations are carried out to ensure the convergence to 2 digits. The simulated results are presented in Table A1, Figure A1, and Figure A2 below. In Figures A1 and A2 results for both 200,000 and 250,000 simulations are shown, and the relative error is within 0.1%.

Table A1. Critical values y_γ and u_γ for various shape parameters α and sample sizes n .

Shape Parameter α		1.0			1.5			2.0			2.5			3.0			3.5			4.0			
Significance Level γ		10%	5%	1%	10%	5%	1%	10%	5%	1%	10%	5%	1%	10%	5%	1%	10%	5%	1%	10%	5%	1%	
Sample Size n	100	y_γ	0.66	0.79	1.10	0.65	0.78	1.08	0.64	0.77	1.07	0.64	0.76	1.06	0.64	0.76	1.05	0.64	0.76	1.05	0.64	0.76	1.05
		u_γ	0.34	0.41	0.58	0.34	0.41	0.57	0.33	0.41	0.57	0.33	0.40	0.57	0.33	0.40	0.57	0.33	0.41	0.57	0.34	0.41	0.57
	200	y_γ	0.66	0.79	1.11	0.65	0.78	1.08	0.65	0.77	1.07	0.64	0.77	1.05	0.64	0.76	1.05	0.64	0.76	1.06	0.64	0.76	1.05
		u_γ	0.34	0.41	0.58	0.34	0.41	0.58	0.34	0.41	0.57	0.34	0.41	0.57	0.34	0.40	0.57	0.34	0.41	0.57	0.34	0.41	0.57
	300	y_γ	0.66	0.79	1.10	0.65	0.78	1.08	0.65	0.77	1.08	0.64	0.77	1.06	0.64	0.76	1.05	0.64	0.76	1.05	0.64	0.76	1.06
		u_γ	0.34	0.41	0.58	0.34	0.41	0.58	0.34	0.41	0.57	0.34	0.41	0.57	0.34	0.41	0.57	0.34	0.41	0.57	0.34	0.41	0.57
	400	y_γ	0.66	0.80	1.11	0.65	0.78	1.08	0.65	0.77	1.07	0.64	0.77	1.06	0.64	0.76	1.06	0.64	0.76	1.06	0.64	0.76	1.05
		u_γ	0.34	0.41	0.59	0.34	0.41	0.58	0.34	0.41	0.58	0.34	0.41	0.57	0.34	0.41	0.57	0.34	0.41	0.57	0.34	0.41	0.57
	500	y_γ	0.66	0.80	1.11	0.65	0.78	1.09	0.64	0.77	1.07	0.64	0.77	1.06	0.64	0.77	1.06	0.64	0.76	1.06	0.64	0.76	1.05
		u_γ	0.34	0.41	0.59	0.34	0.41	0.58	0.34	0.41	0.57	0.34	0.41	0.57	0.34	0.41	0.57	0.34	0.41	0.57	0.34	0.41	0.57

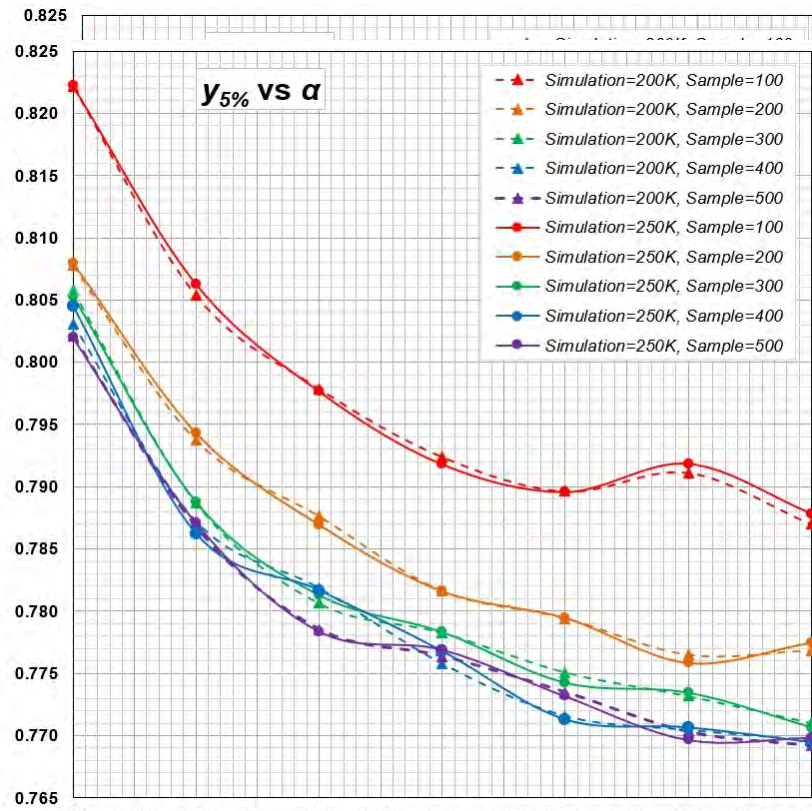


Figure A1. Critical values y_y versus shape parameters α and sample sizes n with 200,000 and 250,000 simulations.

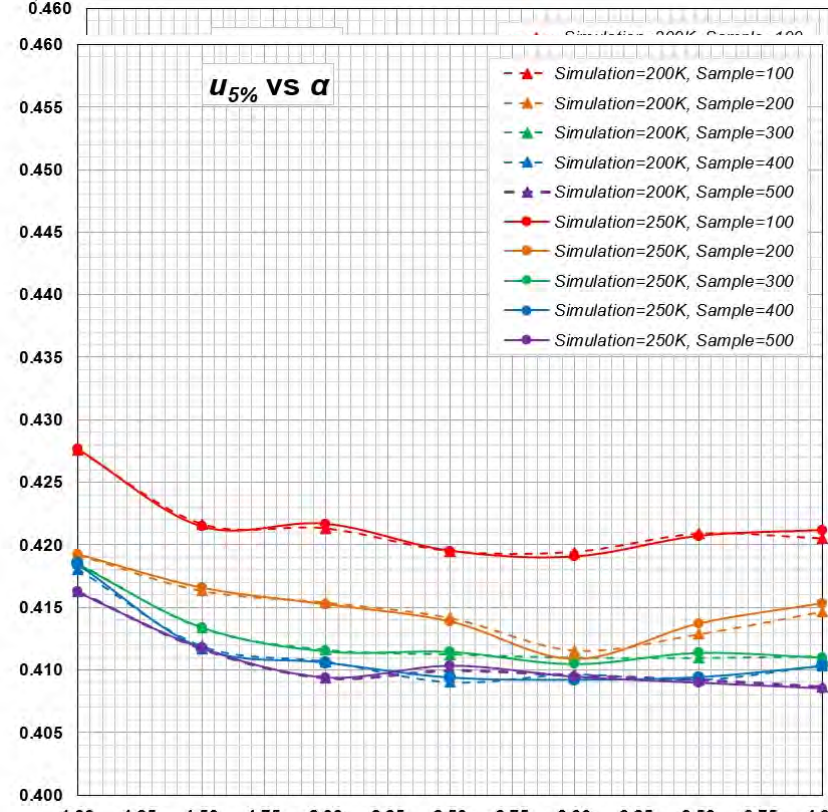


Figure A2. Critical values u_y versus shape parameters α and sample sizes n with 200,000 and 250,000 simulations.

Appendix C: Determination of Minimal Sample Size for Estimation of Statistical Distribution Using Monte Carlo Simulations

It is of practical importance to estimate the minimal sample size necessary to achieve desired accuracy of estimation. To test whether a sample size of 100 is sufficient to yield an accurate estimation of statistical distribution, 500 sets of samples with size = 100 were randomly selected from the whole sample with size = 440, and for each set of selected samples, parameters α and β are computed empirically using Equation (11), and a corresponding GRD is generated.

For a typical simulation, the mean values of α and β , calculated by averaging results from 500 simulations, are within 4%, compared with values of α and β calculated based on the whole sample (size = 440). The maximum errors for α and β between a small-sample (size = 100) and the whole sample (size = 440) is about 10% and 5%, respectively. Figures A3 and A4 show CDFs and PDFs from 10 simulations (randomly selected from a total of 500 simulations), compared with those calculated from the whole sample (size = 440). The reasonably good agreement between the results from samples with size = 100 and those from the whole sample (size = 440) indicates that a smaller sample size of 100 can generally produce a good estimation of the statistical distribution.

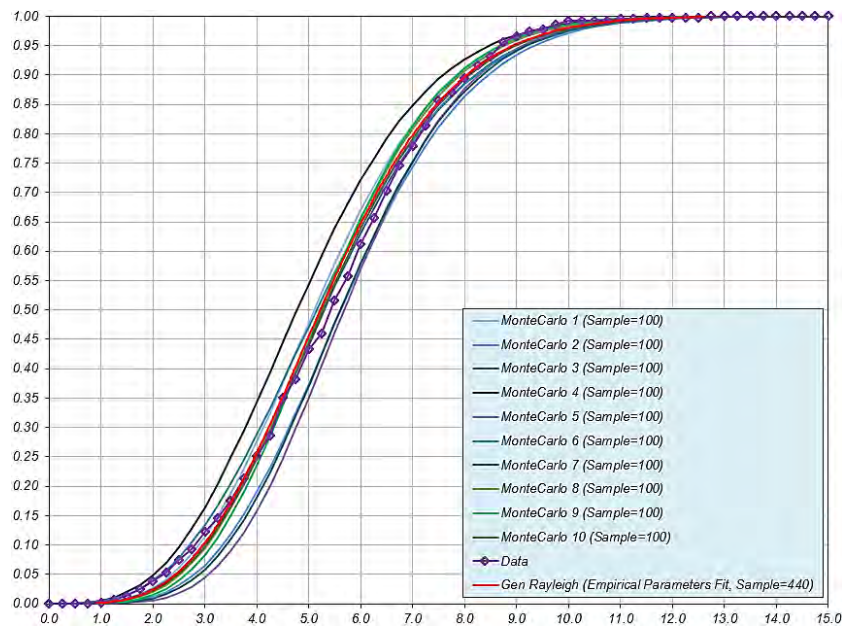


Figure A3. CDF simulated using subsets of sample with Size = 100.

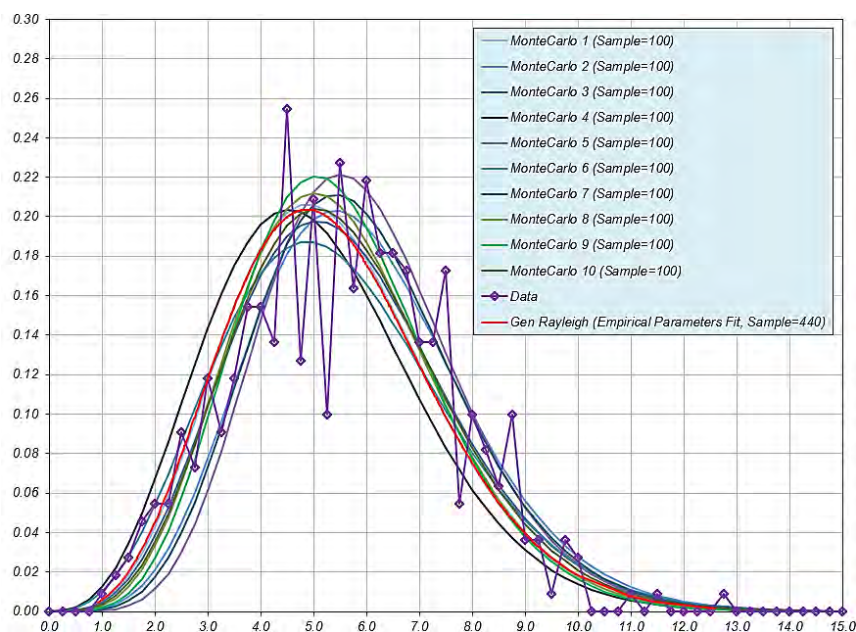


Figure A4. PDF simulated using subsets of sample with Size = 100.
Figure A4. PDF simulated using subsets of sample with Size = 100.

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Multi-scale variations in invertebrate and fish megafauna in the mid-eastern Clarion Clipperton Zone

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ABSTRACT

The abyssal seafloor of the Clarion Clipperton Zone (CCZ) in the central Pacific has the largest known deposits of polymetallic nodules and associated benthic faunal communities with high biodiversity. The environmental factors that structure these communities, both at regional and local scales, are not well understood. In this study, seabed image surveys were used to assess distribution patterns in invertebrate and fish megafauna (> 1 cm) at multiple scales in relation to key environmental factors: food supply to the seabed varying at the regional scale (hundreds of km), seabed geomorphological variations varying at the broad local scale (tens of km), and seabed nodule cover varying at the fine local scale (tens of meters). We found significant differences in megafaunal density and community composition between all study areas. Variations in faunal density did not appear to match with regional productivity gradients, although faunal density generally decreased with increasing water depth (from E to W). In contrast, geomorphology and particularly nodule cover appeared to exert strong control on local faunal abundance and community composition, but not in species richness. Local variations in faunal density and beta-diversity, particularly those driven by nodule presence (within study areas), were of comparable magnitude to those observed at a regional level (between study areas). However, regional comparisons of megabenthic assemblages showed clear shifts in dominance between taxonomic groups (perceivable even at Phylum levels) across the mid-eastern CCZ seabed, suggesting a higher regional heterogeneity than was previously thought.

1. Introduction

Global economic interest in deep-sea mining has grown since the discovery of extensive polymetallic nodule fields in the equatorial Pacific during the HMS *Challenger* expedition (Murray and Renard, 1891). Abyssal plain and hill environments of the Clarion Clipperton Zone (CCZ) in the central eastern Pacific harbour the largest known deposits of polymetallic nodules, rich in manganese, copper, nickel, and cobalt (Hein et al., 2020). Nodule fields constitute an unusual mosaic habitat in the deep sea (Simon-Lledó et al., 2019b). The hard substratum provided by nodules combined with the background soft sediment acts to increase habitat complexity (Simon-Lledó et al., 2019b), which is thought to promote the occurrence of some of the most biologically diverse seafloor assemblages in the abyss (Amon et al., 2016;

Christodoulou et al., 2020; Gooday et al., 2017; Janssen et al., 2015). However, at present, the ecology of these remote habitats is poorly understood, little is known of the environmental factors that drive biodiversity nor the scales at which these operate, and the available biogeographical information is sparse, especially towards the mid-western CCZ.

Abyssal benthic communities are strongly modulated by the flux of particulate organic carbon (i.e. food) sinking through the water column from the euphotic zone (Johnson et al., 2007; Smith et al., 2008). At the CCZ seafloor, where depositional fluxes are generally low (e.g. 1–2 mg $C_{org} m^{-2} d^{-1}$; Lutz et al., 2007; Volz et al., 2018), communities typically exhibit low faunal abundance but a surprisingly high biodiversity (e.g. Glover et al., 2002; Janssen et al., 2015). Regionally, the closer proximity of the southern areas of the CCZ to the equatorial Pacific

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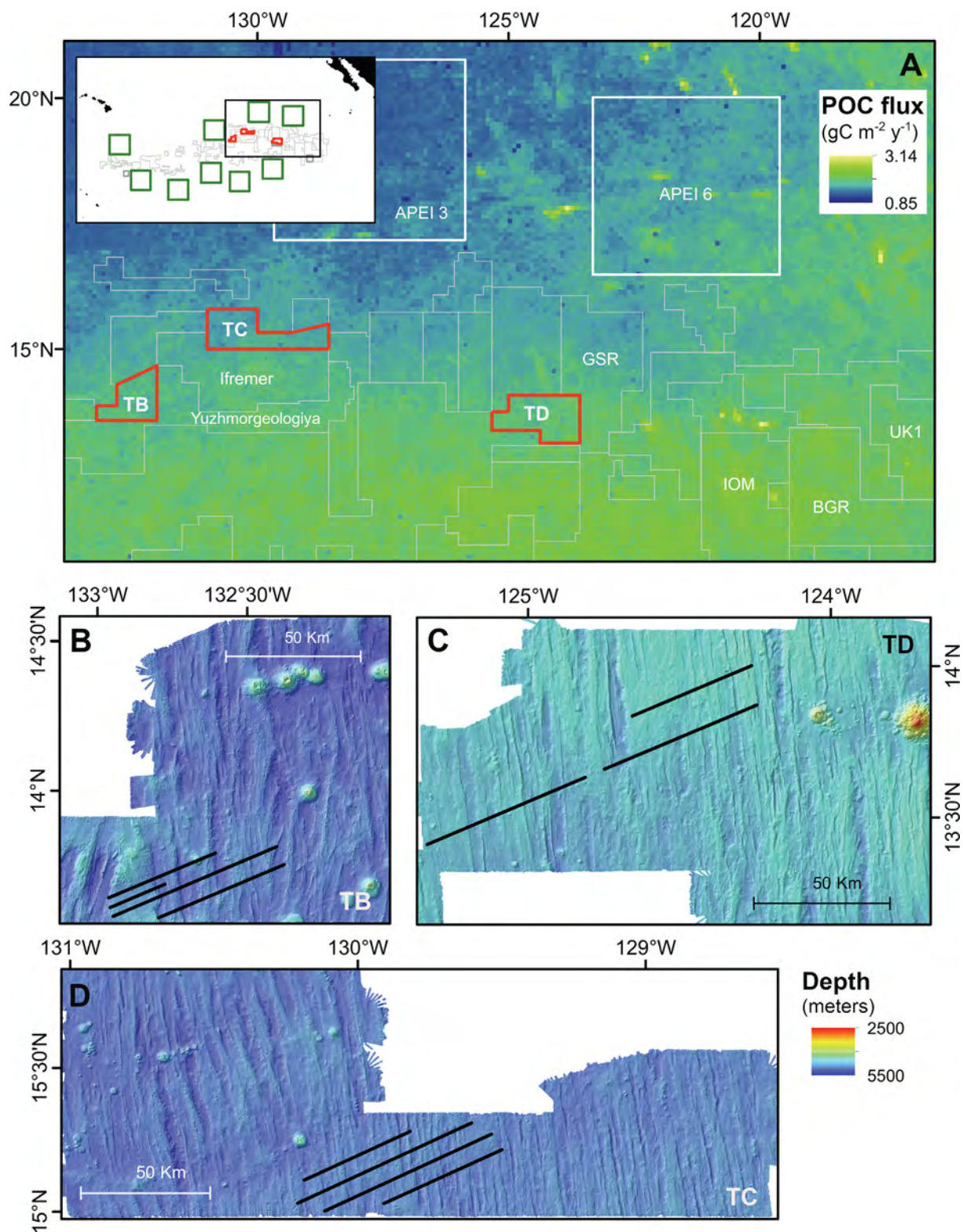


Fig. 1. Survey locations within the mid-eastern Clarion Clipperton Zone (CCZ). (A) Nutrient flux from surface to the seafloor across the mid-eastern CCZ, as reported by Lutz et al. (2007). Red polygons represent the three TOML exploration areas (TB, TC, and TD) target of the present study. Grey polygons represent other exploration licensed areas. White polygons represent Areas of Particular Environmental Interest (APEIs). Image-based megafauna studies have been conducted in all areas with name displayed (see Discussion). A map is inset depicting the location of this sector (grey rectangle) within the CCZ. (B–D) Bathymetric survey charts of the three study areas with detail of image transect locations (dark lines). (B) TOML Area B. (C) TOML Area D. (D) TOML Area C. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

high-productivity zone (e.g. Pennington et al., 2006) has been linked with enhanced invertebrate density and species richness in the benthic communities found beneath (Błażewicz et al., 2019; Glover et al., 2002; Vanreusel et al., 2016; Veillette et al., 2007; Wilson, 2017). Differences in density, diversity and/or body size correspond with productivity gradients observed among the CCZ region in dominant smaller-sized invertebrate groups, such as Polychaeta (Bonifácio et al., 2020; Wilson, 2017), Tanaidacea (Błażewicz et al., 2019; Wilson, 2017), and Nematoda (Hauquier et al., 2019; Lamshead et al., 2003; Macheriotou et al., 2020), although Isopoda show more variable biogeographical patterns (Brix et al., 2019; Wilson, 2017). Fewer assessments have been conducted at a regional scale (e.g. hundreds of km) in megafauna groups (e.g. invertebrates and fish > 1 cm). Vanreusel et al., (2016) depicted the substantially lower benthic megafauna density in the Area of Particular Environmental Interest 3 (APEI3) compared to the more productive southern areas in the eastern CCZ, in both mobile (e.g. Holothuroidea) and sessile taxa (e.g. Alcyonacea soft corals). In contrast, a recent study conducted across the western border of the CCZ (Kiribati EEZ) failed to find any correspondence between megafaunal community features and nutrient flux gradients (Simon-Lledó et al., 2019d). Further assessment of the correspondence between nutrient flux variations and the megafauna -measurable across large seabed areas using imagery data- can be important to better define biogeographical provinces in the CCZ, particularly if coupled with other environmental factors operating at more local scales.

Environmental drivers operating at a local scale within the CCZ seabed, e.g. within exploration license areas or APEIs, have the capacity to drive changes in the benthic community, particularly in megafauna assemblages (Simon-Lledó et al., 2019a,b). At a broader scale, e.g. tens of km, variations in megafaunal abundance and composition have been encountered between adjacent plains, hills and troughs in invertebrate (Simon-Lledó et al., 2019a) and bait-attending (Leitner et al., 2017) assemblages, comparable to variations in other abyssal hill and plain environments in the north Atlantic (Durden et al., 2015; Stefanoudis et al., 2016). At the finer scale, of tens of meters, variations in faunal abundance and community structure have been described between seabed areas with different nodule availability for megafauna (Amon et al., 2016; Simon-Lledó et al., 2019b), macrofauna (Chuar et al., 2020; Mullineaux, 1987), meiofauna (Miljutina et al., 2010; Singh et al., 2016), and foraminifera (Kamenskaya et al., 2013; Simon-Lledó et al., 2019b). These changes are thought to be related to the increased habitat heterogeneity associated with the presence of nodules, as nodule-dwelling taxa can represent 60–70% of the total numerical abundance of fauna present in nodule fields (Amon et al., 2016; Simon-Lledó et al., 2019b). Broad-scale geomorphological variations can regulate bottom water speeds and particle deposition rates in the CCZ (Skorniyakova and Murdmaa, 1992), which are factors that are presumed to modulate nodule growth (Mewes et al., 2014). However, there is no simple relationship between nodule cover and seafloor morphology (Peukert et al., 2018) and hence the effect of each factor on benthic fauna is best assessed independently.

Sixteen nodule mining exploration contract areas have been so far granted in the CCZ by the International Seabed Authority (ISA, 2020), the institution responsible for the management of these resources along with the conservation and protection of the marine environment (Lodge et al., 2014). The ISA requires contractors to document the biota in their license area (Durden et al., 2018; Jones et al., 2019), as the effective management of potential exploitation activities will rely on such baseline information. In 2011, Tonga Offshore Mining Limited (TOML) was granted 6 exploration areas (TOML A, B, C, D, E, and F) by the ISA (NM, 2016) that are spread throughout a wide longitudinal range from west to east across the CCZ. Two expeditions to these sites were conducted by TOML in 2013 and 2015 to map the seafloor and to collect geotechnical and environmental baseline data (NM, 2016). During these expeditions, a vast area of seafloor (~75,000 m²) was imaged at high photographic resolution across three of the exploration-licensed

sites (i.e. TOML B, C, and D; Fig. 1) in the mid-eastern CCZ.

In this paper we present an analysis of megafaunal distributions based on seabed imagery collected in three of TOMLs contract areas (B, C and D) in the CCZ. We explore variations in megabenthic community structure at the large (regional) scale between sites and couple this with independent assessments for each contract area performed at the finer (local) scale, to investigate how variations in the presumed food supply regime, seabed geomorphology, and nodule cover may affect the distribution of megafauna in the mid-eastern CCZ abyss. We discuss these results in the context of similar studies previously conducted in the eastern CCZ to draw preliminary biogeographical patterns along this region.

2. Methods

2.1. Study areas

Data used in this study were acquired during the RV *Mt Mitchell* (2013) and the RV *Yuzhmorgeologiya* (2015) expeditions (NM, 2016) to the mid-eastern CCZ TOML exploration areas B, C, and D, between 13 and 15° N and 123 to 133° W, in the Pacific Ocean (Fig. 1). Four target areas of about 2000 km² were chosen across TOML areas B, C and D: respectively B1, C1, D1 & D2 (NM, 2016) and hereafter referred to as study areas TB (TOML B1), TC (TOML C1), and TD (TOML D1 + D2). Areas TB and TC are ~350 km apart at a similar water depth (~5000 m, Table 1), while Area TD area is ~500 m shallower, ~550 and ~850 km away from areas TC and TB respectively. As is commonplace in central areas of the CCZ (Olive et al., 2015), the seafloor landscape of the three study areas is comprised of a succession of parallel abyssal hills and

Table 1

Survey details and environmental features of each study area. **Box-core surveys:** mean abundance and proportions of different nodule type- and size-classes. **Image surveys (this study):** water depth (mean value and range) across the images collected; mean seabed nodule cover across the images collected; total abundance and number of megafauna morphotypes detected in images. **Other data:** POC flux to the seabed (mean value and range within the surveyed area).

	TOML B	TOML C	TOML D
Box-core surveys ^{*1}			
Nodule abundance (wet kg m ⁻²)	9.93 ± 8.25	7.41 ± 5.54	12.71 ± 7.53
Nodule type			
– Smooth (S)	14%	27%	9%
– Smooth-rough (SR)	62%	73%	74%
– Rough (R)	24%	0%	16%
Nodule size (max. diameter)			
– Small (< 2 cm)	32%	20%	14%
– Medium (2–5 cm)	29%	60%	31%
– Large (> 5 cm)	39%	20%	56%
Image surveys			
Images collected (usable)	6,932	8,124	5,611
Seabed area imaged (m ²)	24,955	29,246	20,200
Water depth (m)	4917 (4418–5175)	4926 (4817–5065)	4557 (4345–4750)
Mean nodule cover (%)	33.7 ± 24.0	37.3 ± 26.8	13.2 ± 10.6
Individuals			
(invertebrates)	3567	3377	8902
Total taxa			
(invertebrates)	168	145	189
Individuals (fish)	46	83	76
Total taxa (fish)	11	14	10
Other data (from lit.)			
POC flux (g C m ⁻² y ⁻¹) ^{*2}	1.58 (1.53–1.61)	1.53 (1.50–1.56)	1.58 (1.51–1.62)

*1 Obtained from NM NI 43-101 Technical report, 2016.

*2 Derived from Lutz et al. (2007).

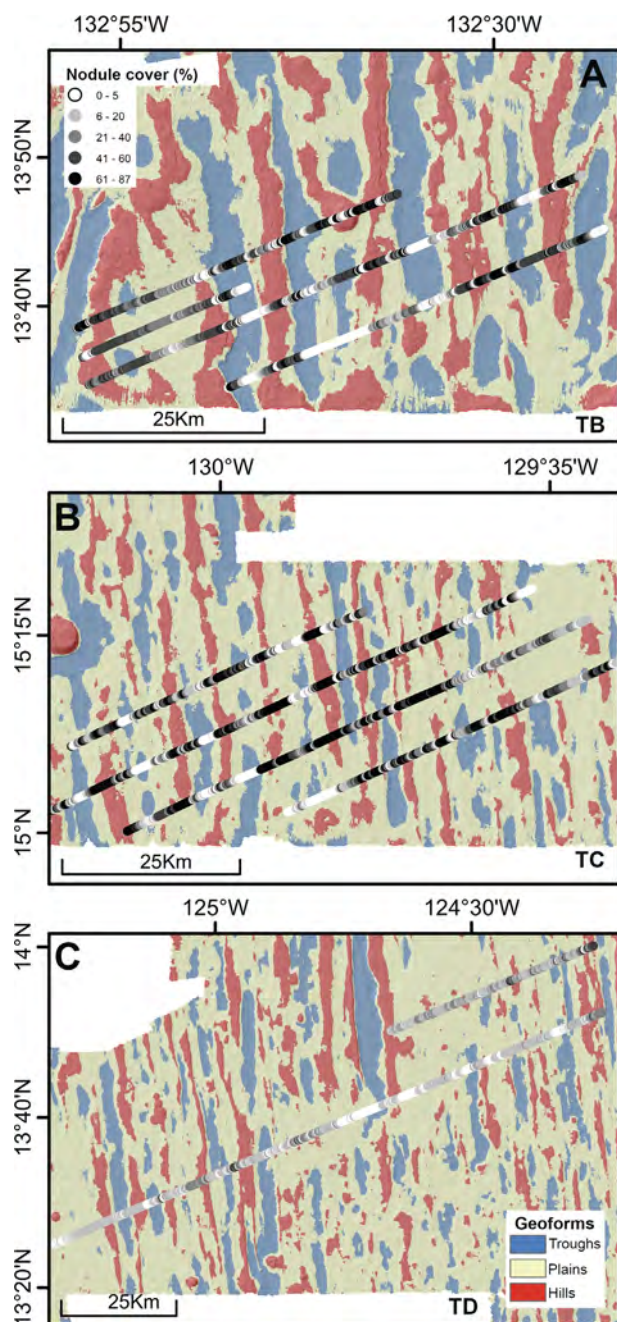


Fig. 2. Variations in seabed geomorphology and nodule-cover mapped within each TOML study area. Lines represent image survey locations. (A) Area TB. (B) Area TC. (C) Area TD.

shallow troughs oriented north–south between dispersed flatter areas (Fig. 1), with a depth range (e.g. hilltops to trough bottom) between 300 and 500 m (see Fig. A1).

The seafloor of the three study areas is composed of unconsolidated sediment and polymetallic nodules with notable differences in shape (e.g. smooth, S; rough, R; smooth-rough, SR) and size (maximum diameter: small < 2 cm; medium 2–5 cm; large > 5 cm). The shape of nodules is thought to be controlled by the formation mechanism, with the smooth nodules being formed predominantly by hydrogenetic growth, the rough nodules by diagenetic growth and the smooth-rough type being formed at the sediment-water interface with hydrogenetic growth on top and diagenetic growth on the underside (NM, 2016). Area TC has very few large nodules with medium sizes and SR shapes dominating in box-core samples (NM, 2016; Table 1). Nodules in areas

TB and TD are mostly of SR type and exhibit a wider range of sizes, although the proportion between nodule size categories was more even in Area TB than in TD, as substantially larger nodules were found in box-core samples collected in Area TD (NM, 2016; Table 1). Consequently, although nodule cover (% seabed surface, in images) was generally lower in Area TD than in areas TB and TC (see Section 2.2 and Fig. 2), the mean nodule abundance (wet kg, in box-core samples) was higher within Area TD (NM, 2016; Table 1). Additionally, two types of ferromanganese crusts were observed across the three study areas, all commonly found at the CCZ (e.g. Radziejewska, 2014). Massive crust 5–10 cm thick and typically found in blocks of 20–50 cm diameter (and occasionally as pavement); while crustal-nodules are small to medium sized (diameter < 20 cm) discrete fragments of ferro-manganese that can grade into nodules (NM, 2016). In total, crusts were found in ~0.6% of areas surveyed, with crustal nodules more common (~0.5%) and massive crusts being present only ~0.1% of the seabed mapped (NM, 2016). Zeolite sheets, a third crust-like material that is very rarely encountered (Venkatarathnam and Biscaye, 1973), were identified in just a few locations in Area TB, and in one location in Area TD (NM, 2016).

2.2. Environmental assessment

2.2.1. Bathymetric mapping and landscape characterization

Bathymetric data were used to map different geomorphological units (i.e. geomorphs) within each study area. Multibeam data were collected with the shipboard Kongsberg EM120 MBES system (191 beams) and processed using CARIS HIPS and SIPS software (TeledyneCARIS; v8.0). The resultant digital elevation model (60 m horizontal resolution) was used to calculate a broad bathymetric position index (BPI; Weiss, 2001) using the Benthic Terrain Modeler tool (Wright et al., 2012) implemented in ArcGIS v10.2 (ESRI, 2012). BPI was calculated using an inner radius of 2.5 km and an outer radius of 5 km to match the horst and graben structure that typically shapes the central areas of the CCZ (usual wavelength: 10 km W-E; e.g. Olive et al., 2015). After visual inspection of the resultant datasets, classification thresholds were set to map hills (BPI > 50), plains (BPI: –50 to 50), and troughs (BPI < –50) within each study area (Fig. 2; Fig S1). Data were projected in Universal Transverse Mercator projection - Zones 8 N (Area TB), 9 N (Area TC) and 10 N (Area TD) - using the World Geodetic System 1984 datum.

2.2.2. Image data collection

Seafloor images were collected using a digital camera (Canon D60; 3456 × 2304 pixels) mounted on the towed camera system Neptune, developed by the Russian marine institute JSC Yuzhmoregeologiya (NM, 2016). The Neptune system was towed at a speed of 0.1–0.2 m s⁻¹ and pictures were taken at an altimeter-triggered altitude of 3.5 m above the seafloor, with an interval of at least every 30 s to avoid overlap between frames. At the target altitude, individual photographs imaged 3.6 m² of seabed. A total of 11 image transects were collected using the Neptune system across the three study areas (Figs. 1 and 2). Four transects were surveyed in Area TB (total seabed area: 24,955 m²), four in Area TC (total seabed area: 29,246 m²), and 3 in Area TD (total seabed area: 20,199 m²). The full resultant dataset comprised a total of 20,667 non-overlapping images, representing a total seafloor area of 74,401 m² (Table 1).

2.2.3. Nodule cover assessment

Nodule cover (%) of the seabed was quantified in each image using a custom MATLAB (The Math Works Inc.) routine based on colour contrast. This routine performed a binary classification of each image pixel, e.g. sediment (bright coloured) or nodule (dark coloured) substrate, based on visually determined RGB thresholds, to then estimate the approximate seafloor exposed area composed by nodules or rocks in each image.

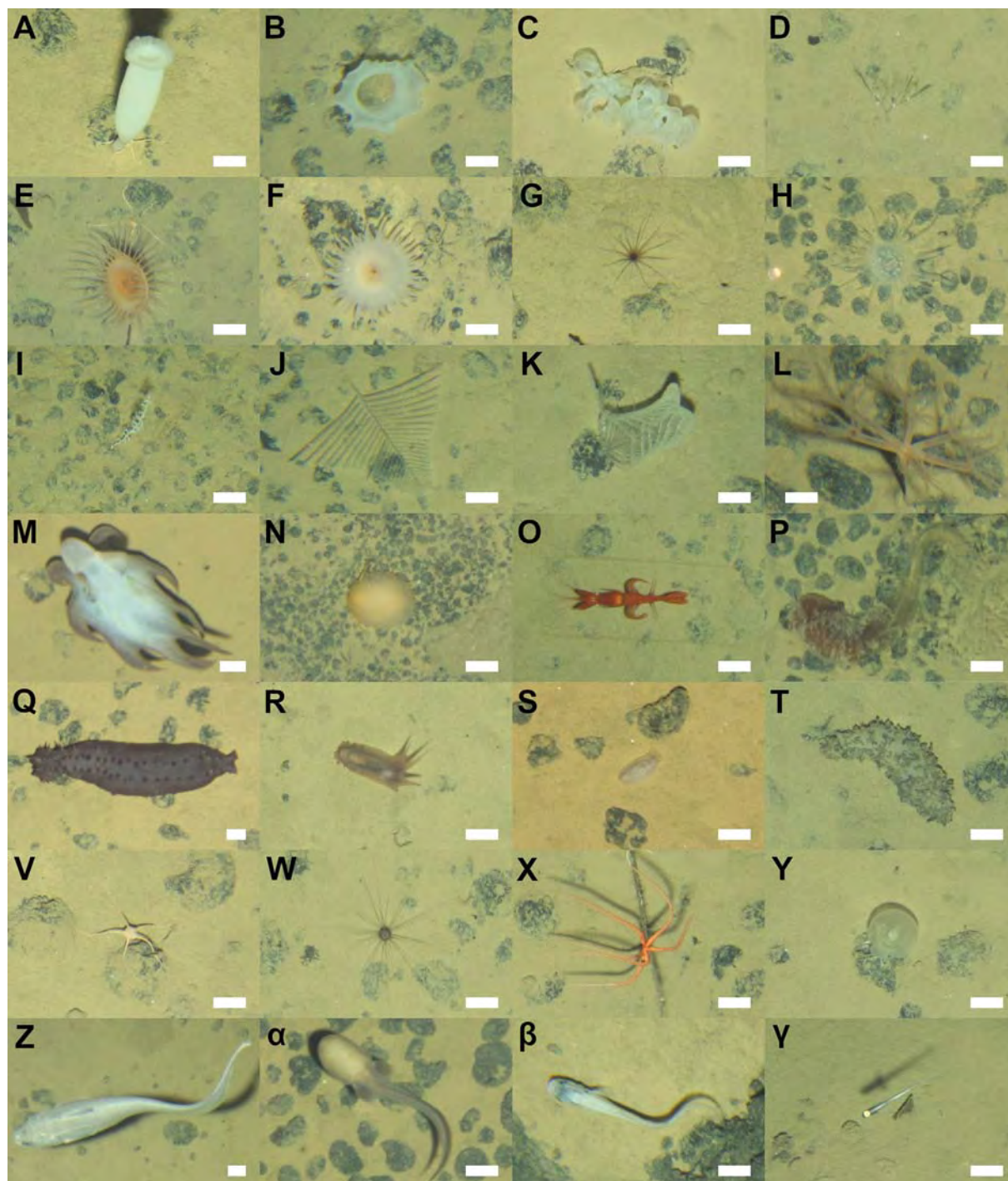


Fig. 3. Examples of megafauna photographed during towed-camera surveys. Scale bar = 5 cm. (A–Z) Invertebrates. (A) Euplectellidae mtp-5. (B) *Holascus euonyx* sp. inc. (C) Porifera mtp-77. (D) Bryozoa mtp-5. (E) Actiniaria mtp-9. (F) Actiniaria mtp-2. (G) Ceriantharia mtp-1. (H) Corallimorpharia mtp-3. (I) *Bathygorgia* sp. mtp-5. (J) *Schizopathes* sp. mtp-1. (K) *Abyssopathes lyra* sp. inc. (L) *Umbellula* sp. mtp-3. (M) *Grimpot euthis* sp. mtp-1. (N) Nudibranchia mtp-1. (O) *Cerataspis monstrosus* sp. inc. (P) Torquaratoridae mtp-5. (Q) *Psychronaetes hansenii* sp. inc. (R) *Amperima* sp. mtp-3. (S) *Ellipinion* sp. mtp-1. (T) *Pseudostichopus* sp. mtp-2. (V) *Ophiosphalma glabrum* sp. inc. (W) *Aspidodiadema* sp. mtp-1. (X) *Freyastera* sp. mtp-2. (Y) Phlebobranchia mtp-16. (Z–γ) Fishes. (Z) *Coryphaenoides* sp. (α) *Typhlonus nasus*. (β) *Leucicorus* sp. (γ) *Ipynops meadi* sp. inc.

2.3. Biological assessment

Images were annotated using a two-step approach. Metazoan megafauna specimens (> 1 cm) were first detected and then identified to the lowest taxonomic hierarchy possible (morphotype [mtp]: typically Genus or Family level) using BIIGLE 2.0 (Langenkämper et al., 2017). To ensure consistency in specimen identification, abyssal-Pacific standardized megafauna catalogues (invertebrates and fish, some

examples shown in Fig. 3) were compiled from previous studies in the basin and by reference to existing literature (Amon et al., 2017; Dahlgren et al., 2016; Drazen et al., 2019; Kersken et al., 2019; Molodtsova and Opresko, 2017; Simon-Lledó et al., 2019b, 2019c, 2019d). The likely feeding behaviour of each morphotype was inferred from similar organisms described in the literature. Although xenophophores were the most abundant specimens on the seabed (up to 15–20 tests per image) these were not included in this study as it is not

possible to determine whether foraminiferal tests are alive in images (Hughes and Gooday, 2004). Similarly, invertebrates living in a shell or tube (e.g. most polychaete and gastropod taxa) were also excluded from the analyses. Specimen counts in each image are provided in the Supplementary material: Appendix A.

2.3.1. Data analysis

Patterns in diversity and distribution of fauna were investigated at different scales: i) regionally, between geographically distant study areas (hundreds of km: areas TB, TC, and TD), ii) locally, at a broad-scale, between different geomorph types of each study area (tens of km: Troughs, Plains, and Hills), and iii) locally, at a fine-scale, along the gradient of seabed nodule-cover of each study area (tens of meters; nodule cover levels L1 to L5). A different analytical approach was applied to conduct each of these three assessments. A stratified random sampling design (Andrew and Mapstone, 1987) was used for the regional assessment, with true replication across study areas. However, the information needed to assess local patterns was only available from photographic/terrain analysis (nodule abundances) and mapping work both done after sampling. Thus, to control the impact of the physical sample size on the estimation of ecological parameters, we chose to apply a modified form of bootstrapping (Davison and Hinkley, 1997; Manly, 2007) to explore variations between different strata in the local assessments. Resampling techniques provide robust estimates of variability and confidence intervals of sample parameters (Crowley, 1992; Rodgers, 1999), and are particularly well suited to analyse data derived from survey designs that lack true sample replication (see e.g. Simon-Lledó et al., 2019b, 2019d). Note though that given the relatively low total number of fish megafauna observations (208 specimens), and that some deep-sea fish groups can exhibit avoidance behaviour to towed camera systems (e.g. McIntyre et al., 2015), fish distribution data were analysed separately from invertebrates and using a more simplistic approach (i.e. no sample replication). Total fish observations were collated for each of the strata of interest targeted in the study (regional study areas, local geomorphs, and local nodule cover levels) relative to the total seabed area sampled and results are consequently presented with no associated error margins. Data processing and analyses were implemented in R (R Core Team, 2017) using functions provided in the ‘vegan’ package (Oksanen et al., 2018), unless specified differently.

2.3.1.1. Regional assessment. Image data (faunal records in images) were pooled for each separate study area ($n = 3$: areas TB, TC, and TD) to investigate variations in faunal characteristics at the regional scale. Following recommendations for optimal image-based megafauna sampling at the CCZ (Ardron et al., 2019; Simon-Lledó et al., 2019a), image data from each study area were randomly sampled without replacement to generate replicate samples with a fixed minimum size of 500 individuals (range: 500–503 ind.). This process yielded 7 replicate samples for Area TB, 6 for Area TC, and 17 for Area TD, each encompassing a different seabed area coverage (range: 1098–4424 m²). A set of ecological parameters were calculated for each replicate sample: numerical density (ind. m⁻²) and Hill’s diversity numbers of order 0 and 2 (Jost, 2006), respectively morphotype richness (S_i) and the inverse form of Simpson’s index (1/D), to explore both the richness and the evenness components of diversity (Magurran, 2004). Additionally, morphotype density (S_A) was calculated following a controlled seabed-area approach: images were randomly resampled without replacement to generate replicate samples with a fixed size of 1000 m² (278 images), which yielded 24 replicate samples for Area TB, 29 for Area TC, and 20 for Area TD, each with a different specimen count (range: 70–565 ind.).

The statistical significance of variations in faunal density and diversity between study areas was tested using generalized linear models (GLM; Dobson and Barnett, 2008), as implemented in the ‘car’ package (Fox et al., 2016). Homogeneity of variance and probability-distribution assumptions were verified by visual inspection of model

histograms and QQ plots. Models were fitted with Gaussian errors (Freund and Littell, 1981). Where significant differences were detected in global tests, multiple comparisons tests were conducted between individual study areas using the ‘multcomp’ package (Hothorn et al., 2017), p-value adjustments for multiplicity were made using the ‘mv’ single-step procedure (Hasler and Hothorn Ludwig, 2011). The effect size measure η^2 (eta-squared, Levine and Hullett, 2002) was also calculated to assess magnitude of the variations encountered, using the ‘sjstats’ package (Lüdecke, 2018).

Variations in community composition between study areas were assessed following an abundance-based multivariate approach. Dissimilarity in faunal composition between all pairs of (c. 500 ind.) replicate samples was calculated using the Bray-Curtis dissimilarity measure, i.e. beta-diversity (β_{BC}), based on square-root transformed faunal abundance. Non-metric multidimensional scaling (MDS) ordination was conducted, to visualize the rate of dissimilarity between all pairs of replicate samples. A one-way permutational MANOVA (PERMANOVA) analysis (Anderson, 2001) with follow-up pairwise tests was used to test for statistically significant variations in assemblage composition between study areas.

Taxon accumulation curves were calculated to assess the representability of the sampling conducted, following Colwell et al. (2012), by random resampling of pooled image data for each study area 100 times without replacement forming increasingly larger sampling units, using EstimateS v.9.1 software (Colwell, 2013). Additionally, rank-abundance and taxa intersection plots between sites were also generated (Supplementary material: Appendix A).

2.3.1.2. Local assessments

2.3.1.2.1. Geomorphological strata (broad-scale). Image data were split for each geomorph (i.e. Troughs, Plains and Hills) within each separate study area to investigate variations in faunal characteristics between geomorphological units. This survey design resulted in 9 subsets (three for each study area) with markedly uneven sample sizes, e.g. specimen counts in each subset ranged between 765 and 5469 individuals (see Table A2). To implement the bootstrap, each image data subset was randomly resampled with replacement until a minimum of 500 individuals were encountered (range: 500–502 ind.), and that process was repeated 1000 times for each geomorph type. The same set of ecological parameters assessed at the regional scale were calculated for each bootstrap-like sample: numerical density (ind. m⁻²); morphotype richness (S_i), and the inverse form of Simpson’s index (1/D). Morphotype density (S_A) was also calculated following a controlled seabed-area approach: images were randomly resampled with replacement to generate bootstrap-like samples with a fixed size of 1000 m² (278 images). Mean values of these parameters were calculated from each bootstrap-like sample set, together with corresponding 95% confidence intervals based on the simple percentile method (Davison and Hinkley, 1997). We report statistical assessments of variations in ecological parameters between study areas by comparisons of the 95% confidence intervals, i.e., the upper limit of a given estimate must be lower than the lower limits of the estimate that is compared to. Such cases are significant at $p < 0.05$, though the true (undetermined) p-value will, necessarily, be considerably lower. Variations in community composition were assessed on a set of 10 randomly selected bootstrap-like samples for each geomorph type (in each study area), based on β_{BC} calculated from square-root transformed faunal abundance, and then visualised using MDS ordination.

2.3.1.2.2. Seabed nodule cover (fine-scale). Image data were ordered by estimated nodule cover within each study area to investigate variations in faunal characteristics along the nodule cover gradient. Image data were then divided into 5 subsets at nodule-cover breakpoints chosen to yield approximately equal numbers of megafaunal observations in each subset (levels L1 to L5, each representing a different nodule-cover range in each study area). This survey design resulted in 15 subsets (five for each study area) with

markedly larger sizes in the subsets of Area TD, e.g. Area TB and TC subsets were composed of 713 and 675 individuals (respectively) while area TD subsets were composed of 1780 individuals (see Table S3). We applied the same form of bootstrapping as used in the local geomorphological assessment; each image data subset was randomly resampled with replacement until a minimum of 500 individuals were encountered (range: 500–504 ind.), and that process was repeated 1000 times for each nodule-cover level. Again, numerical density (ind. m^{-2}), morphotype richness (S_1), and the inverse form of Simpson's index ($1/D$) were calculated for each bootstrap-like sample while morphotype density (S_A) was calculated following a controlled seabed-area (c. 1000 m^2) approach. Mean values and 95% confidence intervals of these parameters were calculated from each bootstrap-like sample set. We report statistical assessments of variations in ecological parameters between study areas by comparisons of the 95% confidence intervals. Variations in community composition were assessed on a set of 5 randomly selected bootstrap-like samples for each nodule-cover level (in each study area), based on β_{BC} calculated from square-root transformed faunal abundance, and then visualised using MDS ordination.

3. Results

3.1. Invertebrate megafauna

3.1.1. Variations in standing stock

Mega-faunal density exhibited statistically significant regional variations ($F_{[2,27]} = 3748$, $p < 0.001$, $\eta^2 = 0.996$). Mean faunal density in Area TD (0.44 ind. m^{-2}) was about three times higher than in Area TB (0.14 ind. m^{-2}) and almost four times higher than in Area TC (0.11 ind. m^{-2} ; Fig. 4A). Variations in density were statistically significantly different across all study areas (pairwise comparisons, $p < 0.001$). Density of different functional groups was consistently higher in Area TD. For instance, mean density of sessile suspension feeding fauna (predominantly sponges and anemones) was substantially higher in Area TD (0.22 ind. m^{-2}) than that in both TB and TC (0.09 and 0.06 ind. m^{-2} , respectively); in addition, mean density of mobile deposit-feeding fauna (predominantly brittle stars) was > 5 times higher in Area TD (0.17 ind. m^{-2}) than in TB and TC (0.03 ind. m^{-2} , in each area). Mean density of mobile predators & scavenger fauna (predominantly crustaceans) was also substantially higher in Area TD (2.01 ind. $100 m^{-2}$) than in areas TB (0.70 ind. $100 m^{-2}$) and TC (0.76 ind. $100 m^{-2}$).

Locally, faunal density exhibited substantial variations, both between different geofoms and across the nodule-cover gradient mapped in each study area. At the broad scale, substantially and consistently higher faunal densities were found in Hill areas (e.g. higher mean values and non-overlapping confidence intervals) than in Plain and particularly Trough geofoms (Fig. 4B–D). In Area TD these differences were more pronounced and the faunal density found in Troughs was also substantially lower than in Plain areas (Fig. 4D). At a finer scale, faunal density in all study areas was substantially and consistently reduced in the lowest nodule cover level (L1) compared to areas with higher nodule-cover (L2 to L5), where similar mean densities were found (Fig. 5A). This pattern was more pronounced in Area TD, where faunal density increased from 0.36 ind. m^{-2} in the lowest nodule cover level (L1, mean nodule-cover: 1.9%) to 0.52–0.56 ind. m^{-2} in the rest of areas (L2 to L5, mean nodule-cover $> 9.1\%$).

3.1.2. Variations in alpha-diversity

Patterns in taxon richness (S_1) and taxon density (S_A) varied between study areas. While mean S_1 was broadly consistent (Fig. 4E), with mean values ranging 72–76 morphotypes in c. 500 ind. (Fig. 4E), mean S_A (Fig. 4I) was significantly different between study areas ($F_{[2,70]} = 464.9$, $p < 0.001$, $\eta^2 = 0.92$) owing to the inherently different faunal densities in these locations (Fig. 4A). A statistically

significantly higher S_A (pairwise comparisons, $p < 0.001$) was found in Area TD (68.8 morphotypes in c. 1000 m^2) compared to areas TB and TC (39.2 and 35.7 morphotypes in c. 1000 m^2 , respectively), which were not significantly different (pairwise comparisons, $p > 0.05$). Taxon accumulation curves supported these results; the larger S_A in Area TD generated a different taxon accumulation pattern in this study area when assessed in relation to seabed surface sampling effort (a significantly higher richness detectable in samples $> 1000 m^2$, Fig. 6A), while individual-based sampling assessments revealed a relatively similar taxa accumulation pattern in all three study areas (Fig. 6B). Mean $1/D$ index (taxa evenness) was significantly different between study areas ($F_{[2,27]} = 82.9$, $p < 0.001$, $\eta^2 = 0.86$), and variations were significant across all sites (pairwise comparisons, $p < 0.001$). The assemblage in Area TC had the highest values of $1/D$ index (19.9 effective taxa in c. 500 ind.), followed by Area TB (15.1 effective taxa in c. 500 ind.), and Area TD (11.3 effective taxa in c. 500 ind.; Fig. 4Q).

Locally, faunal diversity metrics showed no substantial variations between geofom types (e.g. overlapping confidence intervals, Fig. 4F–H, J–L, N–P), other than slightly lower mean $1/D$ values in Hill geofoms from areas TC and TD (Fig. 4O and P). S_1 was almost invariable across the nodule cover gradient of all study areas (Fig. 5B), but S_A in the lowest nodule-cover level of Area TD (L1, mean nodule cover: 1.9%) was substantially lower than in the most nodule-covered areas (L4–L5, mean nodule-cover $> 16.9\%$; Fig. 5C).

3.1.3. Variations in beta-diversity

From the 256 invertebrate megafauna taxa surveyed in this study, 95 morphotypes were found in all study areas, 57 morphotypes (28 rare; ≤ 3 specimens) were found only in Area TD, 30 morphotypes (25 rare) were found only in Area TB, and 10 morphotypes (8 rare) were found only in Area TC (see Fig. A4A). Area TB and TC shared a higher number of unique taxa (23 morphotypes) than Area TB shared with TD (20 morphotypes) and Area TC did with TD (15 morphotypes). MDS ordination of faunal composition data readily distinguished the samples from the three study areas, particularly those from Area TD from the rest (Fig. 7A). Formal comparison of faunal composition across the assemblages of different study areas indicated a statistically significant difference overall (PERMANOVA, $R = 0.58$, $p = 0.001$) and statistically significant differences in all pairwise comparisons (pairwise PERMANOVA $R \geq 0.69$, $p < 0.007$), although with a smaller dissimilarity exhibited between the assemblages of Area TB and TC (β_{BC} : 43.2%) than each of these with Area TD samples (β_{BC} : 55.0 and 58.9%, respectively).

There were clear variations in the abundance of the most dominant taxonomic groups between study areas (Fig. 8). Mean densities in Area TD were consistently higher across all taxonomic groups except for Holothuroidea, which exhibited a substantially higher density within Area TC than the other areas (Fig. 8H). The higher densities of Alcyonacea (Fig. 8C) and Porifera fauna (Fig. 8D) in Area TD were coupled with an also substantially higher taxonomic richness of these groups in that site. Alcyonacea (Fig. 8C), Bryozoa (Fig. 8E), and Ophiuroidea fauna (Fig. 8G) were almost virtually absent from Area TB and TC compared to TD, while the density of Echinoidea (Fig. 8I) was substantially reduced in Area TC compared to the other areas. The most remarkable variations in distribution at the morphotype level between study areas were: (i) no bamboo corals, e.g. *Bathygorgia* spp. (Fig. 3I) and *Keratoisis* spp., were found in areas TB and TC, while these taxa had a combined total mean density of 0.75 ind. $100 m^{-2}$ in Area TD; (ii) Mean density of the nodule-encrusting sponge Porifera mtp-5 was substantially reduced in areas TB and TC (0.14 and 0.26 ind. $100 m^{-2}$, respectively) compared to Area TD (2.25 ind. $100 m^{-2}$). In contrast, mean density of the also nodule-encrusting sponge Porifera mtp-88 was substantially reduced in Area TD (0.02 ind. $100 m^{-2}$) compared to areas TB and TC (0.67 and 0.69 ind. $100 m^{-2}$, respectively); (iii) The two most abundant holothurian morphotypes found in Area TC,

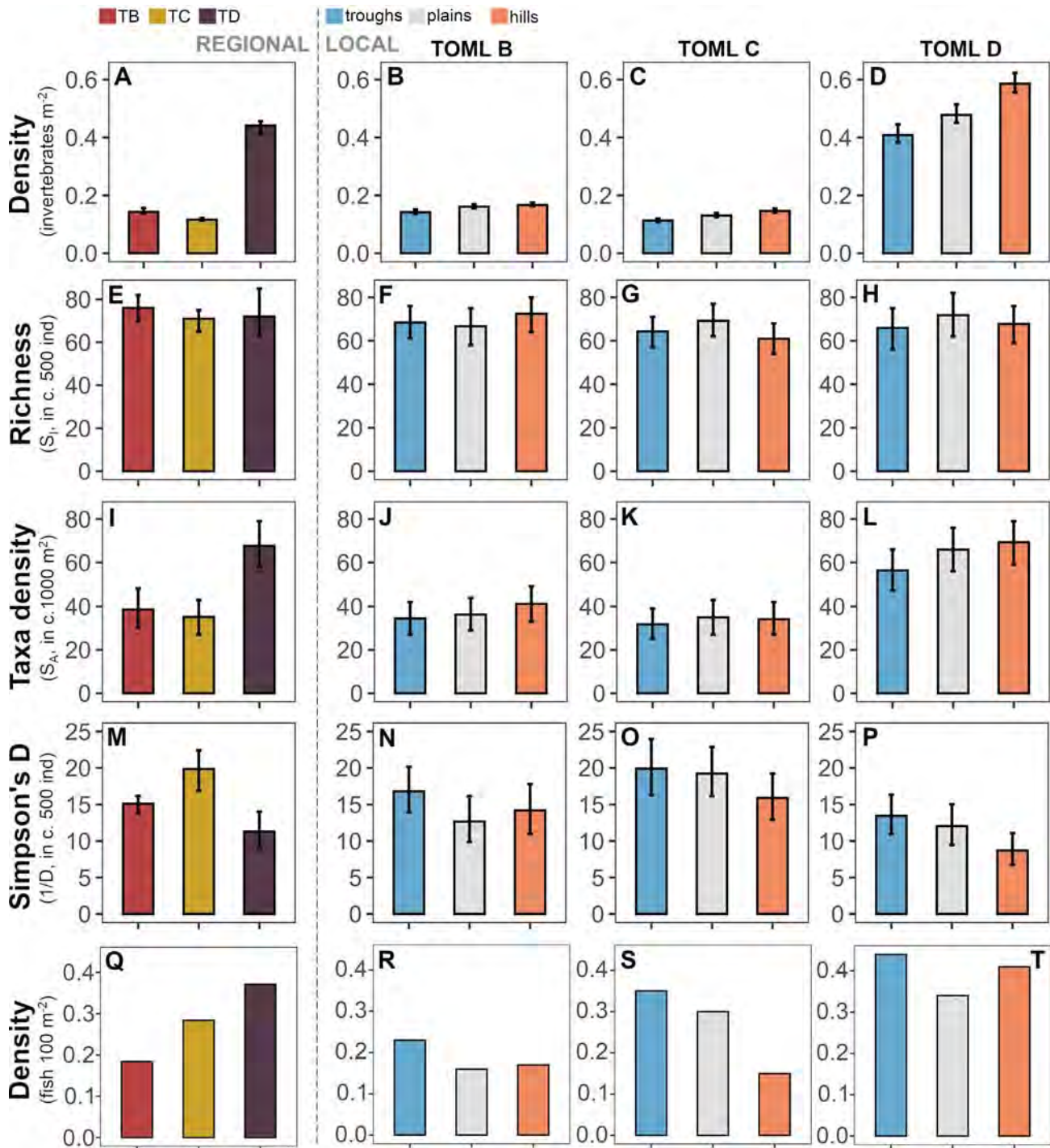


Fig. 4. Regional and local variations in megafaunal density and diversity. Bars indicate mean values across replicate sample sets (regional assessment) or bootstrap-like sample sets (local assessment) surveyed in each study area. Error bars represent 95% confidence intervals. Regional assessment. Study areas: TB, TC, and TD. (A) Invertebrate density. (E) Invertebrate taxa richness. (I) Invertebrate taxa density. (M) Invertebrate heterogeneity diversity; inverse Simpson's index. (Q) Fish density (total). Local assessment. Geofom types: Troughs, Plains, and Hills in respective study areas TB, TC and TD. (B–D) Invertebrate density. (F–H) Invertebrate taxa richness. (J–L) Invertebrate taxa density. (N–P) Invertebrate heterogeneity diversity; inverse Simpson's index. (R–T) Fish density (total).

Amperima sp. mtp-3 and *Ellipinion* sp. mtp-1 (Fig. 3R and S: 0.64 and 1.10 ind. 100 m⁻² in Area TC, respectively), had reduced mean density in Area TB (0.13 and 0.11 ind. 100 m⁻², respectively) and were almost absent from TD (only 2 specimens of *Amperima* sp. mtp-3 found in Area TD); (iv) Mean densities of the ophiuroid *Ophiosphalma glabrum* sp. inc. (Fig. 3V) were two orders of magnitude lower in Areas TB and TC (0.15 and 0.17 ind. 100 m⁻², respectively) compared to that found in Area TD (7.58 ind. 100 m⁻²); (v) Mean density of the sea urchin

Aspidodiadema sp. mtp-1 (Fig. 3W) was substantially lower in Area TC (0.19 ind. 100 m⁻²) compared to those found in areas TB (1.83 ind. 100 m⁻²) and TD (2.13 ind. 100 m⁻²).

Locally, we found a markedly higher variability in multivariate assemblage dissimilarity at the finer scale (across the nodule-cover gradient; Fig. 7C) than at the broader-scale (between geofoms; Fig. 7B). At the broader scale, assemblage dissimilarity among different geofoms was consistently higher between Hills and Troughs (Fig. 7B),

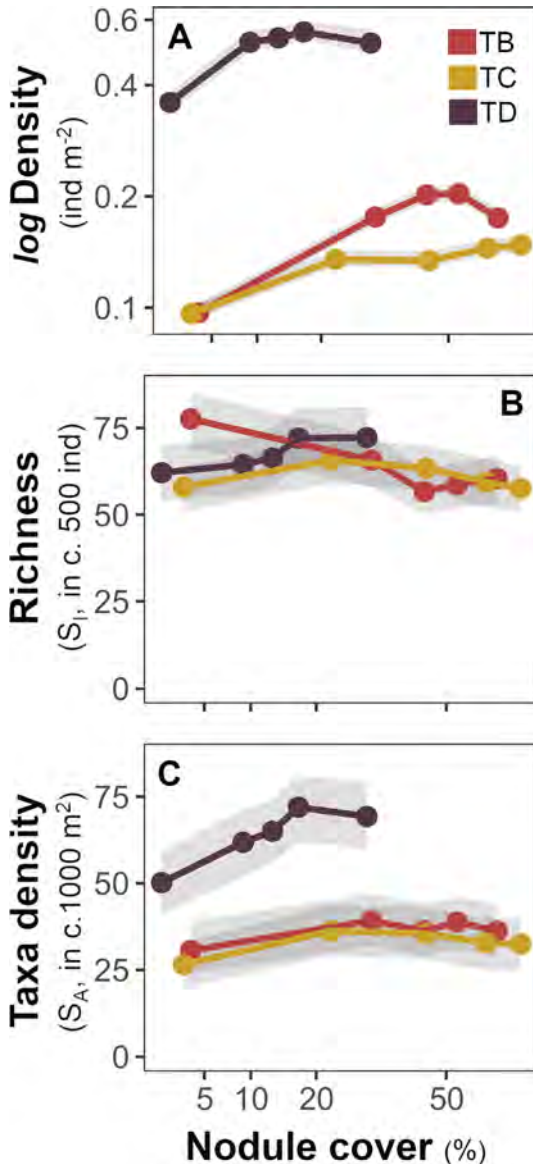


Fig. 5. Local variations in faunal density and diversity across the nodule cover gradient of each study area. Points indicate mean values across bootstrap-like sample sets representing different nodule cover levels surveyed in each study area. Shadowing represent 95% confidence intervals. (A) Invertebrate density. (B) Invertebrate taxa richness. (C) Invertebrate taxa density.

particularly in areas TB and TD (β_{BC} : 40.4 and 41.7%, respectively), while samples from Plains exhibited a higher resemblance with those from the other geoforms (e.g. β_{BC} < 40.0%) in all three areas. The most remarkable variations in the abundance of dominant taxonomic groups between geoform types were: i) Sessile Cnidaria (Actinaria, Alcyonacea, and Antipatharia) consistently exhibited lowest density in Troughs and highest in Hills, in all study areas (e.g. mean densities in Area TD: 11.9 ind. 100 m^{-2} in Troughs; 13.0 ind. 100 m^{-2} in Plains; and 16.1 ind. 100 m^{-2} in Hills), ii) Ophiuroidea density showed the same pattern as sessile Cnidarians (e.g. mean densities in Area TD: 10.6 ind. 100 m^{-2} in Troughs; 15.1 ind. 100 m^{-2} in Plains; and 22.9 ind. 100 m^{-2} in Hills), iii) In contrast to other sessile suspension feeding fauna, Porifera showed no significant variations in density between geoforms (e.g. mean densities in Area TD: 4.8 ind. 100 m^{-2} in Troughs; 5.9 ind. 100 m^{-2} in Plains; and 4.3 ind. 100 m^{-2} in Hills).

At the finer scale, ordination of faunal composition samples (Fig. 7C) readily and consistently distinguished the assemblages of the lowest (L1) and the highest (L5) nodule-cover levels in all study areas

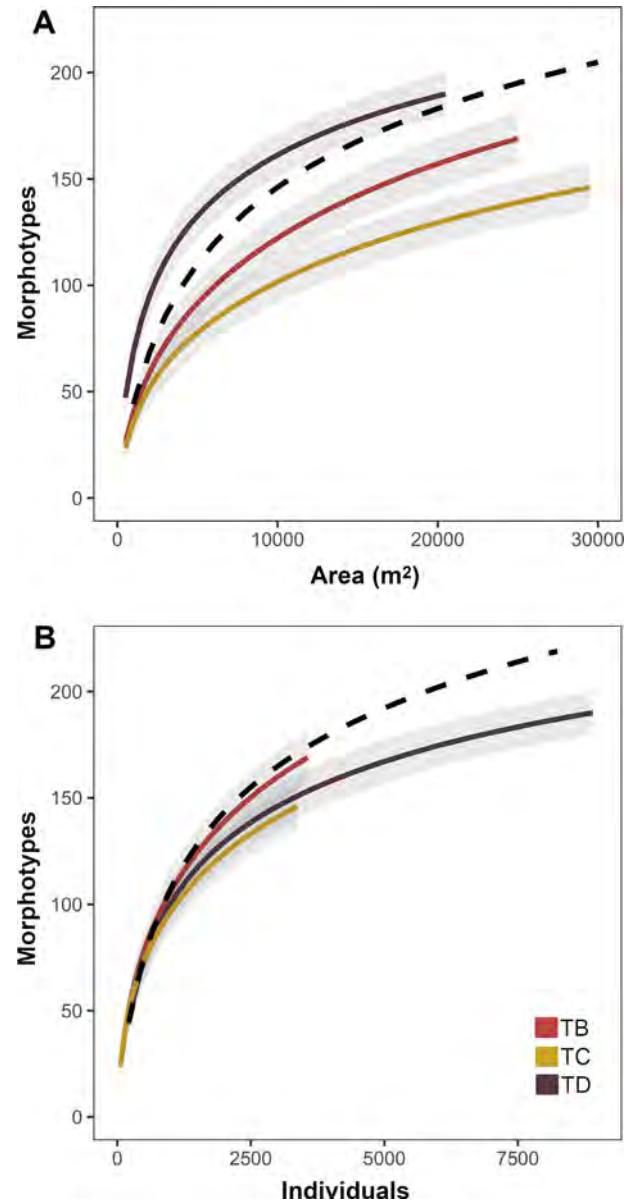


Fig. 6. Invertebrate morphotype accumulation curves for each study area. Dashed line represents combined data. Lines represent mean values across the 100 randomizations performed at each sample unit size increase, for each study area. Shadowing representing 95% confidence intervals. Dashed line represents mean values of curve calculated using whole-study combined data. (A) Curves calculated as a function of the seabed area sampled. Slope coefficients at line end: 0.0022x (TB); 0.0015x (TC); 0.0020x (TD), 0.0007x (Combined). (B) Curves calculated as a function of the number of the individuals sampled. Slope coefficients at line end: 0.0156x (TB); 0.0131x (TC); 0.0046x (TD), 0.0032x (Combined).

(β_{BC} : 47.5, 47.0, and 43.8% in areas TB, TC, and TD respectively). Remarkably, both the assemblages of the lowest and those of the highest nodule-cover levels in areas TB and TC exhibited a higher resemblance with the corresponding ‘homologous’ level (across study areas) than with samples representing other nodule cover levels surveyed within the same study area. The most notable variations in the abundance of dominant taxonomic groups across nodule-cover gradients were (Fig. 9): i) Actinaria density increased to an asymptote with increasing nodule cover in all study areas, stabilizing at low (L2) cover levels (Fig. 8A), ii) Ophiuroidea density increased to an asymptote with increasing nodule cover in Area TD (Fig. 9G), iii) Alcyonacea, Antipatharia, and Bryozoa densities increased consistently with

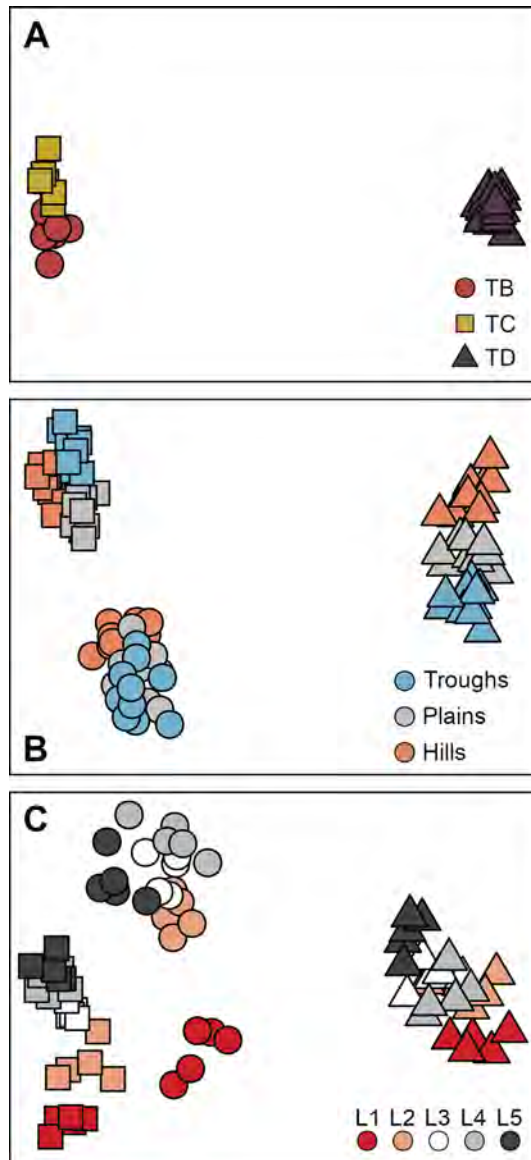


Fig. 7. MDS plots showing regional and local variations in invertebrate assemblage composition. (A) Regional assessment based on replicate samples of each study area (MDS stress: 0.009). Study areas, in all panels: TB (circles); TC (quadrats); and TD (triangles). (B) Local geomorphological assessment based on 10 randomly selected bootstrap-like samples for each geoform type in each study area (MDS stress: 0.070). (C) Local nodule-cover assessment, based on 5 randomly selected bootstrap-like samples from each of the 5 nodule cover levels (L1: lowest coverage, to L5: maximum coverage) for each study area (MDS stress: 0.011).

increasing nodule cover in Area TD but showed no variations across the cover gradient in the other two areas, where their presence was overall much reduced (Fig. 9B, C and E), iv) Porifera density slightly increased with nodule cover in areas TB and TC (where most of the sponges encountered where nodule-encrusting), but showed no variations across the nodule cover gradient in Area TD, and v) Echinoidea density increased in Area TB, peaking at intermediate cover levels (L3) before reducing at higher nodule cover (unimodal), but showed no variations across the cover gradient in areas TC and TD (Fig. 9I).

3.2. Fish megafauna

Across all three study areas fishes were seen in 0.99% of images (0.66%, 1.02%, and 1.35% in areas TB, TC, and TD respectively).

Overall estimated fish density was $0.38 \text{ ind. } 100 \text{ m}^{-2}$ ($3800 \text{ fish per km}^2$). These fishes were classified into 18 distinct morphotypes (see Table S5). The most abundant fish taxon both across the entire image dataset and in every study region was *Ipnops meadi* sp. inc. (Fig. 3γ), with a total of 94 occurrences and making up between 30 and 52% of the fish abundance depending on study site. Regionally, total fish density varied substantially between study areas with densities being higher in Area TD ($0.39 \text{ ind. } 100 \text{ m}^{-2}$) than in areas TB ($0.18 \text{ ind. } 100 \text{ m}^{-2}$) and TC ($0.28 \text{ ind. } 100 \text{ m}^{-2}$) (Fig. 4Q). Assemblage composition also showed some variation between study areas. Notably the second most common taxon in both Area TB and TC (*Leucicorus* sp., Fig. 3β) was not seen in Area TD, where *Bathyonus caudalis* sp. inc. was instead the second most abundant taxon. Additionally, *B. caudalis* sp. inc. was only seen once in Area TB and not at all in Area TC. In terms of species overlap, 6 of the 18 morphotypes were found across all three regions, and Area TC had the most unique morphotypes (3) (see Fig. A5). Locally, total fish densities were consistently higher in trough landscapes than in plain and hill areas (Fig. 4R–T). Area TC showed the biggest difference between troughs and hills, whereas Area TD had nearly equivalent fish densities on both troughs and hills. The higher density of fish observed in troughs within Area TC and TD resulted from a higher abundance of *I. meadi* sp. inc. in this geoform, while in Area TB this taxon was more abundant on hills. The higher density of fish observed in troughs within Area TB resulted from slightly higher abundances of *Coryphaenoides* sp. (Fig. 3Z) and *Ophidiidae* mtp-1 in these areas. Assessing patterns of fish distribution at the fine scale, with relation to nodule cover was not directly possible for fishes because of the overall low numbers of observations and the unequal sampling of different nodule covers. Overall, 70% of the sampled area had mid to low nodule density (nodule cover 20%), and for the area with the most fish observations, Area TD, 81% of the surveyed area had less than 20% nodule cover. Nevertheless, it is interesting to note that 56% of the *I. meadi* sp. inc. seen were recorded in images with no nodules (0% nodule cover), and all individuals observed were seen in low nodule areas.

4. Discussion

4.1. Invertebrate megafauna

4.1.1. Regional variations

Clear differences in invertebrate abundance were observed between the three study areas surveyed (Fig. 4A). Density in Area TD (0.44 ind. m^{-2}) was three and four times higher than in areas TB and TC, respectively. Variations of such magnitude in the abyss have typically been linked with differences in the food supply to the benthos, worldwide (Johnson et al., 2007; Rex et al., 2006; Smith et al. 2008) and at the CCZ in particular (Brown et al., 2001; Mullineaux, 1987; Wilson, 2017). For instance, Vanreusel et al. (2016) and Cuvellier et al. (2020) suggested that the higher productivity of the GSR and BGR areas compared to the more northerly APEI3 in the eastern CCZ (e.g. Volz et al., 2018; Fig. 1A) may drive the much higher (i.e. 5 fold) faunal density that these studies found in the southern sites. However, differences in productivity between the three areas surveyed in this study are thought to be minor ($1.53\text{--}1.58 \text{ g C m}^{-2} \text{ y}^{-1}$, Lutz et al., 2007; Table 1). If water depth is considered as a proxy for food supply, the larger faunal density in the $\sim 500 \text{ m}$ shallower Area TD could be explained. However, a significantly reduced density was observed in Area TC compared to TB, which are both at similar depths.

There were clear differences in the predominant nodule size and abundance in each of the three study areas. Nodules were larger and generally less abundant in Area TD than in the other areas. Area TD had the lowest mean surface cover but largest nodule weight per seabed area of all study areas (NM, 2016; Table 1). As variations in nodule size and cover appear to influence megafauna density and distribution

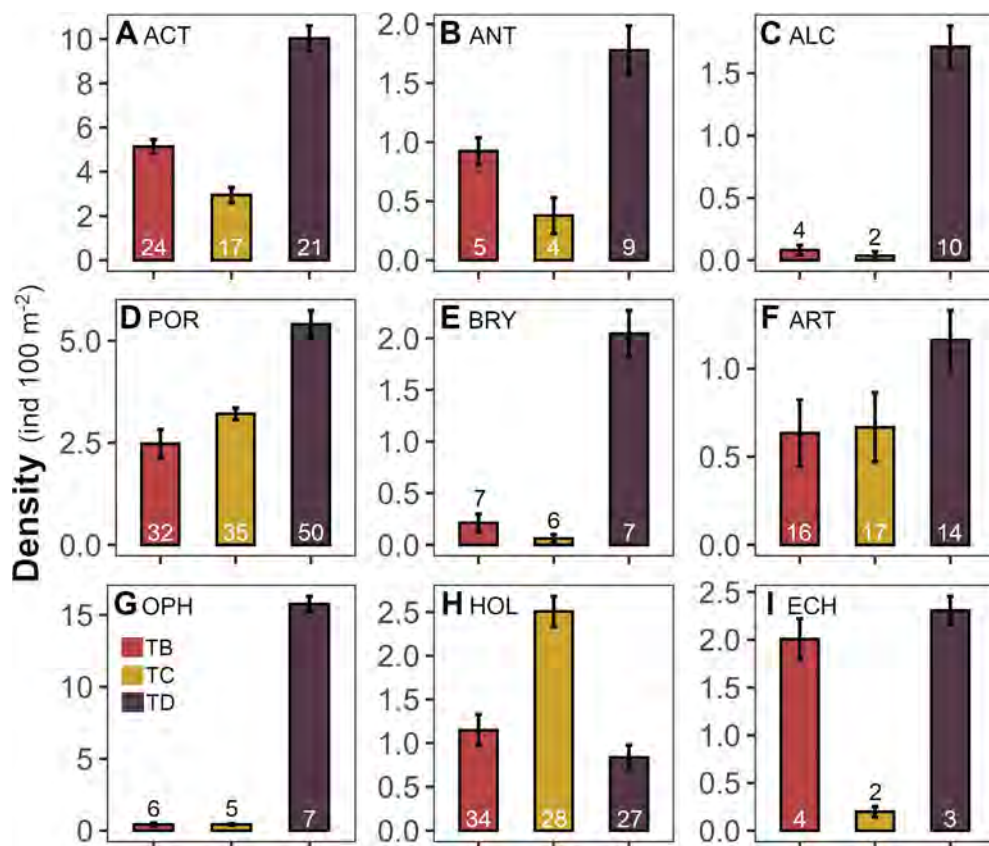


Fig. 8. Regional variations in density and richness of the most abundant faunal groups. Bars indicate mean values across replicate sample sets surveyed in each study area. Error bars represent 95% confidence intervals. Numbers in bars indicate the number of morphotypes encountered in each group. (A) Actiniaria. (B) Antipatharia. (C) Alcyonacea. (D) Porifera. (E) Bryozoa. (F) Arthropoda. (G) Ophiuroidea. (H) Holothuroidea. (I) Echinoidea.

locally (Simon-Lledó et al., 2019b; this study), it is likely that variations in the predominant nodule typology (e.g. shape, volume) may also play an important role in the structuring of communities at the more regional scale. However, it remains unclear how and to what extent these factors regulate the patchy distributions of invertebrate density that seem to characterise the north eastern CCZ region, particularly given the little we know about life history traits of CCZ megafauna.

The three study areas exhibited significantly different assemblage compositions, generally aligning with previous descriptions of communities nearby in the CCZ, and beta-diversity was somewhat proportional to the geographic distance between locations (Figs. 1 and 7A). Variations in composition reflected a substantial degree of taxonomic turnover, perceivable even at Phylum to Class hierarchical levels (Fig. 8). Shifts in the spatial distributions of dominant taxonomic groups were consistent with previous megafaunal assessments conducted in nearby locations (e.g. Amon et al., 2016; Kamenskaya et al., 2013; Simon-Lledó et al., 2019b; Stoyanova, 2012; Vanreusel et al., 2016). For instance, the assemblages of the two western-most study areas (and also most proximal locations), areas TB and TC, had lower densities of Alcyonacea corals and Ophiuroidea, as was reported at the south-east Ifremer area (Vanreusel et al., 2016) which is located right in between the two study areas. The most abundant group in Area TB were Actiniaria, followed by Echinoidea of the genus *Plesiadiadema* sp., as was found in the adjacent Yuzhmorgeologiya area (Kamenskaya et al., 2013). Further north, Area TC exhibited a surprisingly high density of Holothuroidea, the highest reported to date at the CCZ (i.e. 2.5 ind. 100 m⁻²), dominated by a small (max. diameter: ~8 cm) morphotype of the genus *Ellipinion* sp. (Fig. 3S), which accounted for almost half of all the holothurians encountered in Area TC. In contrast, Ophiuroidea were the most abundant group in Area TD, with *Ophisthpalma glabrum* sp. inc. dominating the megafaunal assemblage (e.g. 17% of the total invertebrate abundance), exactly as was reported in the UK-1 area (Amon et al., 2016), at a similar latitude. The dominance of *O. glabrum* sp. inc. in Area TD was such that it reduced the taxa evenness in this

area (e.g. Simpson's D; Fig. 4Q). Ophiuroidea abundances appear to gradually increase towards the mid-eastern most sector of the CCZ, where the diversity of this group has also been shown to peak (Christodoulou et al., 2020). Although substantial efforts are still required to further synthesise (and collect) megafaunal distribution data, the observed shifts in the dominant taxonomic groups across sites could be indicative of an underappreciated heterogeneity across the eastern CCZ, and by extension across the whole CCZ area.

Taxon accumulation patterns (Fig. 6) suggest that the differences in the total number of taxa encountered between study areas (TB: 168 mtps; TC: 145 mtps; TD: 189 mtps) reflected the different faunal densities inherent to each location (i.e. S_A , Fig. 4I) rather than actual variations in taxa richness (e.g. S_B , Fig. 4E). Morphotype accumulation curves suggest that the sampling conducted characterized most of the megafaunal assemblage in Area TD and illustrate the large level of sampling effort required (e.g. > 3000 megafaunal specimens) to obtain statistically robust estimations of local taxa richness in abyssal nodule-field areas based on seabed imagery (Ardrón et al., 2019; Simon-Lledó et al., 2019a). Morphotype accumulation patterns indicate that further sampling may be required in areas TB and TC (Fig. 6B) to more fully document megafaunal biodiversity, as required in environmental management plans for contractor areas at the CCZ (ISA, 2014). Richness data obtained in Area TD allows a preliminary comparison with the APEI6, the protected area in closest proximity to TOML D, and one of the few CCZ studied areas where the megafaunal sampling effort conducted was also sufficient to adequately quantify this parameter (Simon-Lledó et al., 2019a). There was a larger total taxon richness in Area TD than at the APEI6; excluding fish taxa, a total of 126 invertebrate morphotypes (in 18,500 m²) were found at the APEI6 (Simon-Lledó et al., 2019b), whereas 189 morphotypes (in 20,200 m²) were encountered in Area TD (i.e. mean S_1 in c. 500 specimens: 57 in APEI6; 72 in Area TD). There was also a lower megafaunal richness in APEI3 (both in seamount and nodule field areas) than the more southern GSR and BGR sites (Cuvelier et al., 2020). Combined, these

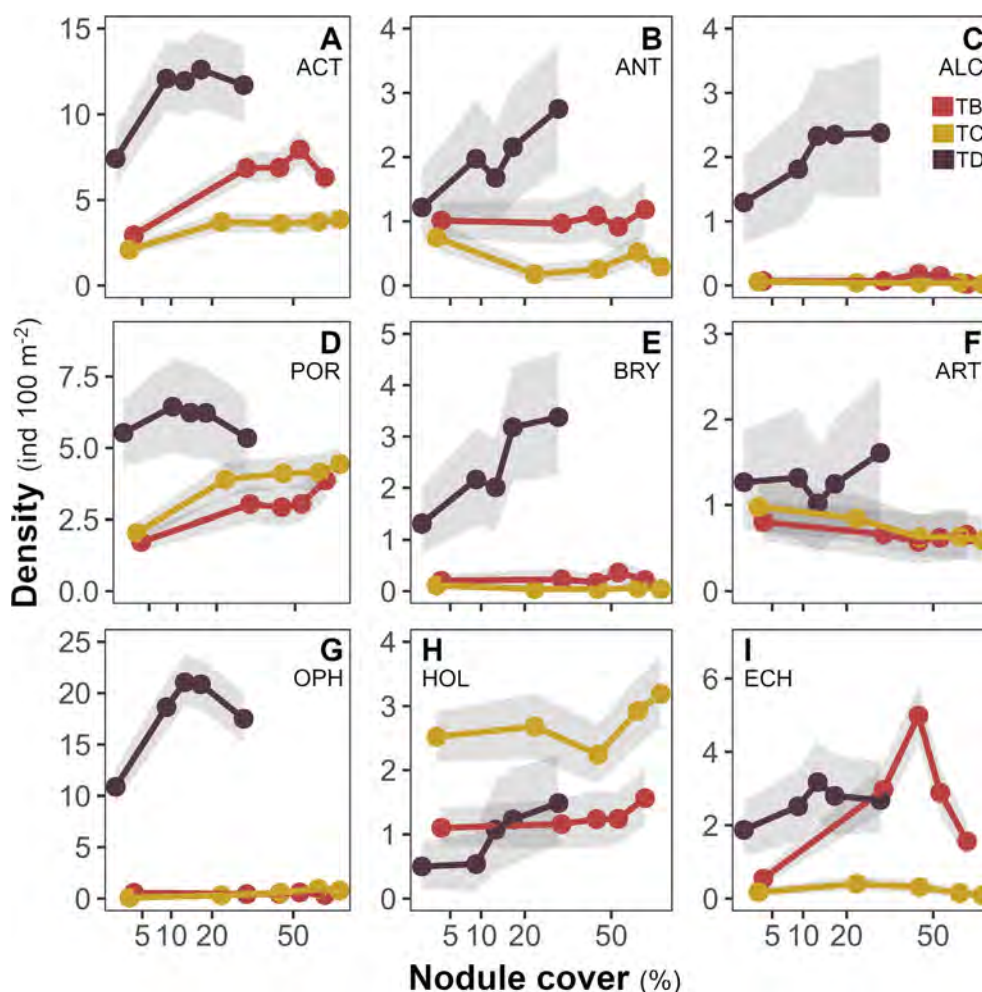


Fig. 9. Local variations in faunal density of the most abundant faunal groups across the nodule cover gradient of each study area. Points indicate mean values across bootstrap-like sample sets representing different nodule cover levels surveyed in each study area. Shadowing represent 95% confidence intervals. (A) Actiniaria. (B) Antipatharia. (C) Alcyonacea. (D) Porifera. (E) Bryozoa. (F) Arthropoda. (G) Ophiuroidea. (H) Holothuroidea. (I) Echinoidea.

results suggest the existence of a latitudinal decrease in megafaunal richness from North to South in this sector of the CCZ, in accordance with the trends described for some macro- and meiofaunal groups (Błażewicz et al., 2019; Bonifácio et al., 2020; Macheriotou et al., 2020; Wilson, 2017). As these and other studies have point out (e.g. Taboada et al., 2018), accumulating evidence is raising concerns on the appropriateness of the north easternmost APEIs (e.g. APEIs 3 and 6) to meet their objective of preserving the full biodiversity range found within this region of the CCZ. Research in the least known south easternmost APEIs (APEIs 8 and 9), and in other almost unexplored contractor areas, is required to further contextualise latitudinal variations.

4.1.2. Local variations

Standing stocks were consistently lowest in Troughs when explored at a broad scale (i.e. tens of km) and in the least nodule-covered areas (L1) when assessed at a fine scale (i.e. tens of meters). The variations across the nodule gradient were much more prominent than between geoforms, as was previously documented in homologous assessments conducted at the APEI6 (Simon-Lledó et al., 2019a, 2019b). In those studies, the abundance of suspension feeders (Actiniaria, Antipatharia, Alcyonacea and Bryozoa) was generally lower in Troughs and higher in Hills, except for Porifera fauna, as we found here. Similarly, reduced densities of Ophiuroidea fauna in nodule-free areas and enhanced densities in Hill areas were also documented at the APEI6. Interestingly, variations in Ophiuroidea density (in Area TD, since virtually absent elsewhere) did not align with those of other deposit feeding fauna, such

as Holothuroidea or Echinoidea, as was found at the APEI6. These variations may be related with enhanced (food) particle flows potentially resulting from the higher hydrographical complexity of hill areas in the CCZ (van Haren, 2018). On the other hand, Ophiuroidea may benefit from micro-scale accumulations of food particles near the base of nodules (e.g. Mullineaux, 1989). In turn, CCZ sessile Cnidarians and Bryozoan taxa typically exhibit a high affinity for nodules (Amon et al., 2016; Simon-Lledó et al., 2019a). Nodules provide stable anchoring for suspension feeders and enable the placement of food-trapping structures into higher, accelerated boundary flows (Mullineaux, 1989), enhancing the abundance of these taxa in areas where nodules are present (Amon et al., 2016; Simon-Lledó et al., 2019b; Vanreusel et al., 2016). Our results concur with Simon-Lledó et al. (2019b) in that a nonlinear, asymptotic relationship exists between standing stock and nodule cover and this response may be explained by resource limitation (Tilman, 1982), i.e. hard substratum is initially limiting, but food resource becomes limiting as attached suspension feeder density increases.

Variations in assemblage composition were more prominent across nodule gradients (β_{BC} range: 43.8–47.5%) than between geoform types (β_{BC} range: 31.1–41.7%), despite the much smaller spatial scale of influence of nodule cover variations. Differences in composition at the local scale reflected the variations in density of the most dominant taxonomic groups, i.e. more prominent across nodule gradients. Surprisingly, although smaller in range, beta-diversity rates associated with local variations in nodule cover appear to be of comparable magnitude to the rates observed at a regional scale (β_{BC} range:

43.2–58.9%) (Fig. 7C). These results stress the key role that nodules appear to play in the structuring of invertebrate communities at the local scale across the CCZ, but also that further research may be needed to understand if/how regional variations in nodule abundance (e.g. Morgan, 2012), or even typology (e.g. Table 1), may also influence megafaunal distributions at more regional scales.

4.2. Fish megafauna

Regional differences in the fish community were evident and followed the patterns observed for invertebrate megafauna though the environmental drivers responsible are not clear. As with invertebrates, a much higher fish density was found in Area TD and density variations did not appear to match with variations in food supply, which are thought to vary little between the study areas. Rather there was a clear decrease in density moving from east to west, as depth increases. Fish density detected in Area TD (3800 fishes km⁻²) was similar to those at the APEI6 (3980 fishes km⁻²), and at the DISCOL site in the Peru Basin (3020 fishes km⁻²), but much higher than reported from the Porcupine Abyssal Plain (751 fish km⁻²) using generally similar vertical imaging survey methodologies (Drazen et al., 2019; Milligan et al., 2016; Simon-Lledó et al., 2019b, 2019c). In contrast, fish densities detected in areas TC (2840 fishes km⁻²) and particularly TB (1840 fishes km⁻²) were lower. From a variety of CCZ image databases, *Ipnops meadi* sp. inc. is by far the most frequently seen fish and while this most likely does reflect a true density, it should also be noted that these fishes are especially easy to identify even in high altitude images owing to their large, reflective, dorsally oriented eyes, and they generally remain motionless on the seafloor, showing little to no avoidance behaviour even when approached by large, bright, and noisy remotely operated vehicles (Simon-Lledó, pers comm).

Given their mobility it was somewhat surprising that the fish community composition varied regionally. For instance, a taxon so frequently observed in areas TB and TC (*Leucicorus* sp.) was entirely absent in the images from Area TD. The second most frequently observed taxon in Area TD (*B. caudalis* sp. inc.) was almost entirely absent from the other two sites. Area TD is the furthest east of the three study sites, and Leitner et al. (2017) also documented a significant change in bait-attempting faunal composition from east to west across the CCZ. It should also be noted that both areas TD and TB are found at lower latitudes and slightly higher presumed nutrient flux than Area TC; however, areas TD and TB were not the most similar regions, nor did they share the largest number of taxa. In fact, only one morphotype was uniquely shared between the two sites while 3 taxa were uniquely shared by areas TD and TC. So, while some studies suggest relationships between abyssal fish community composition and density with food availability (e.g. Armstrong et al., 1992; Linley et al., 2017), a longitudinal driver may be more important in the CCZ.

At the local scale, the higher density of fishes found in Troughs was surprising, given that invertebrate megafaunal densities in this and other studies showed the opposite relationship (Durden et al., 2015; Simon-Lledó et al., 2019a). Further, using baited camera techniques across a bathymetric gradient, abyssal hills (isolated, circular hills) had higher fish relative densities than areas off the hills (Leitner et al., 2017). However, the invertebrate taxa observed in higher abundance on the Hills in this study were sessile Cnidaria and these taxa are not frequently consumed by fishes (Drazen and Sutton, 2017). In the present analysis, higher fish densities in Troughs appears driven by *I. meadi*, which is a benthic fish not seen in baited studies. It is usually found on flat, fine, soft terrain. Indeed, the relationship for areas TC and TD was directly related to the high abundance of this taxon in Troughs, though this did not hold true for Area TB or the APEI6 (e.g. more abundant in hill and plain geofoms; Simon-Lledó et al., 2019a). Given the low abundances of fishes in this study further insights into local scale fish dynamics will require synthesis of data from across the CCZ.

5. Conclusions

This paper presents an assessment of megabenthic faunal distribution in response to multiple environmental factors known to generate habitat variability in abyssal environments. We found significant variations in faunal density and assemblage compositions both at a regional and at a local scale. In agreement with previous studies in the region, broad-scale geomorphological variations (extending tens of km, e.g. Leitner et al., 2017; Simon-Lledó et al., 2019a) and particularly fine-scale variations in polymetallic nodule cover (extending tens of meters; e.g. Simon-Lledó et al., 2019b) emerged as strong drivers of megafaunal variation at the local scale. The presence of nodules appeared to enhance the abundance of the most dominant fauna, somewhat irrespectively of functional group (particularly sessile Cnidaria and Ophiuroidea), driving gradual changes in assemblage compositions (largest dissimilarity rates between the least and the most nodule-covered areas), and enhancing thereby local beta-diversity rates. The effect of nodule presence within a contract area (local scale) was comparable in magnitude to the variation observed between contract areas (regional scale). Finally, preliminary biogeographical exploration of megafaunal variation across the eastern CCZ suggests a substantial degree of underappreciated heterogeneity within this sector, reflected in: i) a longitudinal variation of faunal abundance (decrease towards the west), ii) the clear shifts in the dominant taxa between sites (in < 350 km), and iii) an apparently higher taxa richness in the more southerly areas of the mid-eastern CCZ (e.g. in the TOML D, GSR, BGR, UK-1 belt) than in the north easternmost sector (APEIs 3 and 6). Results of this contribution shall aid the effective implementation of conservation management strategies at the CCZ, both at local and regional operational levels.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: AF was employed by company Fathom Pacific. JP, AA, and CP were employed by company Nautilus Minerals. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.pocan.2020.102405>.

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Preliminary Observations of the Abyssal Megafauna of Kiribati

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We report on preliminary observations of the abyssal megafauna communities in the exclusive economic zone of Kiribati, a huge abyssal area with few previous studies. These observations also provide useful context for marine minerals exploration within the exclusive economic zone (EEZ) and for the neighboring Clarion Clipperton Zone (CCZ), where deep-sea mining operations are planned. Seafloor images collected during seabed mining exploration were used to characterize megafaunal communities (fauna > 1 cm) in three abyssal plain areas in the eastern Kiribati EEZ (study area extending from 1 to 5°N and 173 to 156°W). Additionally, hydrographic features in each of the survey locations were inferred by reference to near-seabed current flows modeled using open-sourced oceanographic data. The images showed a dominance of foraminiferal organisms. Metazoan communities were high in morphospecies richness but had low density. These general patterns were comparable to abyssal megabenthic communities in the CCZ. There was evidence of spatial variation between the assemblages in Kiribati, but there was a relatively large pool of shared morphospecies across the entire study area. Low metazoan density limited detailed assessment of spatial variation and diversity at local scales. This finding is instructive of the levels of sampling effort required to determine spatial patterns in low density abyssal communities. The results of this study are preliminary observations that will be useful to guide future biological survey design and marine spatial planning strategies.

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INTRODUCTION

The Republic of Kiribati is a Pacific Micronesian small island state comprised of three island groups: the more populous Gilbert Islands in the West, the largely uninhabited Phoenix Islands in the middle and Line Islands to the East. The three groups of islands each occur on major Cretaceous volcanic chains (Epp, 1984) that form approximately NW-SE oriented ridge systems rising from the abyssal seafloor in the central Pacific. Although the total land area of Kiribati is only 811 km² (Rotjan et al., 2014), the exclusive economic zone (EEZ) covers around 3.5 million km² and > 89% of this is abyssal (> 4000 m water depth) ocean (Weatherall et al., 2015).

Marine mineral exploration in Kiribati has been intermittent since the early 1980s (e.g., Gauss, 1980) and has revealed extensive deposits of polymetallic nodules and metalliferous sediments on the abyssal seafloor and ferromanganese crust resources on the seamount areas (Okamoto, 2005).

The Line Islands form the westernmost boundary of the Clarion Clipperton Zone (CCZ, at 2–20°N; 115–155°W), which is of significant interest for polymetallic nodules. A Mineral Resource (minerals in sufficient quantities to provide reasonable prospects for eventual economic extraction) has never been declared for the deposits in Kiribati waters. However, baseline knowledge of the environment is important in developing plans for exploitation of mineral resources and management of mining activities particularly in areas of high uncertainty like the deep-sea.

There have been few deep-water seabed biological investigations in Kiribati and almost no assessment of the abyssal plain areas. The only abyssal sample obtained to the authors' knowledge was a single dredge sample that was collected in the Line Islands EEZ at 5029 m depth during the Challenger expedition (station 274) on 11 September 1875, which contained a xenophyophore (*Psammima nummulina*), several sponges (*Euplectella crassistellata* and *Cladorhiza abyssicola*), holothurians (including *Benthothytes selenkiana* and *Psycheotrepes exigua*), an asteroid (*Hyphalaster hyalinus*), an echinoid [*Phormosoma* (now *Tromikosoma*) *tenuis*], polymetallic nodules and fossil shark teeth (Théel, 1882; Murray and Renard, 1891; Murray, 1895). On the shallower slopes (1000–1300 m depth) of the Phoenix Islands investigations have been made with baited video (Obura et al., 2011). The limited deeper water work around the Phoenix Islands was stimulated by the creation of the Phoenix Islands Protected area (PIPA) in 2008, which is one of the largest (encompassing 408,250 km²) marine parks in the world (Rotjan et al., 2014). Deep water assessment of the seamount communities of the Phoenix Islands and primarily the PIPA area have been made recently by ROV in March 2017 (Okeanos Explorer expedition “Discovering the Deep: Exploring Remote Pacific Marine Protected Areas”) and October 2017 (RV Falkor expedition “Discovering Deep Sea Corals of the Phoenix Islands”). These assessments primarily focused on the impressive deep-water coral communities associated with seamounts, including those on ferromanganese crusts (Cordes, 2017; Kennedy, 2017).

In this paper we present observations from an opportunistic assessment of some of the first photographs of the abyssal seabed of Kiribati. We aim to describe the variation in epibenthic megafaunal assemblages in the northern Phoenix Islands and Line Islands of Kiribati. We use consistent morphospecies taxonomy with studies carried out in the CCZ, enabling comparison between these areas.

MATERIALS AND METHODS

Study Areas

Data were acquired during the RV Yuzhmorgeologiya expedition to the western Kiribati EEZ, between –1 to 5° N and 173 to 156° W, in the mid Pacific Ocean (Figure 1). Three abyssal areas of interest were defined from W to E within this region: Area A (east of the Phoenix Group Islands, mean water depth: 5460 m), Area B (west of the Line Island Group, mean water depth: 5020 m), and Area C (east of Line Island Group, mean water

depth: 4630 m). Area A and B are ~1200 km apart, separated by an abyssal basin. Areas B and C are ~700 km apart and separated by the Line Islands ridge system (Figure 1). Areas B and C exhibited a similar seafloor geomorphology with slopes <5° and unconsolidated sediment bed (Figure 2A). Area A had similar geomorphology with the exception of one transect (Dive 4, Figure 2B) conducted upon on steeper terrain (>5° slope), where hard substratum was present in the form of partially sediment-covered ferromanganese-coated basalt bedrock and polymetallic nodules (see section “Image Data Collection and Processing”).

Environmental Assessment

Hydrographic Variations

The potential hydrographic isolation between sites was assessed by reference to near-seabed current flows. Since appropriate measurements were not available, seafloor current velocities for areas greater than 3000 m depth were drawn from a high-resolution ocean general circulation model. The model used was a global 1/12° configuration of the Nucleus for European Modeling of the Ocean model (NEMO; Madec, 2008), simulated for the period 1978 to 2010. The model's temperature and salinity fields were initialized using the World Ocean Atlas (WOA) 2005 climatology, and it was forced at the air-sea boundary using the DFS4.1 reanalysis product, which includes observationally-derived 6-hourly fields of atmospheric properties and winds, daily fields of heat fluxes and monthly precipitation fields (Brodeau et al., 2010). Full details of the simulation can be found in Marzocchi et al. (2015).

Biological Assessment

Image Data Collection and Processing

Seafloor images were collected using a digital camera (Canon D60; 3456 × 2304 pixels) mounted on the towed camera system Neptune, developed by the Russian marine institute Yuzhmorgeologiya (Nautilus Minerals, 2016). The Neptune system was towed at a speed of 0.5–1.0 m s⁻¹ and pictures were taken at an altimeter-triggered altitude of 3.5 m above the seafloor, at least every 30 s to avoid overlap between frames. At the target altitude, individual photographs imaged 3.6 m² of seabed. A total of six image transects (Dives 1 to 6) were surveyed using the Neptune system, but each of a different length, as these were originally collected for the geological scouting of the area by Nautilus Minerals (Nautilus Minerals, 2016). Four transects were collected in Area A (Dives 1 to 4), one in Area B (Dive 5), and one in Area C (Dive 6) (Figure 1, Table 1, and Supplementary Table S1). The full resultant dataset was composed of data from 4,074 non-overlapping images, representing a total seafloor area of 14,666 m² (Table 1).

Images were reviewed in random order to minimize time or sequence-related bias (Durdin et al., 2016). Megafauna specimens (>1 cm) were identified to the lowest taxonomic hierarchy possible (morphospecies: typically Genus or Family level; see Supplementary Table S2), and their physical dimension measured, using BIIGLE 2.0 (Langenkämper et al., 2017).

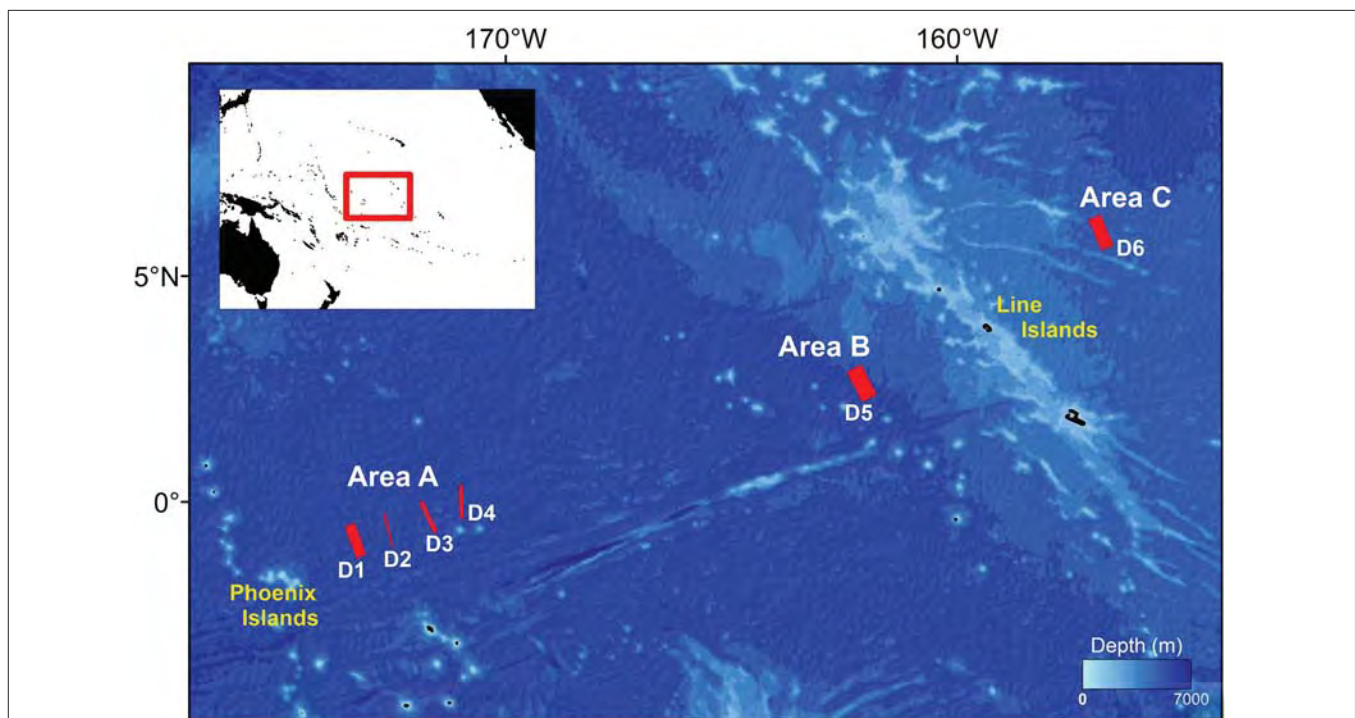


FIGURE 1 | Map of survey locations used for the present study within the eastern Kiribati EEZ. Red lines indicate image transect locations. Line thicknesses represent the relative seabed area coverage (i.e., the length) of each survey dive (D). A map of the mid Pacific Ocean is inset, showing the studied area region (empty red rectangle). Water depth data obtained from Becker et al. (2009). Further survey metadata are provided in **Supplementary Table S1**.

To ensure consistency in specimen identification, an abyssal-Pacific standardized megafauna morphospecies (msp) catalog (e.g., **Figure 3**) was compiled from previous studies in the Pacific basin (Amon et al., 2016; Simon-Lledó et al., 2019a,b,c) and by reference to existing literature (Molodtsova and Opresko, 2017; Kersken et al., 2018; Drazen et al., 2019). The likely feeding behavior of each morphospecies was inferred from similar organisms described in the literature (i.e., Iken et al., 2001). Foraminifera specimens (Protists > 1 cm; miliolids and xenophyophores; see e.g., **Figures 3M–O**) were identified in a subset of 2000 images selected at random across the six transects collected (i.e., half of the images of each transect), and these were only classified into four categories (miliolids and plate-, reticular-, and tubular-shaped xenophyophores).

Data Analysis

Observation data (faunal records in images) were pooled for different study areas to investigate variations in megabenthic characteristics between these. A total of four study areas were considered since observation data from Dive 4 were processed separately (Area A_H) from the rest of Area A data, owing to the different seabed morphology and surface composition in this location (i.e., ~40% of Dive 4 images were collected in areas with >5° slope and hard substratum present). However, the pool of images in Area A_H subsample was about four times smaller than that in each of the other three areas (**Table 1**). Metazoan and foraminiferal data were processed separately and the latter were

excluded from diversity assessments because: (i) it is not possible to determine whether foraminifera are alive in images (Hughes and Gooday, 2004); (ii) the taxonomic resolution allowed in image assessments is lower to that achieved in metazoans (see e.g., Gooday et al., 2017b); and (iii) there is a substantial mismatch between the biomass of metazoan and foraminifera specimens, since the protoplasm volume of the latter represents only 1–0.01% of their visible test (Levin and Gooday, 1992; Gooday et al., 2018).

Observation data from each area (Areas: A, A_H, B, and C) were resampled using a modified form of bootstrapping (Davison and Hinkley, 1997). Bootstrapping is a statistical method for estimating the distribution of a given parameter (or a set of these) by sampling with replacement from the original sample. Resampling techniques provide robust estimates of standard errors and confidence intervals of sample parameters (Crowley, 1992; Rodgers, 1999), and are particularly well suited to analyze data derived from survey designs that lack true sample replication (see e.g., Simon-Lledó et al., 2019b). To implement the bootstrap, each study area image data subset was randomly resampled with replacement until a minimum of 500 m² of seafloor (139 images) were encompassed, and that process was repeated 1000 times for each area. This resampling process yielded bootstrap-like samples (bootstrap generated sub-samples with fixed size) that ranged in metazoan specimen counts of 17–140. The same process was repeated using only those images where foraminifera were identified, which yielded bootstrap-like samples with foraminiferal specimen counts of 233–2042. We adopted this controlled seabed

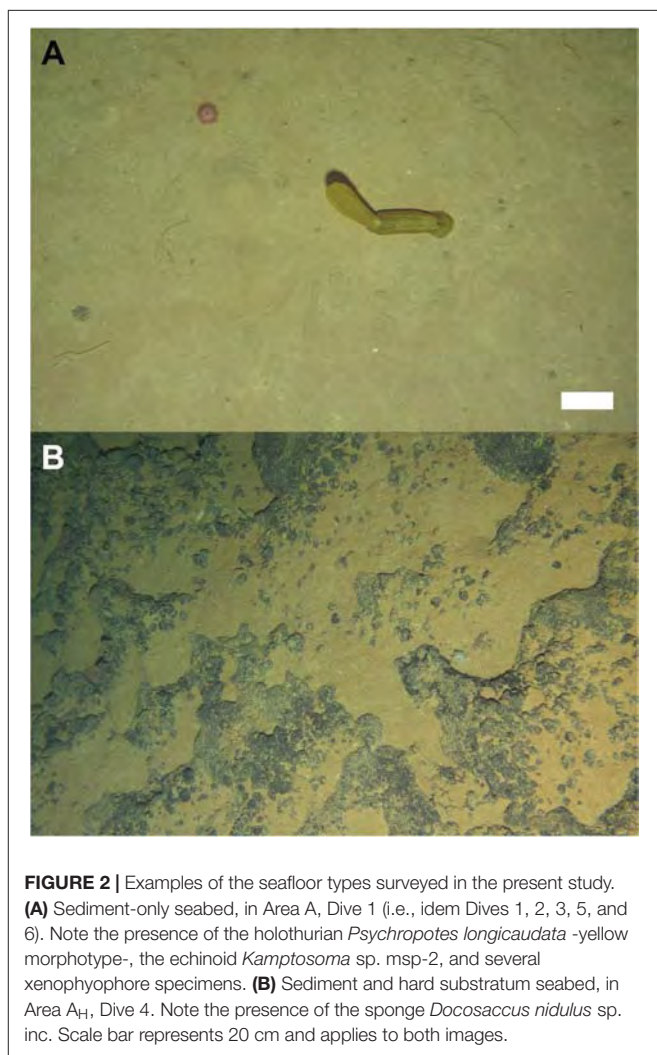


FIGURE 2 | Examples of the seafloor types surveyed in the present study. **(A)** Sediment-only seabed, in Area A, Dive 1 (i.e., idem Dives 1, 2, 3, 5, and 6). Note the presence of the holothurian *Psychropotes longicaudata* -yellow morphotype-, the echinoid *Kamptosoma* sp. msp-2, and several xenophyophore specimens. **(B)** Sediment and hard substratum seabed, in Area A_H, Dive 4. Note the presence of the sponge *Docosaccus nidulus* sp. inc. Scale bar represents 20 cm and applies to both images.

area approach to control the impact of the physical sample size on the estimation of biological diversity and faunal composition parameters.

A range of ecological parameters was calculated for each of the 4×1000 bootstrap-like samples, including metazoan and foraminiferal numerical density (ind m^{-2}) and metazoan taxa density, i.e., morphospecies richness (S) in $c. 500 \text{ m}^2$. Variation in metazoan community composition was assessed by 2-d non-metric multidimensional scaling (nMDS) ordination of all 4×1000 bootstrap-like samples, based on square-root transformed faunal density and use of the Bray-Curtis dissimilarity measure (Clarke, 1993). Mean values of these parameters were calculated from each bootstrap-like sample set, together with corresponding 95% confidence intervals based on the simple percentile method (Davison and Hinkley, 1997). Data processing and analyses were performed using a custom R (R Core Team, 2017) script incorporating multiple functions from the “vegan” package (Oksanen et al., 2018). We report statistical assessments of variations in ecological parameters between study areas by comparisons of the 95% confidence intervals, i.e., the upper limit of a given estimate must be lower

TABLE 1 | Environmental features and sampling details in each of the survey locations investigated in the present study.

	A	A _H	B	C
Survey dive(s)	D1-D3	D4	D5	D6
Center latitude (°)	-0.7404	-0.0001	2.5958	5.9568
Center longitude (°)	-172.9507	-171.0011	-162.1570	-156.8213
Water depth m; min-max)	5536-5224	5575-5250	5116-5020	4667-4631
Images	1400	265	1172	1237
Total area (m^2)	5040	954	4219	4453
POC flux* ($\text{g C}_{\text{org}} \text{m}^{-2}$ y^{-1} ; min-max)	1.83-1.96	1.97-1.99	1.75-1.83	1.50-1.56
Bottom current speed (m s^{-1} ; min-max)	0.01-0.04	0.01	0.003-0.005	0.008-0.01

*Values interpolated from image locations based on Lutz et al., 2007.

than the lower limits of the estimate that is compared to. Such cases are significant at $p < 0.05$, though the true (undetermined) p -value will, necessarily, be considerably lower.

Additionally, a rarefaction approach was applied to assess the potential impact of sampling unit size on morphospecies density (Chao et al., 2014). Sampling unit size was quantified as both number of individuals and seabed area observed. Metazoan observation data for each separate survey area, and for the whole dataset combined, were randomly resampled 100 times without replacement, to form increasingly larger image sampling units. The mean and 95% confidence intervals of each parameter were calculated at each sampling unit size using Estimate S v.9.1 software (Colwell, 2013).

RESULTS

Hydrographic Variations

Modeled bottom current speeds in seabed areas below 3000 m water depth within the Kiribati EEZ ranged between 0.001 and 0.1 m s^{-1} (Figure 4A). Modeled current speeds in the seafloor of Areas A, A_H, and C were similar ($\sim 0.01 \text{ m s}^{-1}$) and substantially stronger than those obtained for Area B (Table 1). Model results suggested that the current speed at the seabed area where Dive 01 was collected (in Area A) was ~ 4 times stronger than in the rest of Area A survey locations.

Megafauna Assessment

Foraminiferal tests numerically dominated the assemblages recorded during the present study; being overall, almost 15 times more abundant than metazoans (Figure 5). A total of 15,196 foraminifera specimens (in $7,200 \text{ m}^2$ of seabed) and 1948 metazoans (in $14,666 \text{ m}^2$ of seabed), all $> 1 \text{ cm}$, were recorded across all the study areas surveyed within the Kiribati EEZ.

Metazoan Megafauna

A total of 118 metazoan morphospecies, and 5 higher taxonomic categories (i.e., Order, Family), were documented from images (Table 2 and Supplementary Table S2). Rare taxa (≤ 3 records) represented 46% of the total metazoan morphospecies richness.

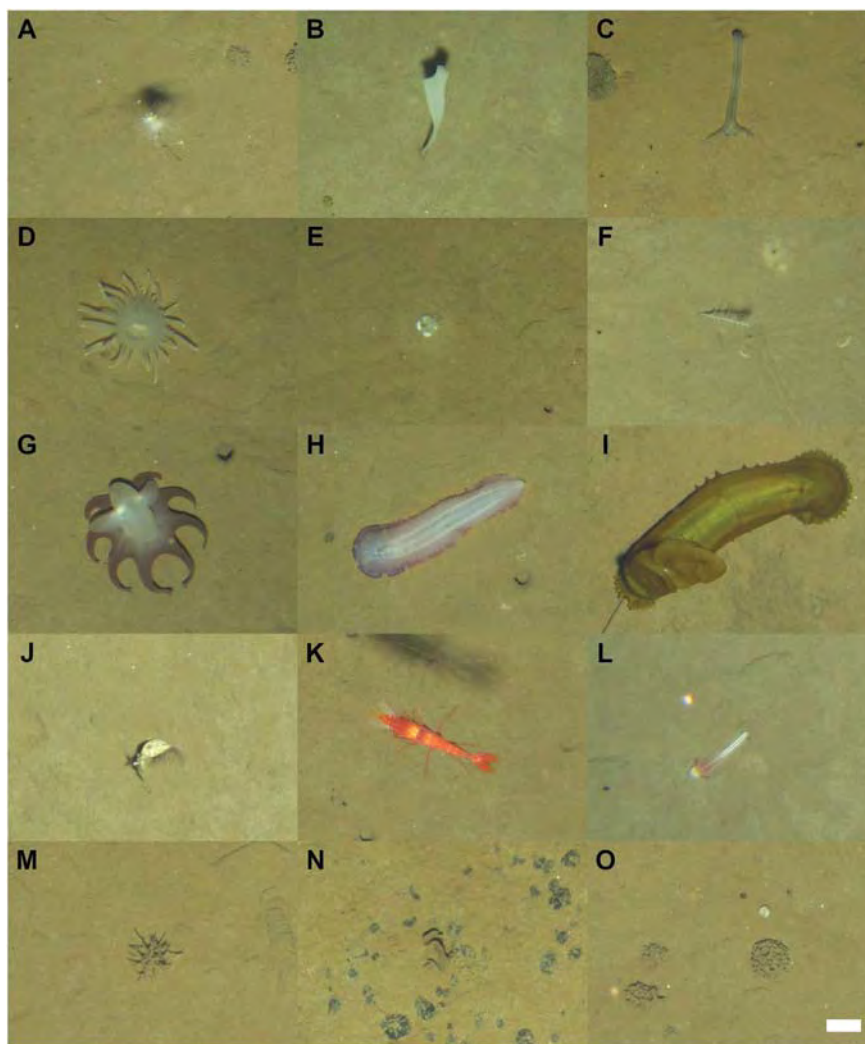


FIGURE 3 | Examples of megafauna photographed at the Kiribati EEZ seafloor during Neptune towed-camera surveys. Scale bar represents 5 cm and applies to all images. **A–L**: Metazoan megafauna. **(A)** *Cladorhiza* sp. msp-4. **(B)** Porifera msp-20. **(C)** Echiura msp-3. **(D)** Actiniaria msp-10. **(E)** Actiniaria msp-36. **(F)** *Bathygorgia* sp. msp-2. **(G)** *Grimpoteuthis* sp. msp-1. **(H)** *Paelopatides* sp. msp-4. **(I)** *Psychropotes longicauda*, yellow-morphotype. **(J)** *Neoscalpellum* msp-1. **(K)** *Cerataspis* sp. msp-3. **(L)** *Torquaratoridae* sp. msp-2. **M–O**: Foraminifera specimens. **(M)** Tubular-shaped xenophyophore. **(N)** Plate-shaped xenophyophore **(O)** Miliolid (white round specimen) and three reticular-shaped xenophyophores.

The metazoan fauna observed were predominantly cnidarians (19 msp; 36% of all metazoan records), arthropods (10 msp; 20% of all metazoan records), sponges (22 msp; 17% of all metazoan records), and echinoderms (37 msp; 15% of all metazoan records). Annelids, chordates, and molluscs (as well as bryozoans, ctenophores, and an enteropneust worm) were also recorded at lower abundances (**Table 2** and **Supplementary Table S2**). Suspension feeding organisms represented >60% of all the metazoan specimens recorded, while deposit feeders and predators and scavengers represented 16 and 23% of all metazoan records, respectively. The three most abundant metazoan morphospecies were: an actinarian (*Actiniaria* msp-22; 240 specimens), a barnacle (*Neoscalpellum* sp. msp-1; 150 specimens; **Figure 3J**), and a hexactinellid sponge (*Docosaccus maculatus* sp. inc.; 78 specimens).

Variations in standing stocks

Metazoan numerical density was variable across the different areas surveyed (**Figure 6A**) with mean values ranging between 0.07 and 0.3 ind m⁻² (in samples c. 500 m²). Metazoan density was lower in Area B than in Areas A and C, which were similar. In Area A_H, mean metazoan density was around twice that of the rest of Area A and Area C, and was almost five times higher than the density found in Area B (**Figure 6A**). These variations primarily resulted from changes in the suspension feeder standing stock across survey areas (**Figure 6B**). Suspension feeder density was considerably reduced in Area B compared to Areas C and A, and was substantially higher in A_H than in any other study area. Densities of deposit feeder (**Figure 6D**) and predator and scavenger metazoan fauna (**Figure 6F**) were similar across study areas.

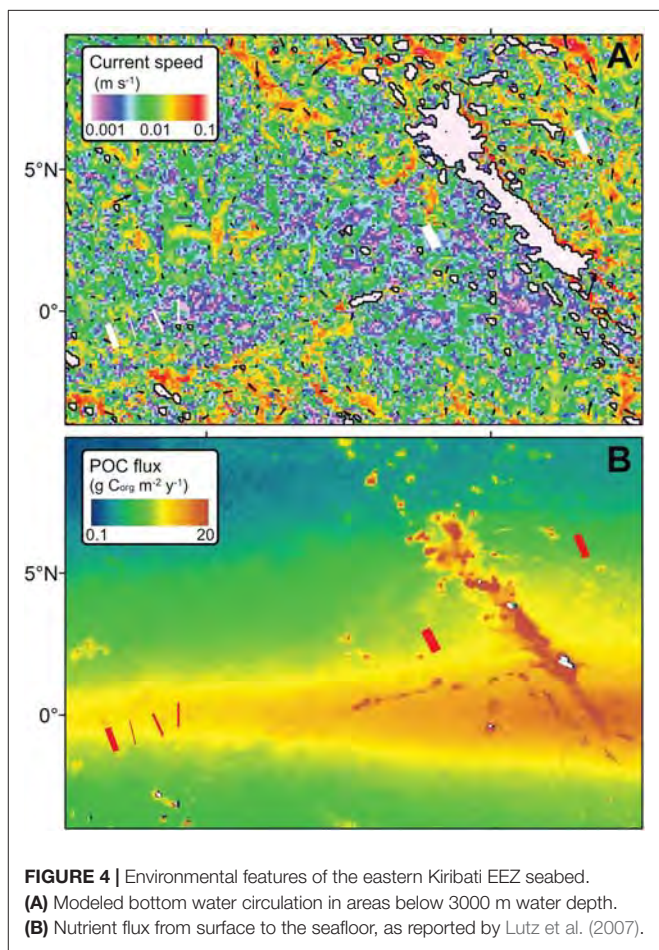


FIGURE 4 | Environmental features of the eastern Kiribati EEZ seabed. (A) Modeled bottom water circulation in areas below 3000 m water depth. (B) Nutrient flux from surface to the seafloor, as reported by Lutz et al. (2007).

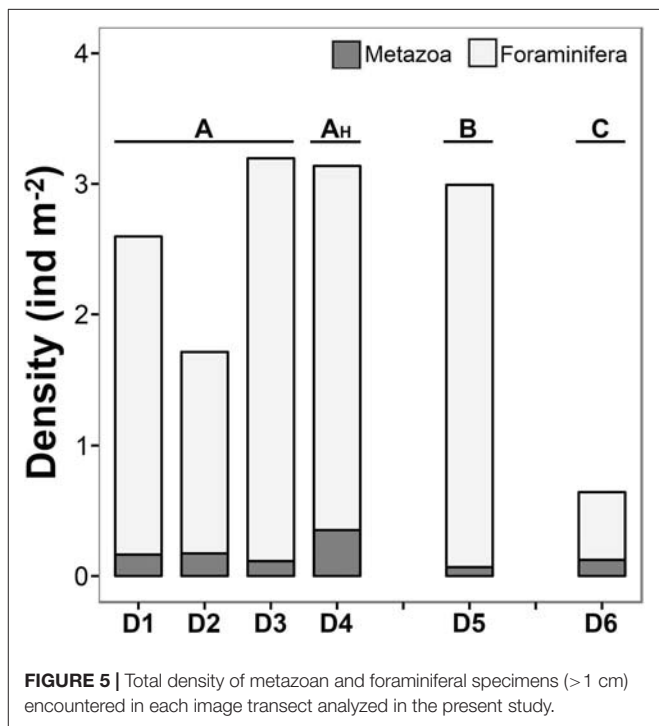


FIGURE 5 | Total density of metazoan and foraminiferal specimens (> 1 cm) encountered in each image transect analyzed in the present study.

TABLE 2 | Total abundance and taxon richness of major metazoan taxa encountered during the present study.

Phylum	Class	Order	Morpho species	Area B	Area A _H	Area B	Area C	
Porifera	Indet. Class		4	19	22	12	20	
	Demospongiae		5	4		7	5	
	Hexactinellida		13	45	14	27	157	
Ctenophora	Tentaculata		3	4				
Cnidaria	Anthozoa	Actiniaria	8	349	126	23	49	
		Alcyonacea	5	13	42	1	11	
		Ceriantharia	3	35	2	25	11	
		Corallimorpharia	1				2	
		Pennatulacea	1	2		2	7	
		Hydrozoa	Trachymedusae	1	3		3	
Bryozoa	Gymnolaemata		2	1	12	1	6	
Annelida	Polychaeta		9	25	46	32	51	
Arthropoda	Hexanauplia		1	52	7	15	76	
		Malacostraca	Amphipoda	2		4	2	1
			Decapoda	4	28	8	30	26
			Isopoda	3	52	13	9	24
			Mysida	1	9	11	1	5
Mollusca	Gastropoda		1	3	2	4	2	
			Scaphopoda	1			4	
		Cephalopoda	Octopoda	1	1		1	
Echinodermata	Asteroidea		5	5	1	2	7	
			Crinoidea	4	4	4	1	1
	Echinoidea	Echinothurioida	2	16	2	2	54	
	Holothuroidea		23	71	6	21	6	
	Ophiuroidea		3	28	4	57	8	
Hemichordata	Enteropneusta		1			1		
Chordata	Ascidiacea		4	9	1	1		
		Actinopterygii	7	3		8	19	

Further taxonomic detail, at the morphospecies level, is provided in **Supplementary Table S2**. The taxonomic nomenclature used follows Horton (2018).

Variations in diversity and composition

Mean metazoan morphospecies richness ranged between 19.6 and 29.6 (S, in samples c. 500 m²) across the different areas surveyed (Figure 6C). Area B exhibited the lowest mean taxa richness and Area A_H the highest, but variations between areas were not substantial (i.e., overlapping confidence intervals: Figure 6C). Morphospecies richness curves showed no significant variations between different study areas in sample sizes up to 4,000 m² (Figure 7A). However, individual-based assessments (Figure 7B) revealed a different taxa accumulation pattern in Area B, which indicates that the lower taxon richness found in this area resulted from its inherent lower faunal density, as opposed to Area A_H. These patterns were consistent at whole study level (dashed-depicted accumulation curves; Figure 7).

In total, 33% of the metazoan morphospecies recorded were present in all three study areas, 18% were noted in only two areas, and 49% were detected in only one area (Figure 8A). More than half (53%) of the records exclusively found in a single area were singletons. Areas A and B shared a larger number of metazoan taxa (50%) than Area C with Areas A

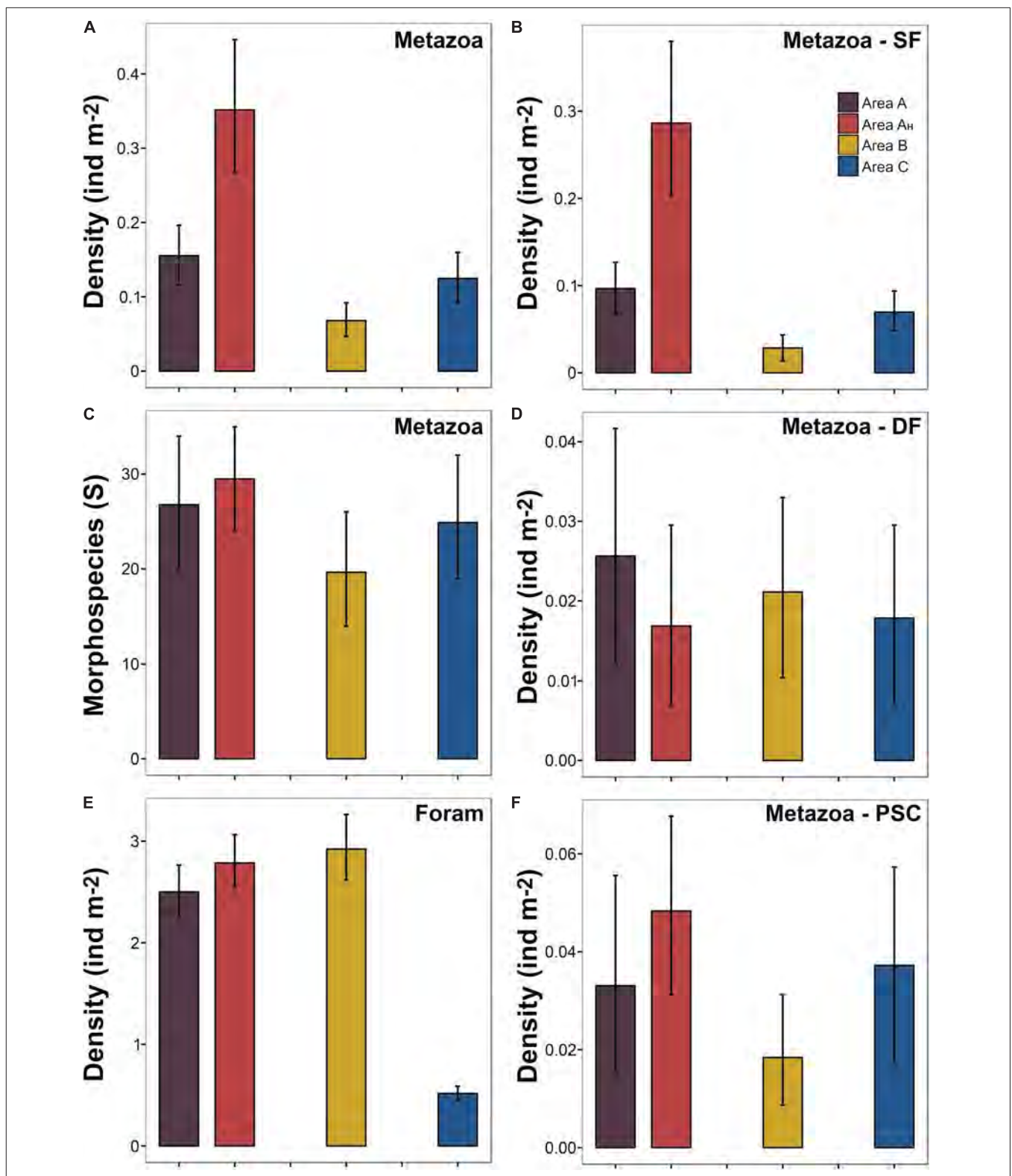


FIGURE 6 | Variation in different biological parameters across the areas surveyed. Bars indicate mean density calculated from the bootstrap-like sample set generated for each area. Error bars represent 95% confidence intervals. **(A)** Density of metazoan fauna (note that B, D, and F are each a subset of A). **(B)** Density of metazoan suspension feeder fauna. **(C)** Metazoan morphospecies richness (in c. 500 m² samples). **(D)** Density of metazoan deposit feeders. **(E)** Density of foraminiferal tests. **(F)** Density of metazoan predator and scavenger fauna. Abbreviations: *Foram*: foraminifera; *SF*: suspension feeders; *DF*: deposit feeders; and *PSC*: predators and scavengers.

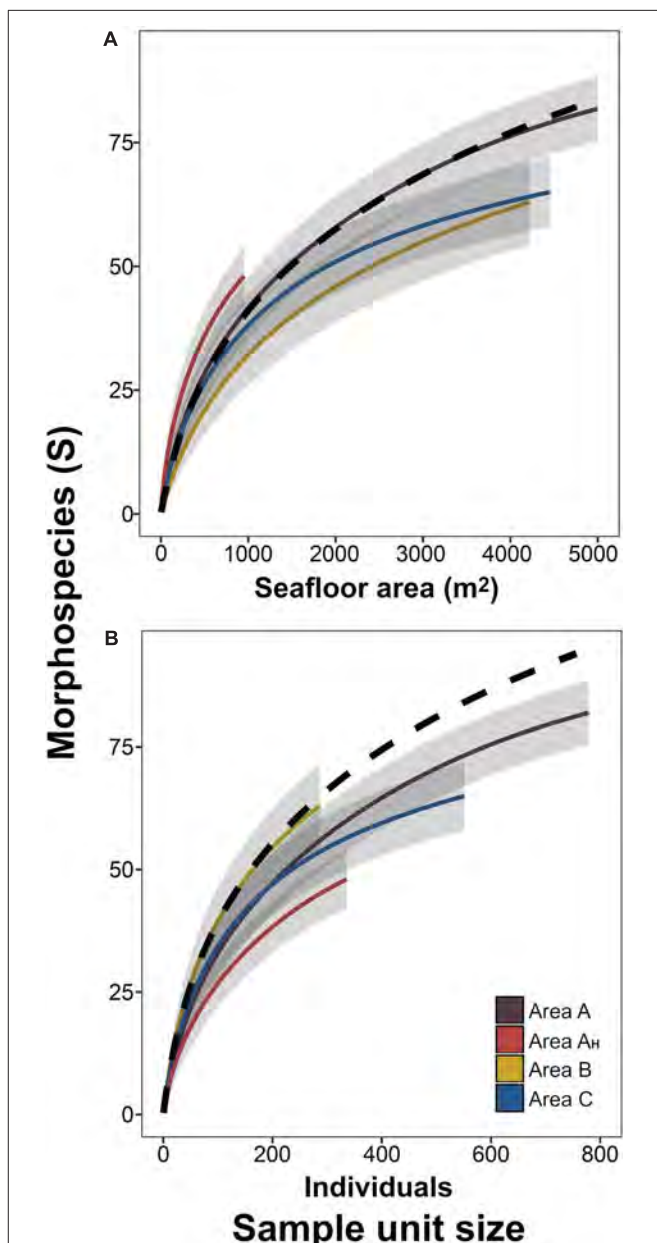


FIGURE 7 | Metazoan morphospecies accumulation curves for each survey area. Curves were calculated as a function of the seabed area (A) or the number of individuals encompassed by the sample unit size (B). Lines represent mean values across the 100 randomizations performed at each sample unit size increase, for each study area. Shading representing 95% confidence intervals. Dashed line represents mean values of curve calculated using whole-study collated data.

(36%) and B (35%). Two dimensional ordination of faunal composition by density readily distinguished Area A, B, and C samples, and Area A_H samples from the rest of Area A (Figure 8B). However, within-site dissimilarity was substantial in Areas A, B, and C, with Area B exhibiting the highest heterogeneity; some bootstrap-like samples generated for Area B showed a higher similarity to those generated for Areas

A and C than to other Area B samples. Density distribution of the four most-abundant metazoan phyla across study areas was variable (Figure 9). While the mean density (in samples c. 500 m²) of arthropods and particularly echinoderms was similar across study areas (Figures 9C,D), the mean density of cnidarians was substantially higher in Area A, especially in Area A_H, compared to the other two areas (Figure 9A). On the other hand, mean sponge density (in samples c. 500 m²) was substantially higher (and similar) in Areas A_H and C compared to that in Areas A and B (Figure 9B). The most remarkable variations in distribution at the morphospecies level between study areas were: (i) 95% of all Actiniaria msp-22 records ($n = 228$) were found in Areas A and A_H; (ii) 97% of all the records ($n = 76$) of the sponge *Docosaccus maculatus* sp. inc. were found in Area C, (iii) 97% of all the records ($n = 43$) of the holothurian *Psychropotes longicaudata* (yellow morphotype; Figure 3I) were found in Areas A and B, while only one specimen was recorded in Area C, and (iv) all the records ($n = 14$) of the fish *Ipnops meadi* were found exclusively in Area C.

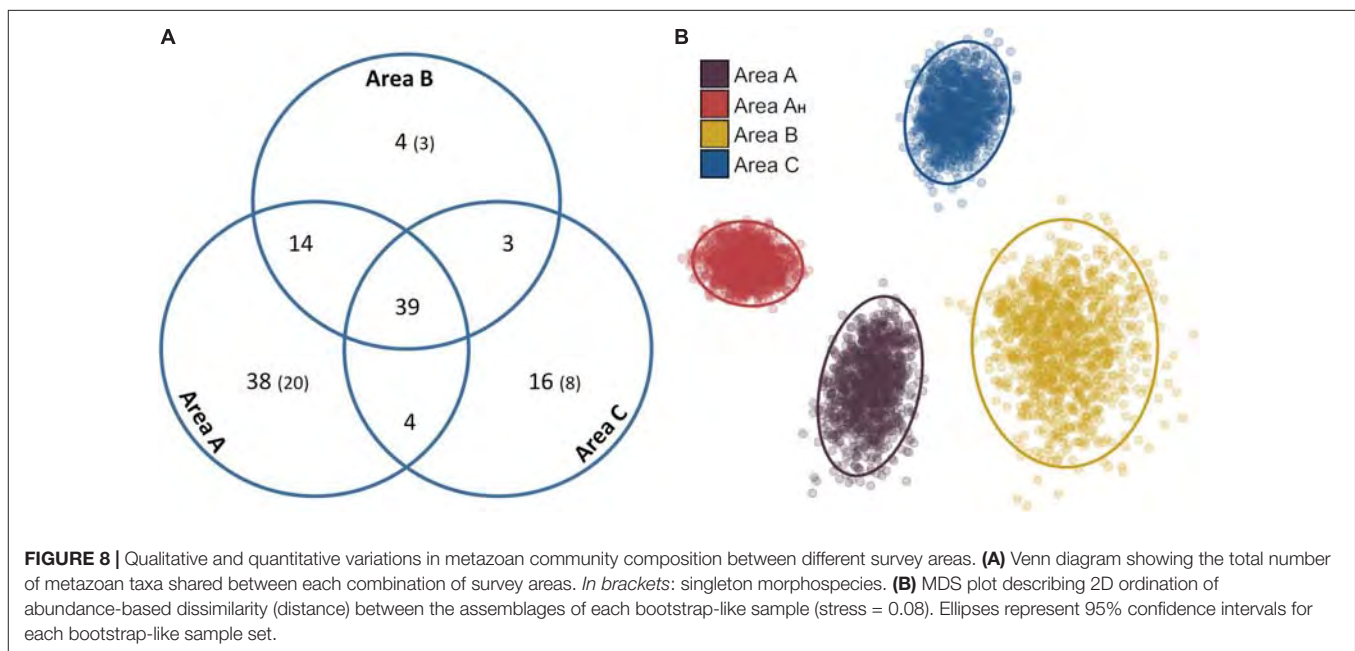
Foraminiferal Megafauna

Most foraminiferal specimens observed were xenophyophores exhibiting reticulated (57%), plate-shaped (36%), and tubular (4%) morphologies, while miliolids represented only a small fraction (3%). Mean numerical density of foraminiferal tests was variable across the different areas surveyed (0.5 to 2.9 ind m⁻²), but exhibited different between-site patterns to those recorded in metazoan fauna (Figure 6E). Mean foram density was almost 6 times lower in Area C than in Areas A and B, and test density in Area A_H was similar to that in the rest of Area A (Figure 6E). Reticulated xenophyophore morphospecies dominated the foraminiferal assemblages in Areas A (53%) and B (67%), while plate-shaped forms dominated the foraminiferal assemblages in Areas A_H (47%) and C (50%). Total miliolid density in Area A (1230 ind ha⁻¹) was higher than in Areas B (495 ind ha⁻¹) and C (15 ind ha⁻¹).

DISCUSSION

Environmental Setting

Modeled bottom current speeds in the studied areas were relatively modest (~ 0.01 cm s⁻¹) compared to the ranges estimated below 3000 m water depth in the Kiribati region (~ 0.001 to ~ 0.1 m s⁻¹; Figure 4A). Bottom current speed ranges obtained in our model were broadly comparable to those reported from *in situ* observations performed in eastern (Aleynik et al., 2017) and western (Hayes, 1979) areas of the CCZ. In turn, presumed ranges of vertical nutrient supply amongst the studied areas (1.50–1.99 g C_{org} m⁻² y⁻¹) were only comparable to those in more southern areas of the CCZ (Lutz et al., 2007; Figure 4B) as spring blooms in surface waters are more pronounced toward the equator (Pennington et al., 2006). As a result, despite that Area C is found ~ 1000 m shallower than Areas A and B, and food supply usually decreases inversely with water depth (Buesseler et al., 2007), the closer proximity of Areas A and B to the equator



is presumed to provide these with a comparably higher vertical nutrient input than Area C (Lutz et al., 2007).

Metazoan Megafauna Standing Stocks

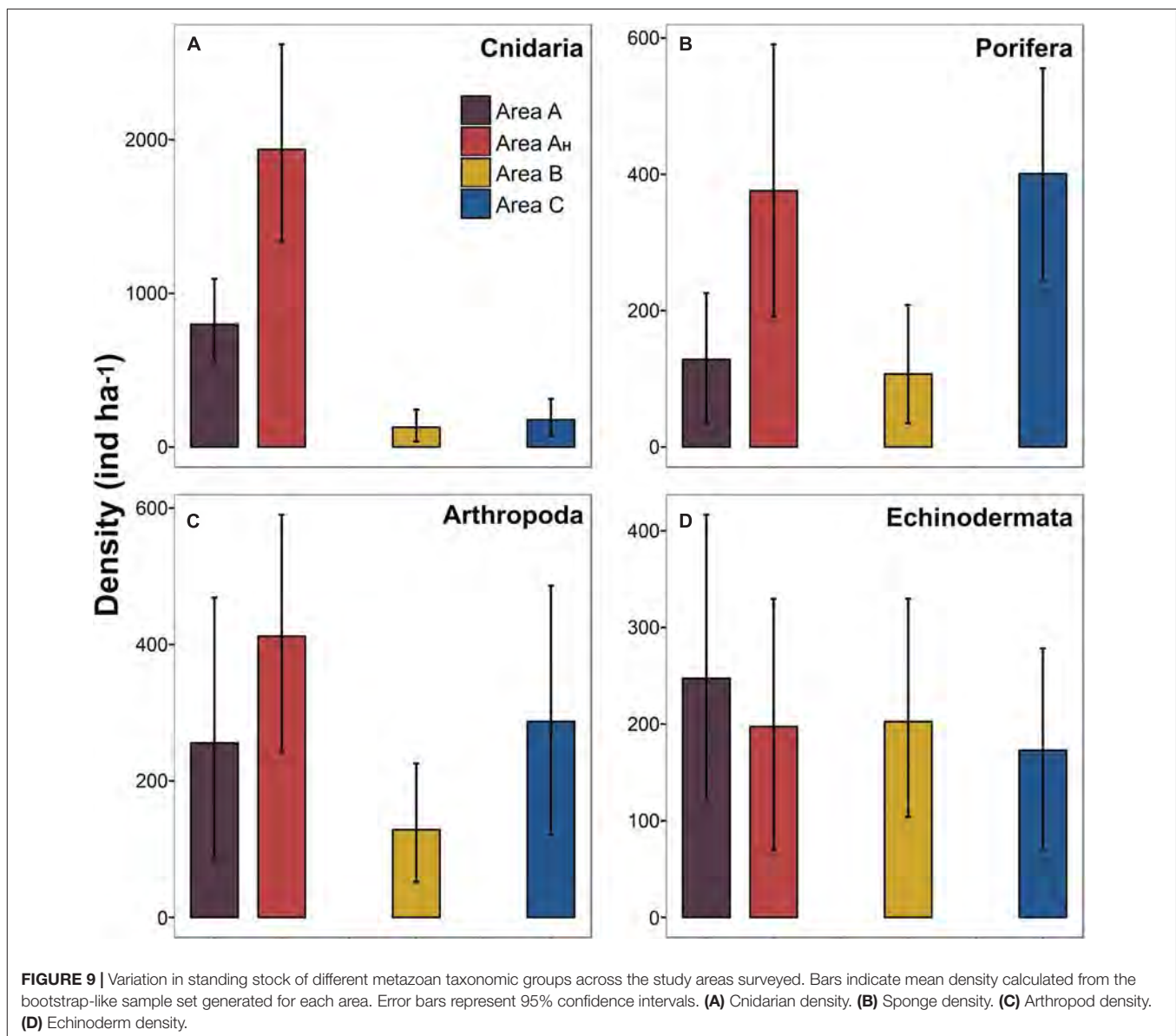
Metazoan standing stocks varied across the abyssal locations explored. Perhaps contrary to expectation, environmental factors differing between study areas (Table 1) that typically affect faunal density, such as water depth (Rex et al., 2006) and surface production (Johnson et al., 2007), appeared to have no observable effect on the relative megabenthic standing stock across study areas. The metazoan density surveyed in Area C was similar to that in Area A despite the comparably higher food supply that Area A is presumed to have (Lutz et al., 2007, Figure 4A). It is important to consider that differences in metazoan abundance across the areas surveyed were predominantly a result of variations in suspension feeder fauna density (e.g., sessile cnidarians and sponges). These organisms clearly dominated the metazoan megabenthos of the Kiribati abyss, with densities about an order of magnitude higher than those observed in deposit feeding or predator and scavenger fauna, a pattern that has been commonly reported in eastern areas of the CCZ (Amon et al., 2016; Simon-Lledó et al., 2019a). Deep-sea suspension feeder standing stocks are sensitive to variations in bottom water current speeds as these can alter the flux of laterally transported organic particles (Thistle et al., 1985; Angel and Boxshall, 1990). The substantially reduced presence of suspension feeders in Area B may hence be influenced by the comparably weaker bottom water circulation strength expected in this location (Table 1 and Figure 4A). These results suggest that the available environmental information was not sufficient to predict megabenthic standing stocks in this region, which may result from scale mismatches and local effects being more important than broad-scale generalizations.

Therefore, further environmental characterization of the Kiribati abyssal seabed will be needed to fully understand the controls on metazoan abundance.

Area A_H, the only survey location where some hard substratum was present in the seabed (i.e., partially sediment-covered exposed bedrock and polymetallic nodules), exhibited a substantially larger metazoan standing stock than the other study areas (Figure 6A) as a result of an enhanced abundance of sessile cnidarians (i.e., Actiniaria and alcyonacea; Table 2 and Figure 9A). Simon-Lledó et al. (2019b) recently showed that the availability of hard substratum can be key in the regulation of standing stocks and assemblage composition in abyssal megabenthic communities. For instance, at the CCZ, populations of sessile cnidarians are usually significantly reduced in areas where polymetallic nodules are absent (Vanreusel et al., 2016; Simon-Lledó et al., 2019b), as some of these taxa are typically obligate hard-substratum dwellers (Amon et al., 2016; Lim et al., 2017). In turn, metazoan densities observed in sediment-only areas (Area A, B, and C) were comparable to those reported in nodule-free areas explored in the eastern CCZ (Simon-Lledó et al., 2019b) using a similar image-sampling methodology (i.e., similar altitude of collection above-seabed and resolution). These results support that the availability of hard substratum in abyssal sedimentary habitats may be an important environmental driver in the structuring of local megabenthic communities. However, the total area surveyed in Area A_H (~1000 m² of seabed) was substantially lower than those in the other study areas (i.e., 4200–5000 m²) and hence comparisons between this area and the rest should be drawn with caution, as a larger sampling effort may reveal further/different biological features.

Diversity and Assemblage Compositions

We found similar mean metazoan taxa richness across study areas, but taxa accumulation patterns suggested that the



sampling effort applied was insufficient to fully characterize the richness of each separate study area (Figure 7). The low metazoan density characteristic of the North Pacific abyss, especially on sediment beds, can limit the representativeness of image-based megafauna samples (Simon-Lledó et al., 2019a). While the assessment of faunal density in deep-sea benthic environments typically requires relatively small sample sizes (e.g., >30 individuals per sample; Benoist et al., 2019; Simon-Lledó et al., 2019a), precise characterization of taxa richness and composition usually require a larger number of individuals in each sample (e.g., >500 individuals and >140 individuals per sample, respectively; Benoist et al., 2019; Simon-Lledó et al., 2019a) than was possible to obtain here (samples c. 500 m², range: 27–151 individuals per sample). Consequently, while discussions of patterns across the areas studied here are presumably robust in terms of standing stocks, our results

should be interpreted with caution with respect to community composition and are best limited to whole-of-study-area with respect to taxa richness. The total metazoan richness recorded in the Kiribati abyss (118 morphospecies: Table 2 and Supplementary Table S2) upon collation of all sample data (1948 metazoans) was comparable to that found in eastern CCZ locations, like the APEI6 (7837 metazoans, 133 taxa: Simon-Lledó et al., 2019b) or the UK-1 area (~3500 metazoans, ~126 taxa: Amon et al., 2016). Synthesis studies collating taxonomical data across all these studies are critical to determine the variability and biogeographical patterns across the North Pacific abyss.

Qualitative and quantitative analyses enabled a preliminary interpretation of variations in faunal composition across the areas studied. Qualitatively, a larger shared morphospecies pool was found between Areas A and B (42%) than between

each of these and Area C (34–33%) (**Figure 8A**). A possible explanation is that the Line Islands volcanic ridge may isolate Area C populations from those to the west, as shown for other ridge systems on the abyssal plains (Carey, 1981; McClain et al., 2009). However, there was still a relatively large pool of shared taxa (30%) across all the areas, despite the large spatial distances (e.g., Area A to C: ~2000 km) and the relatively small specimen sample sizes obtained, so dispersal pathways could exist (**Figure 1**). In contrast, quantitatively, faunal compositions varied across the four areas investigated (**Figure 8B**) owing to differences in the relative density of particular suspension feeder taxa between areas, such as sessile cnidarians and sponges (**Figures 9A,B**). Metazoan assemblages in Area A were numerically dominated by actinarians (e.g., *Actinaria* msp-22), whilst hexactinellid sponges (e.g., *Docosaccus maculatus* sp. inc.) dominated the assemblages in Area C. Moreover, the availability of hard substratum in Area A_H appeared to generate a different metazoan aggregation than in the rest of Area A, with an enhanced presence of hard-substratum-dwelling taxa (e.g., alcyonacea soft corals; Cairns, 2016), as typically occurs between nodule-free and nodule-bearing sites at the local scale within the CCZ (Vanreusel et al., 2016; Simon-Lledó et al., 2019b). Results of quantitative analysis of composition were driven by the different faunal abundances encountered across the areas studied. For instance, the mean number of individuals encountered in Area A_H (fixed area) samples was 96 (± 11 standard deviation) while this number was 35 (± 6 standard deviation) in Area B samples. Consequently, while Area B exhibited the largest within-site heterogeneity, Area A_H exhibited the most homogeneous assemblage (e.g., **Figure 8B**). These results suggest that further, larger, and comprehensively designed surveys will need to be conducted across the abyssal areas of Kiribati to determine if the preliminary patterns in richness and composition drawn in this study are consistent at larger scales. Future assessments should be sensitive to the environmental stratification (e.g., seabed composition, geomorphological setting, depth, etc.) that can drive biological variations and also to the low density -yet high richness- that is characteristic of metazoan megabenthic communities in the abyssal Pacific (Amon et al., 2016; Simon-Lledó et al., 2019a, this study).

Foraminifera Assemblages

Foraminiferal specimens (forams; xenophyophores and miliolids, **Figures 3M–O**) numerically dominated the megabenthic assemblages in the Kiribati abyss; being overall, an order of magnitude more abundant than metazoans, and reaching a peak density of 16.6 ind m⁻² in an image from Area B. These results are consistent with previous assessments in abyssal Pacific megabenthic communities, which are typically dominated by giant foraminifera (Kamenskaya et al., 2013; Simon-Lledó et al., 2019a). Standing stocks of the larger sized fauna decrease dramatically with water depth (Rex et al., 2006) as diminishing food supply appears to prevent growth to larger body sizes (McClain et al., 2005). This hypothesis is consistent with the large dominance

of foraminifera in the abyssal megabenthos, as their protoplasm volume represents a minor fraction of their visible test (Levin and Gooday, 1992), and because benthic bacteria dominate carbon consumption of these ecosystems (Sweetman et al., 2019).

Mean foram density in Areas A and B was comparable, though slightly lower, to that found in eastern CCZ locations surveyed using a similar sampling methodology (Simon-Lledó et al., 2019a). Forams are a key group in the functioning of abyssal Pacific communities (Kamenskaya et al., 2013), particularly at the CCZ, where these organisms are exceptionally diverse and abundant (Gooday et al., 2017a). The substantially reduced xenophyophore density within Area C is hence remarkable (**Figure 6E**), and somewhat unexpected given the closer proximity of this location to the CCZ compared to Areas A and B. Moreover, previous studies have shown increased abundances of xenophyophores in areas where hard substratum is present (Amon et al., 2016; Simon-Lledó et al., 2019b) as a result of the hard-substratum-attached life-habit of some taxa (Kamenskaya et al., 2013; Gooday et al., 2015). However, we found no substantial differences in the foram density between Area A_H and the rest of Area A, despite the availability of hard substratum in the former, but only a shift in dominance from reticular to plate-shaped morphologies. Further investigation of the factors driving the development of foram taxa in abyssal depths is in urgent need, particularly in the North Pacific, where their extremely large abundance has been suggested to play a crucial role in providing habitat structures and enhancing the organic content of sediments surrounding their tests (Gooday et al., 2017a).

CONCLUSION

This study presents the first quantitative assessment of megafauna in the abyssal benthos of Kiribati, and an example of successful collaboration between industry and academic research. We found clear differences in the density of both the metazoan and the foraminiferal standing stocks across the study areas, but little if any substantive variation in biological diversity, and a potentially sample-size biased variation in community composition. Despite the low metazoan faunal density recorded, this study provides evidence of the high biodiversity of megafauna found in the Kiribati abyss. However, only a minor proportion of Kiribati's deep seabed has been targeted for biological exploration (Rotjan et al., 2014; Cordes, 2017; Kennedy, 2017; this study), and hence further research will be required to characterize the true taxonomic richness of benthic communities in this region. Although no commercial activities have been proposed to date in the Kiribati abyss, future conservation plans and exploration efforts within this area should consider the high biodiversity and low density of megabenthic populations reported in this study if they are to be effective.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the manuscript/**Supplementary Files**.

AUTHOR CONTRIBUTIONS

All authors contributed to the design and implementation of the experimental strategy. JP, AF, and CP supervised the collection and processing of the seafloor imagery data. AY conducted the hydrographic data analysis. ES-L, ST, and CP performed the biological annotation of images. ES-L, AF, and DJ steered the biological survey design. ES-L and ST conducted biological data analysis. ES-L drafted the manuscript, which was critically revised and accepted by all the co-authors.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fmars.2019.00605/full#supplementary-material>

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Conflict of Interest: AF was employed by company Fathom Pacific. JP and CP were employed by company Nautilus Minerals.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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(54) **DECOUPLED SEAFLOOR MINING SYSTEM**

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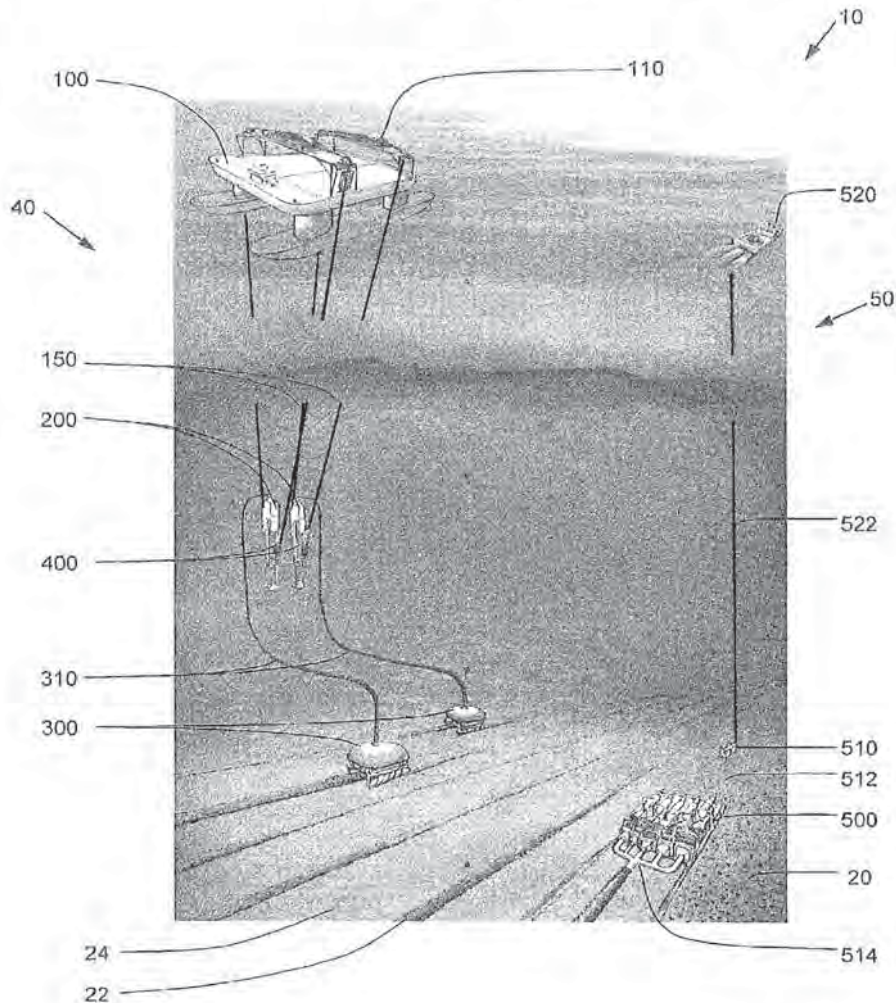
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(57) **ABSTRACT**

A multi-stage seafloor mining system that has at least
concentration stage, a reclamation stage, and a haulage
stage. The system includes a concentrating system (50)
that processes seafloor materials, a reclaimer machine (300)
that collects the processed seafloor materials, and a mechanical
haulage system (40) that receives the processed seafloor
materials collected by the reclaimer machine (300) and
conveys discrete parcels of the processed seafloor materials
to a surface vessel (100).



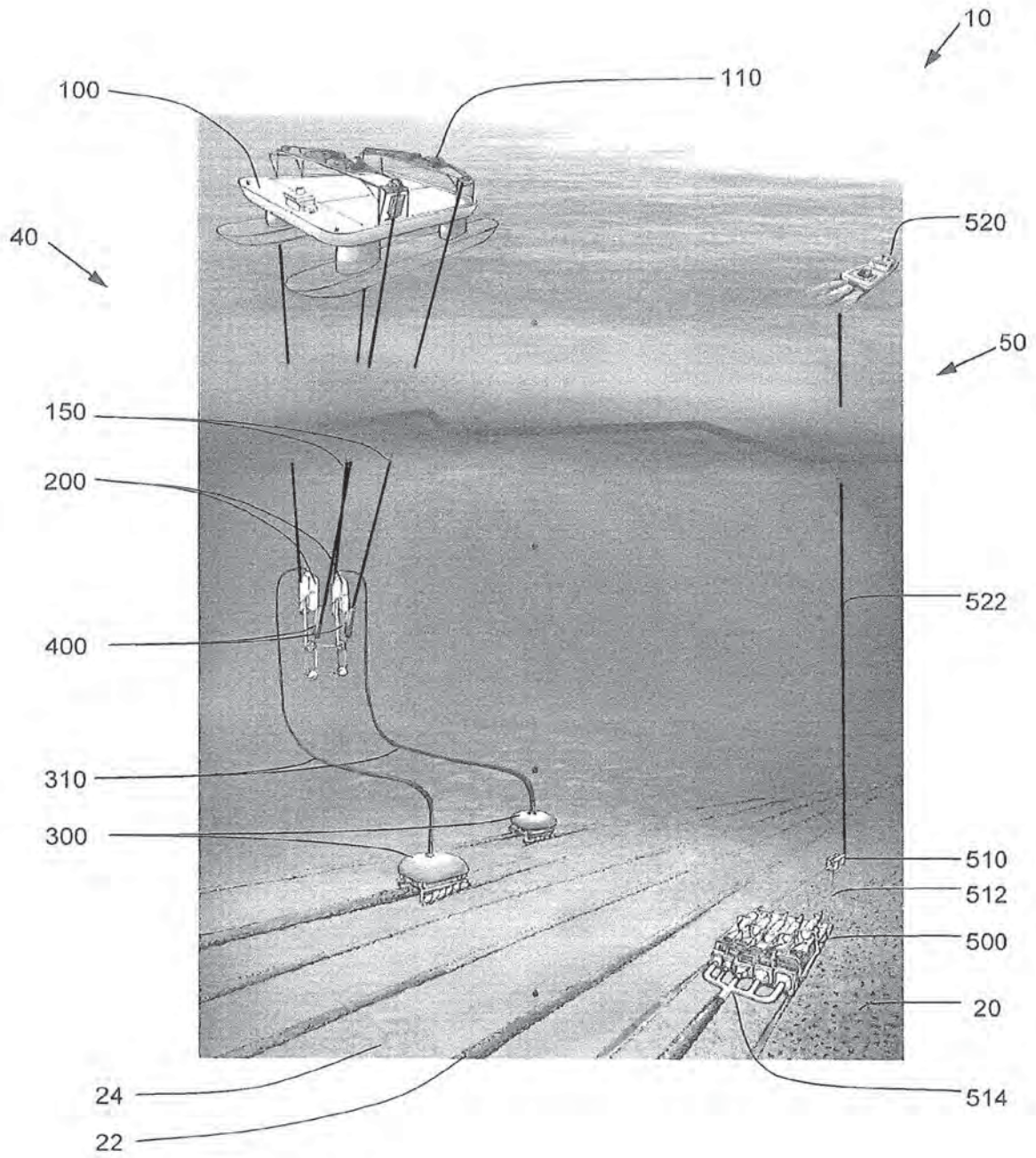


FIGURE 1

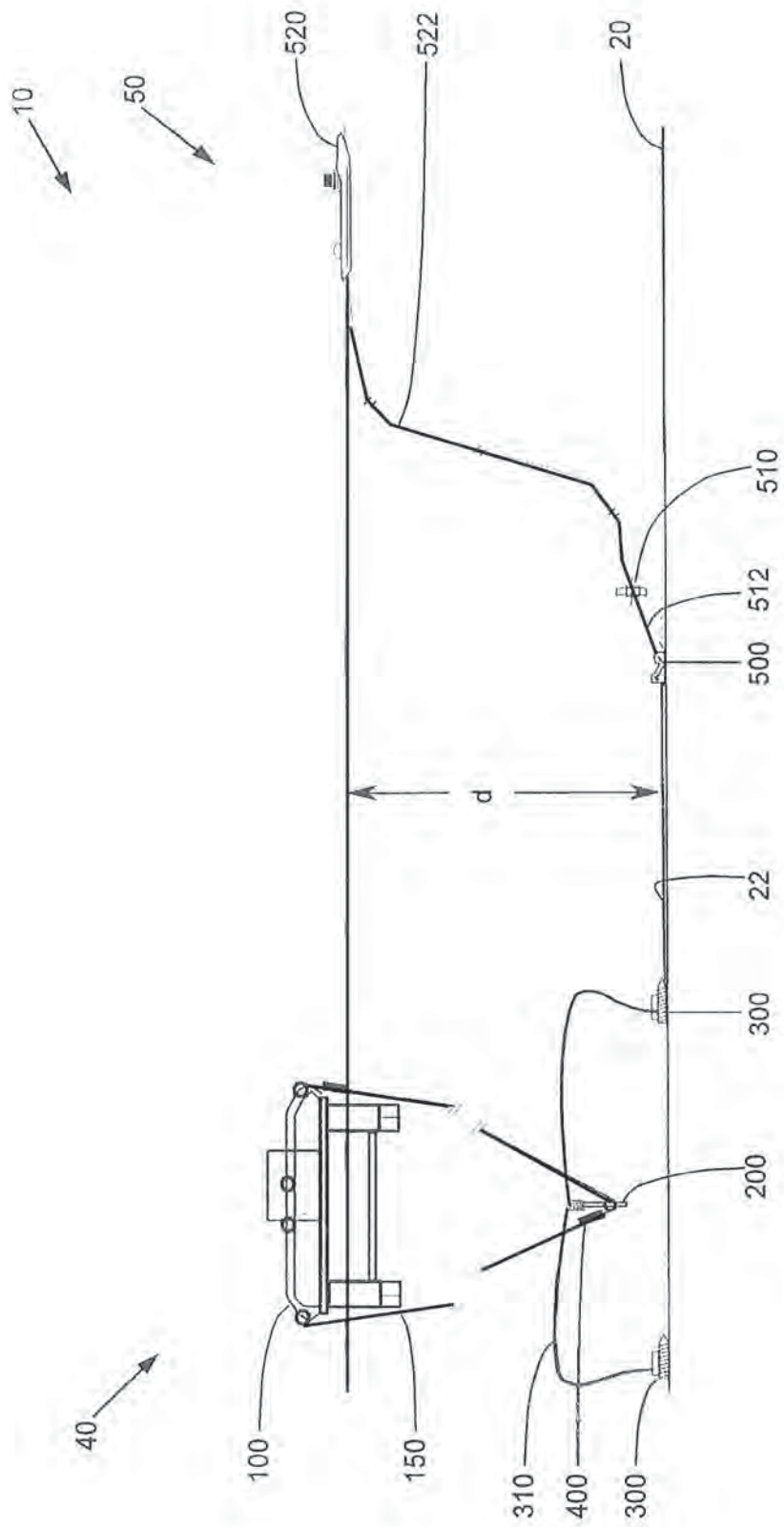


FIGURE 2

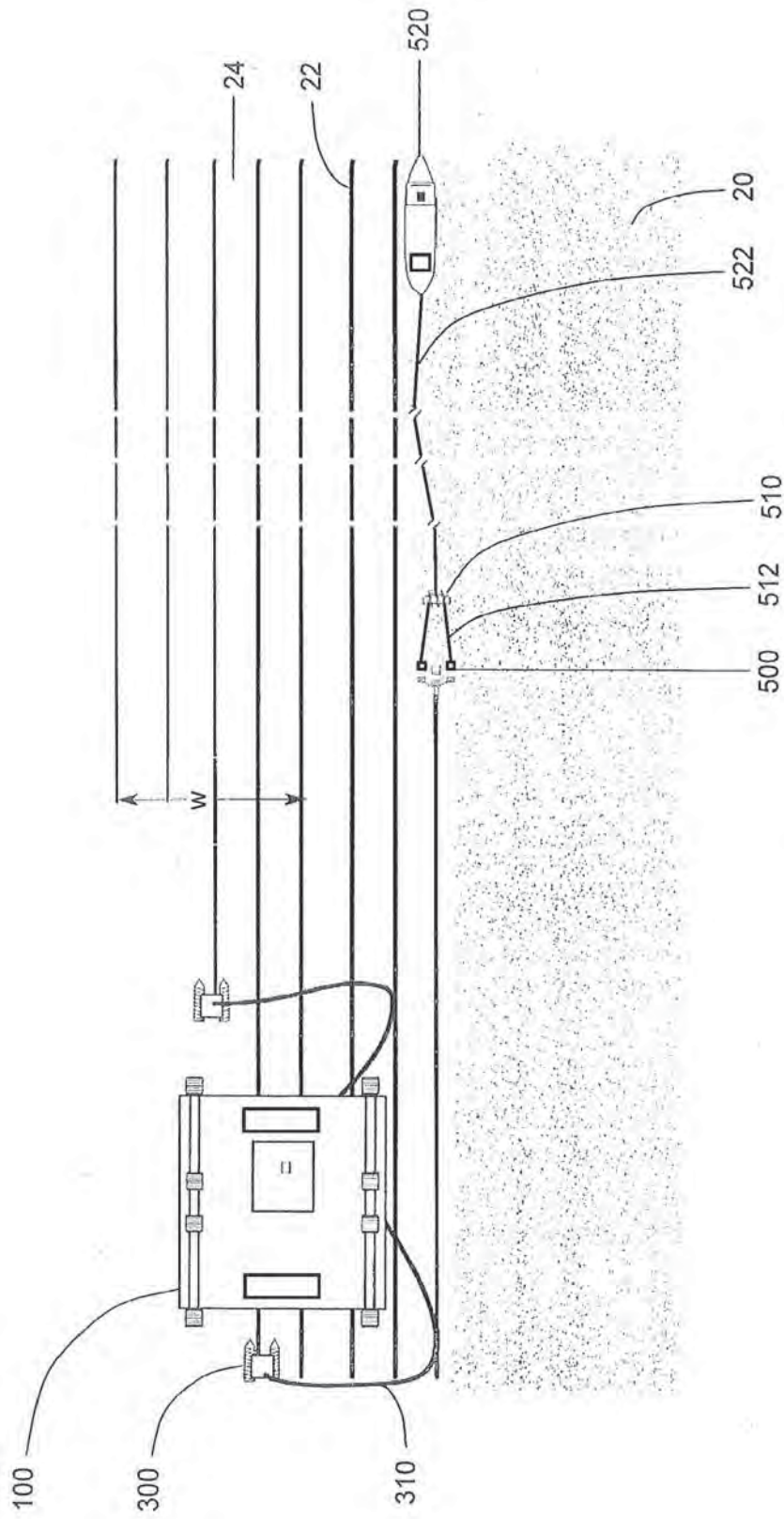


FIGURE 3

DECOUPLED SEAFLOOR MINING SYSTEM

FIELD OF THE INVENTION

[0001] The invention relates to a seafloor mining system decoupled into multiple stages. In particular, the invention relates, but is not limited, to a decoupled seafloor mining system comprising a concentration stage, a reclamation stage, and a haulage stage.

BACKGROUND TO THE INVENTION

[0002] Reference to background art herein is not to be construed as an admission that such art constitutes common general knowledge.

[0003] In various locations in the ocean valuable seafloor materials, such as sulphide precipitates or polymetallic nodules, exist in a surface layer on the seafloor at water depths of between around 300 to 6,000 metres, often around 4,000 to 5,000 metres.

[0004] There have been various attempts to develop commercially viable mining systems that collect and then convey the nodules from the seafloor. Typically such systems are complex as several different actions need to be accounted for. For example, there can be seafloor mining machines which mine the seafloor, seafloor reclaimer machines which gather the seafloor material, and seafloor haulage systems, such as a riser, which hauls the gathered seafloor material to the surface. If these machines are integrated into a single mining system these all must operate simultaneously and co-operatively to obtain maximum output efficiency of the system.

[0005] However, as soon as one machine encounters a problem the entire production system halts or, at least, has reduced throughput. Furthermore, the large amount of infrastructure on or near the seafloor can create traffic problems with different machines or equipment getting in the way of other machines or equipment. Not only can this result in reduced productivity, but there can be collisions or entanglement of lines (e.g. umbilical lines) which can damage or reduce productivity of the machines or equipment.

[0006] A particularly costly part of the process relates to the surface vessel and associated haulage system. The surface vessel needs to be large enough to have a riser system extending towards the seafloor of a length sufficient to deliver the ore to the surface vessel. The weight associated with a riser system of this scope is significant and thus the surface vessel needs to be of a size to be able to carry that weight. Additionally, a significant amount of energy is expended in hauling the nodules to the surface. This leads to very high operating costs in reclaiming gathered seafloor materials, particularly when relatively small amount of nodules may be gathered in any given time period, or where water depths are great and the hauling vertical distance is large.

OBJECT OF THE INVENTION

[0007] It is an aim of this invention to provide a seafloor mining system which overcomes or ameliorates one or more of the disadvantages or problems described above, or which at least provides a useful alternative.

[0008] Other preferred objects of the present invention will become apparent from the following description.

SUMMARY OF INVENTION

[0009] In one form, although it need not be the only or indeed the broadest form, there is provided a seafloor mining system comprising:

[0010] at least one concentrating system that processes seafloor materials;

[0011] at least one reclaimer machine that collects the processed seafloor materials; and

[0012] at least one haulage system that receives the processed seafloor materials collected by the reclaimer machine and lifts the processed seafloor materials to a surface vessel;

[0013] wherein the haulage system is a mechanical haulage system that conveys discrete parcels of seafloor material collected by the reclaimer machine to the surface vessel.

[0014] Preferably the at least one concentrating system is adapted to arrange processed seafloor materials on the seafloor and the at least one reclaimer machine is adapted to collect the processed seafloor materials from the arranged processed seafloor materials on the seafloor. Preferably the at least one concentrating system is adapted to arrange the processed seafloor materials in windrows on the seafloor. Preferably the at least one reclaimer machine is adapted to collect the processed seafloor from the windrows on the seafloor.

[0015] Preferably the at least one concentrating system comprises an undersea vehicle. Preferably the undersea vehicle is towed by a tow vessel, preferably located on the surface. Preferably the undersea vehicle comprises a nodule collecting apparatus located on the seafloor. Preferably the nodule collecting apparatus is connected to a steering vehicle. Preferably the steering vehicle is adapted to be towed by the tow vessel.

[0016] Preferably the undersea vehicle comprises a position determination device adapted to determine the position of the nodule collecting apparatus. Preferably the position determination device communicates position information of the nodule collecting apparatus to the steering vehicle and/or tow vessel.

[0017] Preferably, the steering vehicle is adapted to alter the direction of the nodule mining apparatus. Suitably, the steering vehicle is adapted to alter the direction of the nodule collecting apparatus in response to receiving position information of the nodule collecting apparatus from the position determination device.

[0018] Preferably the nodule collecting apparatus comprises a plurality of nodule collection devices. Preferably the nodule collection devices are secured to a support member. Preferably each nodule collection device is adapted to collect ore nodules from the seafloor adjacent an underside thereof and communicate those nodules to an outlet pipe. Preferably the nodule collecting apparatus comprises a combined outlet pipe adapted to receive collected ore nodules from the outlet pipe of each nodule collection device and re-deposit the collected nodules on the seafloor in the form of a windrow.

[0019] Preferably the haulage system comprises one or more containers. Preferably the containers receive the processed seafloor materials from the reclaimer machine and carry the processed seafloor materials towards the surface. Preferably the haulage system comprises at least one line member that extends at least partially between the seafloor and the surface. Preferably a container is connected to the line member. Preferably the containers are towed by the line

member. Preferably the line member is driven by a winch. Preferably at least a substantial portion of the line member is synthetic rope.

[0020] Preferably each container has a steerable element that enables the container to manoeuvre as it is propelled, preferably towed, in the water. Preferably the steerable element comprises at least one adjustable surface. The steerable element may comprise a rudder, flap, thruster, and/or at least one adjustable hydrofoil. Preferably the steerable element is controlled to guide the container along a path. The steerable element may be controlled remotely but is preferably controlled autonomously. Preferably the steerable element is controlled by actively trimming the steerable element.

[0021] Preferably the container further comprises a position determination system, even more preferably an inertial navigation system that provides a position estimate based on inertial measurements. Preferably the steerable element is controlled with respect to the position estimate from the position determination system. Preferably the container is programmed to follow a predetermined path.

[0022] Preferably the at least one reclaimer machine comprises a seafloor vehicle that drives on the seafloor over the processed seafloor material. Preferably the reclaimer machine is adapted to collect a windrow of processed seafloor material on the seafloor without collecting a significant proportion of unprocessed seafloor material from the seafloor. Preferably the at least one reclaimer machine comprises a pump to hydraulically pump the processed seafloor material in slurry form, to a temporary storage container. Preferably the temporary storage container is a buffer suspended above the seafloor. Preferably the buffer receives the processed seafloor material from the reclaimer machine via a slurry hose. Preferably the buffer further processes the gathered seafloor material.

[0023] Preferably the temporary storage container is configured to transfer the gathered seafloor material to a container of the haulage system. Preferably the container of the haulage system travels to the temporary storage container and is loaded with a discrete parcel of seafloor material from the temporary storage container. Preferably the container then carries that discrete parcel of seafloor material from the temporary storage container towards the surface.

[0024] Preferably a plurality of containers convey gathered seafloor material from at least one temporary storage container to a single surface vessel. Preferably a plurality of reclaimer machines collect processed seafloor material from the seafloor to the at least one temporary storage container.

[0025] In another form, the invention resides in a method of mining the seafloor, the method comprising the steps of:

[0026] concentrating desirable seafloor materials by processing seafloor materials with a concentrating system;

[0027] collecting the processed seafloor materials with a reclaimer machine;

[0028] conveying collected seafloor materials to a surface vessel using a mechanical haulage system that conveys discrete parcels of seafloor material from the reclaimer machine to the surface vessel.

[0029] Preferably the step of concentrating desirable seafloor materials comprises towing a nodule collecting apparatus behind a tow vessel, preferably located on the surface, along the seafloor. Preferably the step of concentrating desirable seafloor materials comprises determining when the nodule collecting apparatus deviates from a pre-

determined path. Preferably if the nodule collecting apparatus is determined to deviate from a predetermined path the direction of the nodule collecting apparatus is altered to return the nodule collecting apparatus to the predetermined path. Preferably, an undersea steering vehicle is disposed between the tow vessel and the nodule collecting apparatus and is adapted to alter the direction of the nodule mining apparatus.

[0030] Preferably the step of conveying collected seafloor materials to a surface vessel comprises transferring collected seafloor material to at least one container located at or near the seafloor. Preferably the method further comprises towing the container to the surface by at least one line member. Preferably towing the container to the surface comprises guiding the container using at least one steerable element of the container.

[0031] Preferably the step of collecting the seafloor material comprises transferring the collected seafloor materials from the reclaimer machine to a temporary storage container via a pipe, preferably in slurry form. Preferably the step of transferring collected seafloor material to at least one container located at or near the seafloor comprises transferring collected seafloor material from the temporary storage container to the container.

[0032] Further features and advantages of the present invention will become apparent from the following detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

[0033] By way of example only, preferred embodiments of the invention will be described more fully hereinafter with reference to the accompanying figures, wherein:

[0034] FIG. 1 is a perspective view of a seafloor mining system;

[0035] FIG. 2 is a side elevation view of a seafloor mining system; and

[0036] FIG. 3 is a plan view of a seafloor mining system.

DETAILED DESCRIPTION OF THE DRAWINGS

[0037] FIGS. 1 to 3 illustrate a seafloor mining system 10 comprising a concentrating system 50 including an undersea vehicle having a nodule collecting apparatus 500 connected to a steering vehicle 510 which is towed by a tow vessel 520. To achieve desired throughput requirements of the seafloor mining system 10, there may be one or more concentrating systems 50. The seafloor mining system 10 also comprises one or more reclaimer machines 300 and a mechanical haulage system 40 that comprises containers 400 connected to line members 150 that extend between temporary storage containers, in the form of buffers 200, and a surface vessel 100.

[0038] The steering vehicle 510 of the concentrating system 50 is secured to the tow vessel 520 via tow line 522 and nodule collecting apparatus 500 is secured to the steering vessel 510 by way of vehicle lines 512. Tow vessel 520 is in the form of a boat, tug, or ship. Steering vehicle 510 is preferably in the form of a Remotely Operated Towed Vehicle (ROTV) that is adapted to be operated remotely and/or be programmed to follow a predetermined course.

[0039] Steering vehicle 510 is located proximal nodule collecting apparatus 500 and distal tow vessel 520. By way of example, in circumstances where nodule collecting apparatus 500 is operating in waters of depth 'd' (see FIG. 2)

around 5,000 metres, the distance between the tow vessel 520 and the nodule collecting apparatus 500 may be 8,000 metres. On that distance, the steering vehicle 510 is preferably positioned about 20 to 100 metres from the nodule collecting apparatus 500.

[0040] The mechanical haulage system 40 receives collected seafloor material from reclaimer machines 300 via a pipes in the form of slurry hoses 310 connected to an inlet of the buffers 200. The buffers 200 store a quantity of collected seafloor material and when a container 400 is located nearby (as shown in FIG. 1) a discrete parcel of seafloor material is transferred into the container 400. Once the container 400 is loaded, a respective line member 150 tows the container 400 to the surface where it is unloaded to the surface vessel 100. The line member 150 is a synthetic rope driven by winches 110 located on the surface vessel 100. The containers 400 have a steerable element, preferably adjustable flaps, which enable the container 400 to manoeuvre in the water as it is towed by the line member 150 to prevent entanglement of underwater lines and/or collision of adjacent containers 400. To increase the haulage capacity of the overall seafloor mining system 10, more than one mechanical haulage system 40 can be ganged to provide a multiple haulage system 40, as illustrated in FIG. 1.

[0041] In use, the at least one concentrating system 50 processes seafloor 20 by towing nodule collecting apparatus 500, which has a plurality of nodule collection devices secured to a support member, behind tow vehicle 520. The nodule collecting apparatus 500 is directed by steering vehicle 510, which controls the path of the nodule collecting apparatus 500 using positional data from a position determination device to follow a predetermined path.

[0042] As the nodule collecting apparatus 500 traverses the seafloor 20 each nodule collection device of the nodule collecting apparatus collects nodules from the seafloor adjacent an underside thereof and communicates those nodules to a combined outlet pipe 514. The nodules of the seafloor material processed by the nodule collecting apparatus 500 is arranged as a concentrated windrow 22. As the nodule collecting apparatus 500 traverses the seafloor 20 it navigates using the position determination device and creates a plurality of elongate windrows 22 which are then, at a later time, picked up by reclaimer machines 300.

[0043] Depending on the system throughput requirements, one or more reclaimer machines 300 traverse the processed seafloor 24 collecting processed seafloor materials from the windrows 22. The reclaimer machines 300 are preferably either tracked or Archimedes screw propelled vehicles which are able to traverse the soft and often cohesive muds of the seafloor, using their own power and are not towed by any other form of vessel. The reclaimer machines 300 can be steered in a nimble manner so that the reclaimer machine 300 is able to negotiate the terrain and reliably collect the seafloor materials that have been deposited in a windrow 22. The reclaimer machines 300 are each powered and controlled by an umbilical 310 which runs from the buffer 200 to the reclaimer machine 300. By employing power and control from the buffer 200, the umbilicals to the reclaimer machines 300 are much shorter than would be the case if the reclaimer machine is powered and controlled by an umbilical from the surface vessel 100. Collected seafloor materials from the reclaimer machines 300 is then conveyed, in slurry form over flexible slurry hose 310, to the buffers 200.

[0044] The containers 400 travel between the buffers 200 and the surface vessel 100. When the containers 400 are located adjacent a buffer 200 they are filled up with a discrete parcel of seafloor material. Once the seafloor material has been transferred from the buffer 200, the container 400 is towed to the surface by line member 150 powered by winch 110 on the surface vessel 100. As the container travels between the buffer and the surface vessel 100 the steerable element is trimmed to take the container along a path that will avoid entanglement or collision. Once the container arrives at the surface it unloads the parcel of seafloor materials and is sent back down towards the buffer 200.

[0045] Advantageously the seafloor mining system 10 provides an efficient decoupled system of at least three stages being a concentrating stage to form windrows 22 of processed seafloor material on the seafloor, a reclaimer stage conveying material from the windrows 22 to the buffer 200, and a haulage stage which conveys the processed seafloor material from the buffers 200 to a surface vessel 100. The three stages can be performed in different areas at different times enabling a number of efficiency improvements.

[0046] For example, the concentrating system 50 can operate over large areas of the seafloor creating windrows without risk of entanglement with the haulage system 40 or getting in the way of reclaimer machines 300. For example the number of reclaimer machines 300 operating can be varied to ensure the haulage system 40 is kept well supplied in areas of different topography or with different amounts of seafloor materials. Furthermore, if there is any downtime, e.g. due to maintenance or equipment failure, in the haulage system 40 it does not prevent the concentrating system 50 from continuing the process the seafloor 20 into windrows 22 or the reclaimer machines 300 from working to fill the buffer 200 or move to new positions.

[0047] As the seafloor material has already been concentrated into windrows 22, the reclaimer machines 300 can collect the concentrated seafloor materials efficiently. As the reclaimer machines 300 are not part of the concentrating system 50 they can also be operated in areas where the concentrating system has finished operating such that they do not get in the way of the concentrating system. Furthermore, if there is any downtime, e.g. due to maintenance or equipment failure, in the concentrating system 50 it does not prevent the haulage system 40 from continuing to collect and convey previously processed seafloor materials in windrows 22 on the seafloor 20. Furthermore if the reclaimer machines 300 stop production, e.g. to move to a new position the buffer 200 and containers 400 can continue to supply seafloor material to the surface vessel 100.

[0048] The mechanical haulage system is also energy efficient, considerably more energy efficient than risers. The guided containers 400 also overcome many problems associated with mechanical haulage systems underwater such as entanglement and collision which are particularly problematic over such long depths (e.g. approximately 5,000 m).

[0049] The seafloor mining system 10 therefore provides a robust and commercially effective manner to find and obtain valuable seafloor materials.

[0050] While the figures illustrate the distance between the surface and the seabed as being relatively close, this is for convenience only and it will be appreciated that the present invention will typically be used in deep sea applications where the seabed is over 2,000 m, typically around 4,000 to 5,000 m, deep. References herein to the seafloor, seabed,

subsea, or the like are for convenience only and could equally be applied to other bodies of water such as, for example, a lake with a lakebed, etc.

[0051] In this specification, adjectives such as first and second, left and right, top and bottom, and the like may be used solely to distinguish one element or action from another element or action without necessarily requiring or implying any actual such relationship or order. Where the context permits, reference to an integer or a component or step (or the like) is not to be interpreted as being limited to only one of that integer, component, or step, but rather could be one or more of that integer, component, or step etc.

[0052] The above description of various embodiments of the present invention is provided for purposes of description to one of ordinary skill in the related art. It is not intended to be exhaustive or to limit the invention to a single disclosed embodiment. As mentioned above, numerous alternatives and variations to the present invention will be apparent to those skilled in the art of the above teaching. Accordingly, while some alternative embodiments have been discussed specifically, other embodiments will be apparent or relatively easily developed by those of ordinary skill in the art. The invention is intended to embrace all alternatives, modifications, and variations of the present invention that have been discussed herein, and other embodiments that fall within the spirit and scope of the above described invention.

[0053] In this specification, the terms 'comprises', 'comprising', 'includes', 'including', or similar terms are intended to mean a non-exclusive inclusion, such that a method, system or apparatus that comprises a list of elements does not include those elements solely, but may well include other elements not listed.

1.-40. (canceled)

41. A seafloor mining system comprising:

- at least one concentrating system that processes seafloor materials;
- at least one reclaimer machine that collects the processed seafloor materials;
- at least one haulage system that receives the processed seafloor materials collected by the reclaimer machine and lifts the processed seafloor materials to a surface vessel; and
- at least one temporary storage container located between the at least one reclaimer machine and the at least one haulage system;

wherein the haulage system is a mechanical haulage system that conveys discrete parcels of seafloor material collected by the reclaimer machine to the surface vessel;

wherein the concentrating system, reclaimer machine, and haulage system are decoupled from each other; and wherein the at least one reclaimer machine comprises a pump to hydraulically pump the processed seafloor material in slurry form to the temporary storage container.

42. The seafloor mining system of claim **41**, wherein the at least one concentrating system is adapted to arrange processed seafloor materials on the seafloor; and

the at least one reclaimer machine is adapted to collect the processed seafloor materials from the arranged processed seafloor materials on the seafloor.

43. The seafloor mining system of claim **42**, wherein the at least one concentrating system is adapted to arrange the processed seafloor materials in windrows on the seafloor; and

the at least one reclaimer machine is adapted to collect the processed seafloor from the windrows on the seafloor.

44. The seafloor mining system of claim **41**, wherein the haulage system comprises one or more containers.

45. The seafloor mining system of claim **44**, wherein the containers are connected to at least one line member that extends at least partially between the seafloor and the surface.

46. The seafloor mining system of claim **41**, wherein the temporary storage container is a buffer suspended above the seafloor.

47. The seafloor mining system of claim **46**, wherein the buffer receives the processed seafloor material from the reclaimer machine via a slurry hose.

48. The seafloor mining system of claim **46**, wherein the buffer further processes the gathered seafloor material.

49. The seafloor mining system of claim **41**, wherein the temporary storage container is configured to transfer the gathered seafloor material to a container of the haulage system.

50. The seafloor mining system of claim **49**, wherein the container of the haulage system travels to the temporary storage container and is loaded with a discrete parcel of seafloor material from the temporary storage container and the container then carries that discrete parcel of seafloor material from the temporary storage container towards the surface.

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(54) **A SEAFLOOR NODULE CONCENTRATING SYSTEM AND METHOD**

MEERESBODEN-KNOTENKONZENTRATIONSSYSTEM UND VERFAHREN
SYSTÈME ET PROCÉDÉ DE CONCENTRATION DE NODULE DE FOND MARIN

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EP 2 956 590 B1

Note: Within nine months of the publication of the mention of the grant of the European patent in the European Patent Bulletin, any person may give notice to the European Patent Office of opposition to that patent, in accordance with the Implementing Regulations. Notice of opposition shall not be deemed to have been filed until the opposition fee has been paid. (Art. 99(1) European Patent Convention).

DescriptionFIELD OF THE INVENTION

[0001] The invention relates to a seafloor nodule concentrating system. The invention relates in particular, although not exclusively, to a system and method of mining mineral nodules located on the floor of the deep sea.

BACKGROUND OF THE INVENTION

[0002] In various locations in the ocean, and in particular in a large area in the central Pacific Ocean to the South of the Hawaiian Islands, polymetallic nodules exist in a muddy surface layer on the bottom of the deep sea. The size of the nodules varies from pebble size to fist size and generally lie in water depths of around 5000 metres.

[0003] Since the late 1970's, there have been various attempts to engineer a commercially viable solution to mine the nodules from the deep ocean seafloor.

[0004] One prior art solution is described in US Patent 4,042,279. This solution comprises a seafloor nodule recovery vehicle and an ore hoisting system to transport ore from the seafloor nodule recovery vehicle to a surface vessel.

[0005] The seafloor nodule recovery vehicle described in 4,042,279 is of a category of vehicles referred to as benthic sleds. Benthic sleds are typically unable to move under their own power nor do the sleds have the ability to steer. In the system described, the seafloor nodule recovery vehicle and associated ore hoisting system is towed along by the surface vessel and collects nodules from the seafloor adjacent an underside of the recovery vehicle. The nodules, in a slurry, are then pumped from the recovery vehicle to the ore hoisting system, in this case a riser pipe.

[0006] The solution described in US Patent 4,042,279 has various disadvantages. Whilst the seafloor nodule recovery vehicle is effective enough in collecting the nodules from the seafloor and communicating the collected nodules to the ore hoisting system, the seafloor nodule recovery vehicle is unable to steer to follow a predetermined path and tends to "snake" as it travels due mostly to drag on, and vortex shedding off, the riser pipe. This effect worsens with increased speed through the water.

[0007] In circumstances where the seafloor nodule recovery vessel is operating in depths of around 5000 metres, this inability to maintain a desired path greatly reduces the recovery rate of nodules from the seafloor.

[0008] A further disadvantage of the system described in US Patent 4,042,279 is the cost associated with the surface vessel and the ore delivery system. The surface vessel needs to be large enough to have a riser system extending towards the seafloor of a length sufficient to deliver the ore to the surface vessel.

[0009] The weight associated with a riser system of this scope is significant and thus the surface vessel needs

to be of a size to carry that weight. This leads to very high operating costs in circumstances where the seafloor nodule recovery vessel is only able to recover a relatively small amount of nodules in any given time period.

[0010] Any discussion of documents, acts, materials, devices, articles or the like which has been included in the present specification is solely for the purpose of providing a context for the present invention. It is not to be taken as an admission that any or all of these matters form part of the prior art base or were common general knowledge in the field relevant to the present invention as it existed before the priority date of each claim of this application.

[0011] Prior art document US 4,232,903 discloses an ocean mining system for mining manganese nodules comprising a surface subsystem and an ocean bottom subsystem. The ocean bottom subsystem includes a mobile miner vehicle which picks up, handles, washes and crushes nodules. The ocean mining system includes sensors and controls for sensing the location of the miner vehicle within the permitted area of operation.

[0012] Prior art document US 4,052,800 discloses a system for gathering solids disposed on the ocean floor by dragging a collecting apparatus along the ocean floor so as to deposit the solids in an extended pile.

[0013] Prior art document US 4,141,159 discloses a surface vessel that tows a submerged harvesting apparatus which harvests and conveys mineral aggregates or nodules on the ocean floor to the surface vessel.

[0014] Prior art document SU 1,739,704 discloses a deep water extraction unit having a lifting system suspended from a boat. The lifting system includes an extraction unit having extraction modules for extracting deposits on the ocean floor.

OBJECT OF THE INVENTION

[0015] It is an object of the invention to overcome or at least alleviate one or more of the above problems and/or provide the consumer with a useful or commercial choice.

[0016] Other preferred objects of the present invention will become apparent from the following description.

SUMMARY OF THE INVENTION

[0017] In one form, although it need not be the only or indeed the broadest form, the invention resides in a seafloor nodule concentrating system comprising:

- a surface vessel;
- an undersea steering vehicle secured to the surface vessel, the undersea steering vehicle adapted to be towed by the surface vessel;
- a nodule collecting apparatus connected to the undersea steering vehicle, the nodule collecting apparatus located on the seafloor; and
- a position determination device adapted to deter-

mine the position of the nodule collecting apparatus and communicate position information of the nodule collecting apparatus to the undersea steering vehicle and surface vessel.

[0018] Suitably, the undersea steering vehicle is adapted to alter the direction of the nodule mining apparatus. Suitably, the undersea steering vehicle is adapted to alter the direction of the nodule collecting apparatus in response to receiving position information of the nodule collecting apparatus from the position determination device. Also shown is a nodule collecting apparatus comprising:

a support member;
two or more nodule collection devices, each nodule collection device being secured to the support member and being adapted to collect ore nodules from the seafloor adjacent an underside thereof and communicate those nodules to an outlet pipe; and
a combined outlet pipe adapted to receive the collected ore nodules from the outlet pipe of each nodule collection device and re-deposit the collected nodules on the seafloor in the form of a windrow.

[0019] In still a further form, the invention resides in a seafloor mining method including the steps of:

towing a nodule collecting apparatus behind a surface vessel along the seafloor;
determining when the nodule collecting apparatus deviates from a predetermined path;
altering the direction of the nodule collecting apparatus to return the nodule collecting apparatus to the predetermined path.

[0020] Preferably, an undersea steering vehicle is disposed between the surface vessel and the nodule collecting apparatus and is adapted to alter the direction of the nodule mining apparatus.

[0021] Further features of the invention will become apparent from the following description.

BRIEF DESCRIPTION OF THE DRAWINGS

[0022] To assist in understanding the invention and to enable a person skilled in the art to put the invention into practical effect, preferred embodiments of the invention will be described by way of example only with reference to the accompanying drawings, wherein:

FIG 1 shows a plan view of a schematic of a seafloor nodule concentrating system according to an embodiment of the invention;

FIG 2 shows a perspective view of a schematic of a seafloor nodule concentrating system according to an embodiment of the invention;

FIG 3A shows a plan view of a support member form-

ing part of a seafloor recovery apparatus of the seafloor nodule concentrating system shown in FIG 1; FIG 3B shows a plan view of an alternative support member forming part of a seafloor recovery apparatus of the seafloor nodule concentrating system shown in FIG 1;

FIG 3C shows a plan view of an alternative support member forming part of a seafloor recovery apparatus of the seafloor nodule concentrating system shown in FIG 1;

FIG 3D shows a plan view of an alternative support member forming part of a seafloor recovery apparatus of the seafloor nodule concentrating system shown in FIG 1; and

FIG 3E shows a plan view of an alternative support member forming part of a seafloor recovery apparatus of the seafloor nodule concentrating system shown in FIG 1.

20 DETAILED DESCRIPTION OF THE DRAWINGS

[0023] FIG 1 shows a plan view of a schematic of a seafloor nodule concentrating system 100 according to an embodiment of the invention and FIG 2 shows a perspective view of a schematic of the seafloor nodule concentrating system 100.

[0024] Seafloor nodule concentrating system 100 has a surface vessel 110, an undersea steering vehicle 120 secured to the surface vessel by way of line 101 and a nodule collecting apparatus 130 secured to the undersea steering vessel 120 by way of lines 102. Seafloor nodule concentrating system 100 further comprises a position determination device 140 secured to surface vessel 110 by way of line 103.

[0025] Surface vessel 110 is in the form of a boat, tug or ship. As mentioned previously, undersea steering vehicle 120 is connected to surface vessel 110 by way of line 101 in the form of a heavy duty tow cable or the like.

[0026] Undersea steering vehicle 120 is preferably in the form of a Remotely Operated Vehicle (ROV) as is known in the art. ROV's are used extensively in deep sea oil projects and are essentially submarines that are adapted to be operated remotely and/or are programmed to follow a predetermined course.

[0027] Undersea steering vehicle 120 is towed by surface vessel 110.

[0028] Nodule collecting apparatus 130 is connected to undersea steering vehicle 120 by way of lines 102. Undersea steering vehicle 120 is located proximal nodule collecting apparatus 130 and distal surface vessel 110. By way of example, in circumstances where nodule collecting apparatus 130 is operating in 5000 metres of water, the distance between the surface vessel 110 and the nodule collecting apparatus 130 may be 8000 metres. On that distance, the undersea steering vehicle 120 is preferably positioned about 20 to 100 metres from the nodule collecting apparatus 130.

[0029] In the embodiment shown two static cables con-

nect undersea steering vehicle 120 to nodule collecting apparatus 130. Alternative forms may include more cables or even a bridle of cables some of which may feature trim controls via hydraulics or mechanical levers mounted on undersea steering vehicle 120.

[0030] In the embodiment shown undersea steering vehicle 120 is suspended in the water several meters to tens of meters above the seabed. Alternative forms may connect the undersea steering vehicle 120 to the seabed via guiding wheels or skids.

[0031] In the embodiment shown, nodule collecting apparatus 130 comprises a support member 131 having a plurality of nodule collection devices 132 secured thereto. In a preferred form, each nodule collection device is a benthic sled and functions as described in US Patent 4,042,279.

[0032] Each of lines 102 are attached to support member 131 at opposing ends thereof. In the embodiment, support member 131 is arcuate in shape having a concave edge on a leading side thereof and a convex edge on a trailing edge as shown. The support member 131 is preferably in the form of a rigid beam. In a preferred form each nodule collection device 132 is secured to the support member 131 by way of a hinge or spring or the like.

[0033] Each nodule collection device 132 has an outlet pipe or hydraulic conveyor 133 attached to an end thereof. Each outlet pipe or hydraulic conveyor 133 is adapted to receive nodules collected adjacent an underside of a respective nodule collection device and communicate those nodules to combined outlet pipe or hydraulic conveyor 134. In preferred form outlet pipe or hydraulic conveyor 133 is attached with a flexible linkage to nodule collection device 132 and outlet pipe or hydraulic conveyor 134 is attached with a flexible linkage to outlet pipe or hydraulic conveyor 133.

[0034] In another form outlet pipe or hydraulic conveyor 134 may be integrated or adjoined with support member 131.

[0035] Combined outlet pipe or hydraulic conveyor 134 is configured to output the nodules collected by each of the nodule collection devices 132 to the seafloor.

[0036] In preferred form water pressure to communicate the nodules along combined outlet pipe or hydraulic conveyor 134 is provided by forward motion of the seafloor concentration system through the water.

[0037] Position determination device 140 is connected to surface vessel 110 by way of tow line 103. In the embodiment, position determination device 140 is in the form of a surface towed transponder adapted to communicate with beacons (not shown) located on nodule collecting apparatus 130 to together form an Ultra Short Base Line acoustic position system as is known in the art. In this way, position determination device 140 is adapted to determine the position of nodule collecting apparatus 130 and communicate that position in order to assist in controlling the direction of undersea steering vehicle 120 as will be discussed in greater detail below.

[0038] In an alternative embodiment, position determination device 140 may be located on the undersea steering vehicle 120 or indeed on the nodule collecting apparatus 130 and may be in the form of an accelerometer, GNSS system or other similar position determination technology. In such an arrangement, position determination device 140 functions to determine the position of nodule collecting apparatus 130 and communicate that position to undersea steering vehicle 120.

[0039] In use, surface vessel 110 tows all of underwater steering vessel 120, nodule collecting apparatus 130 and position determination device 140 along a predetermined path to thereby mine nodules from the seafloor.

[0040] As nodule collecting apparatus 130 is towed along, drag on line 101 may cause it to snake as mentioned previously. Position detection device 140 is adapted to detect the position of nodule collecting apparatus 130 as previously discussed. As nodule collecting apparatus 130 moves off the predetermined path, position detection device 140 communicates this event and also the details of that movement to underwater steering vessel 120. Underwater steering vessel 120 consequently adjusts course in order to move nodule collecting apparatus 130 back on to the predetermined path.

[0041] Consequently, the seafloor nodule concentrating system 100 of the invention is able to provide for a deep water nodule recovery system that is able to effectively and efficiently recover nodules present on the seafloor by ensuring that recovery may be carried out following predetermined paths. In this way, acceptable amounts of nodules are not left on the seafloor and/or the seafloor mining apparatus is not being towed over seafloor that has already been partly exploited.

[0042] As nodule collecting apparatus 130 is towed by the surface vessel 110 along the predetermined path on the seafloor, each of the nodule collection devices 131 collect nodules from the seafloor adjacent to the underside of each nodule collection device and communicate the collected nodules to a respective outlet pipe 133 thereof.

[0043] As previously mentioned and in a preferred form, this collection occurs as described in US Patent 4,042,279. In an alternative form, each nodule collection device may be in the form of other types of benthic sleds.

[0044] Each of the outlet pipes 133 communicate the collected nodules to combined outlet pipe 134 which then deposits the collected nodules 104 on the seafloor.

[0045] As the seafloor mining apparatus tracks across the predetermined pathway on the seafloor, it leaves behind it a windrow of collected nodules in a relatively narrow track as it travels. This then enables another vessel, equipped with an ore hoisting system connected by a tail line to a seafloor recovery apparatus, to lift and transport the collected nodules from seafloor to surface.

[0046] This process represents commercial benefits over the known methods of collecting as the large operating costs associated with employing a large vessel having an ore hoisting system attached thereto are used to

collect a relatively larger volume of nodules per pass of the surface vessel at a more manageable speed.

[0047] FIGS 3A to 3E show plan views of alternative support members forming part of the nodule collecting apparatus 130.

[0048] Support member 231 shown in FIG 3A is formed from first support member 231A and second support member 2331B arranged at an angle to first support member 231A. In a preferred form that angle is around 90 degrees and support member 231A and 231B form a convex edge on a trailing edge of support member 231.

[0049] Support member 331 shown in FIG 3B is arcuate in shape and has a convex edge on a leading side thereof and a concave edge on a trailing edge.

[0050] Support member 431 shown in FIG 3C is formed from a linear member as shown.

[0051] Support member 131 shown in FIG 3D is as previously described.

[0052] Support member 531 shown in FIG 3A is formed from first support member 531A and second support member 5331B arranged at an angle to first support member 531A. In a preferred form that angle is around 90 degrees and support member 531A and 531B form a convex edge on a leading edge of support member 531.

[0053] Whilst the nodule collecting apparatus 130 is shown with a plurality of nodule collection devices 132, the system and method of seafloor mining 100 may employ a seafloor recovery apparatus that has a single nodule collection device 132, two collection devices 132 or more than two nodule collection devices 132.

[0054] Throughout this specification the word "comprise", or variations such as "comprises" or "comprising", will be understood to imply the inclusion of a stated element, integer or step, or group of elements, integers or steps, but not the exclusion of any other element, integer or step, or group of elements, integers or steps.

Claims

1. A seafloor nodule concentrating system (100) comprising:

a surface vessel (110);

an undersea steering vehicle (120) secured to the surface vessel (110), the undersea steering vehicle (120) adapted to be towed by the surface vessel (110);

a nodule collecting apparatus (130) connected to the undersea steering vehicle (120), the nodule collecting apparatus (130) located on the seafloor; and

a position determination device (140) adapted to determine the position of the nodule collecting apparatus (130) and communicate position information of the nodule collecting apparatus (130) to the undersea steering vehicle (120) and surface vessel (110),

characterised in that the surface vessel (110) tows each of the underwater steering vessel (120), the nodule collecting apparatus (130) and the position determination device (140) along a predetermined path to thereby mine nodules from the seafloor, and

wherein as the nodule collecting apparatus (130) is towed along and moves off the predetermined path, the position determination device (140) communicates this event and the movement of the nodule collecting apparatus (130) to the underwater steering vessel (120) and the underwater steering vessel (120) adjusts course to move the nodule collecting apparatus back (130) on to the predetermined path.

2. The seafloor nodule concentrating system of claim 1, wherein the undersea steering vehicle (120) is located proximal the nodule collecting apparatus (130).

3. The seafloor nodule concentrating system of claim 1, wherein the undersea steering vehicle (120) is in the form a remotely operated vehicle.

4. A seafloor mining method including the steps of:

towing an undersea steering vessel (120) connected to a nodule collecting apparatus (130) behind a surface vessel (110), wherein the nodule collecting apparatus (130) is towed along the seafloor;

towing a position determination device (140) behind the surface vessel (110);

wherein the method is **characterised by** the steps of:

determining the position of the nodule collecting apparatus (130) via the position determination device (140);

communicating position information of the nodule collecting apparatus (130) to the undersea steering vehicle (120) and surface vessel (110);

determining when the nodule collecting apparatus (130) deviates from a predetermined path; and

altering the direction of the undersea steering vessel (120) to alter the direction of the nodule collecting apparatus (130) to return the nodule collecting apparatus (130) to the predetermined path.

Patentansprüche

1. Ein System (100) zum Einsammeln von Meeresbodenknollen, das Folgendes umfasst:

ein Oberflächenschiff (110);
 ein Unterwasser-Lenkfahrzeug (120), das mit dem Oberflächenschiff (110) verbunden ist, wobei das Unterwasser-Lenkfahrzeug (120) angepasst ist, von dem Oberflächenschiff (110) geschleppt zu werden;
 eine Knollen-Sammelvorrichtung (130), die mit dem Unterwasser-Lenkfahrzeug (120) verbunden ist, wobei die Knollen-Sammelvorrichtung (130) auf dem Meeresboden angeordnet ist; und eine Positionsbestimmungseinrichtung (140), die dazu eingerichtet ist, die Position der Knollen-Sammelvorrichtung (130) zu bestimmen und Positionsinformation der Knollen-Sammelvorrichtung (130) an das Unterwasser-Lenkfahrzeug (120) und das Oberflächenschiff (110) zu übermitteln,
dadurch gekennzeichnet, dass das Oberflächenschiff (110) jeweils das Unterwasser-Lenkfahrzeug (120), die Knollen-Sammelvorrichtung (130) und die Positionsbestimmungseinrichtung (140) entlang eines vorbestimmten Weges zieht, um dadurch Knollen von dem Meeresboden zu gewinnen, und
 wobei, wenn die Knollen-Sammelvorrichtung (130) entlang des vorgegebenen Weges geschleppt wird und sich von diesem wegbewegt, die Positionsbestimmungseinrichtung (140) dieses Ereignis und die Bewegung der Knollen-Sammelvorrichtung (130) an das Unterwasser-Lenkfahrzeug (120) übermittelt und das Unterwasser-Lenkfahrzeug (120) den Kurs korrigiert, um die Knollen-Sammelvorrichtung (130) auf den vorgegebenen Weg zurückzubewegen.

2. Das System zum Einsammeln von Meeresbodenknollen nach Anspruch 1, wobei das Unterwasser-Lenkfahrzeug (120) proximal zu der Knollen-Sammelvorrichtung (130) angeordnet ist.

3. Das System zum Einsammeln von Meeresbodenknollen nach Anspruch 1, wobei das Unterwasser-Lenkfahrzeug (120) als ferngesteuertes Fahrzeug ausgebildet ist.

4. Ein Verfahren zum Abbau am Meeresgrund mit den Schritten:

Ziehen eines Unterwasser-Lenkfahrzeugs (120), das mit einer Knollen-Sammelvorrichtung (130) verbunden ist, hinter einem Oberflächenschiff (110), wobei die Knollen-Sammelvorrichtung (130) entlang des Meeresbodens geschleppt wird;
 Ziehen einer Positionsbestimmungseinrichtung (140) hinter dem Oberflächenschiff (110);
 wobei das Verfahren durch die folgenden Schrit-

te gekennzeichnet ist:

Bestimmen der Position der Knollen-Sammelvorrichtung (130) über die Positionsbestimmungseinrichtung (140);
 Kommunizieren der Positionsinformation der Knollen-Sammelvorrichtung (130) an das Unterwasser-Lenkfahrzeug (120) und das Oberflächenschiff (110);
 Bestimmen, wenn die Knollen-Sammelvorrichtung (130) von einem vorbestimmten Weg abweicht; und
 Ändern der Richtung des Unterwasser-Lenkfahrzeugs (120), um die Richtung der Knollen-Sammelvorrichtung (130) zu ändern, so dass die Knollen-Sammelvorrichtung (130) auf den vorbestimmten Weg zurückgeführt wird.

Revendications

1. Un système (100) de concentration de nodules de fond marin comprenant:

un navire (110) de surface ;
 un véhicule sous-marin (120) de guidage attaché au navire (110) de surface, le véhicule sous-marin (120) de guidage étant adapté pour être remorqué par le navire (110) de surface ;
 un appareil (130) de recueil de nodules relié au véhicule sous-marin (120) de guidage, l'appareil (130) de recueil de nodules étant situé sur le fond marin ; et
 un dispositif (140) de détermination de position adapté pour déterminer la position de l'appareil (130) de recueil de nodules et pour communiquer une information de position de l'appareil (130) de recueil de nodules au véhicule sous-marin (120) de guidage et au navire (110) de surface,
caractérisé en ce que le navire (110) de surface remorque chacun du véhicule sous-marin (120) de guidage, de l'appareil (130) de recueil de nodules et du dispositif (140) de détermination de position le long d'un parcours prédéterminé pour ainsi collecter des nodules du fond marin, et
 dans lequel, lorsque l'appareil (130) de recueil des nodules est remorqué le long dudit parcours et s'en écarte, le dispositif (140) de détermination de position communique cet événement et le déplacement de l'appareil (130) de recueil des nodules au véhicule sous-marin (120) de guidage et le véhicule sous-marin (120) de guidage engage un ajustement de trajectoire pour ramener l'appareil (130) de recueil de nodules sur le parcours prédéterminé.

2. Le système de concentration de nodules de fond marin de la revendication 1, dans lequel le véhicule sous-marin (120) de guidage est situé du côté de l'appareil (130) de recueil de nodules. 5
3. Le système de concentration de nodules de fond marin de la revendication 1, dans lequel le véhicule sous-marin (120) de guidage est sous la forme d'un véhicule commandé à distance. 10
4. Un procédé d'exploitation minière de fond marin comprenant les étapes de:

remorquer un véhicule sous-marin (120) connecté à un appareil (130) de recueil de nodules derrière un navire (110) de surface, dans lequel l'appareil (130) de recueil de nodules est remorqué le long du fond marin ; 15

remorquer un dispositif (140) de détermination de position derrière le navire (110) de surface ; 20

le procédé étant **caractérisé par** les étapes de :

déterminer la position de l'appareil (130) de recueil de nodules au moyen du dispositif (140) de détermination de position ; 25

communiquer une information de position de l'appareil (130) de recueil de nodules au véhicule sous-marin (120) et au navire (110) de surface ;

déterminer quand l'appareil (130) de recueil de nodules s'écarte d'un parcours prédéterminé ; et 30

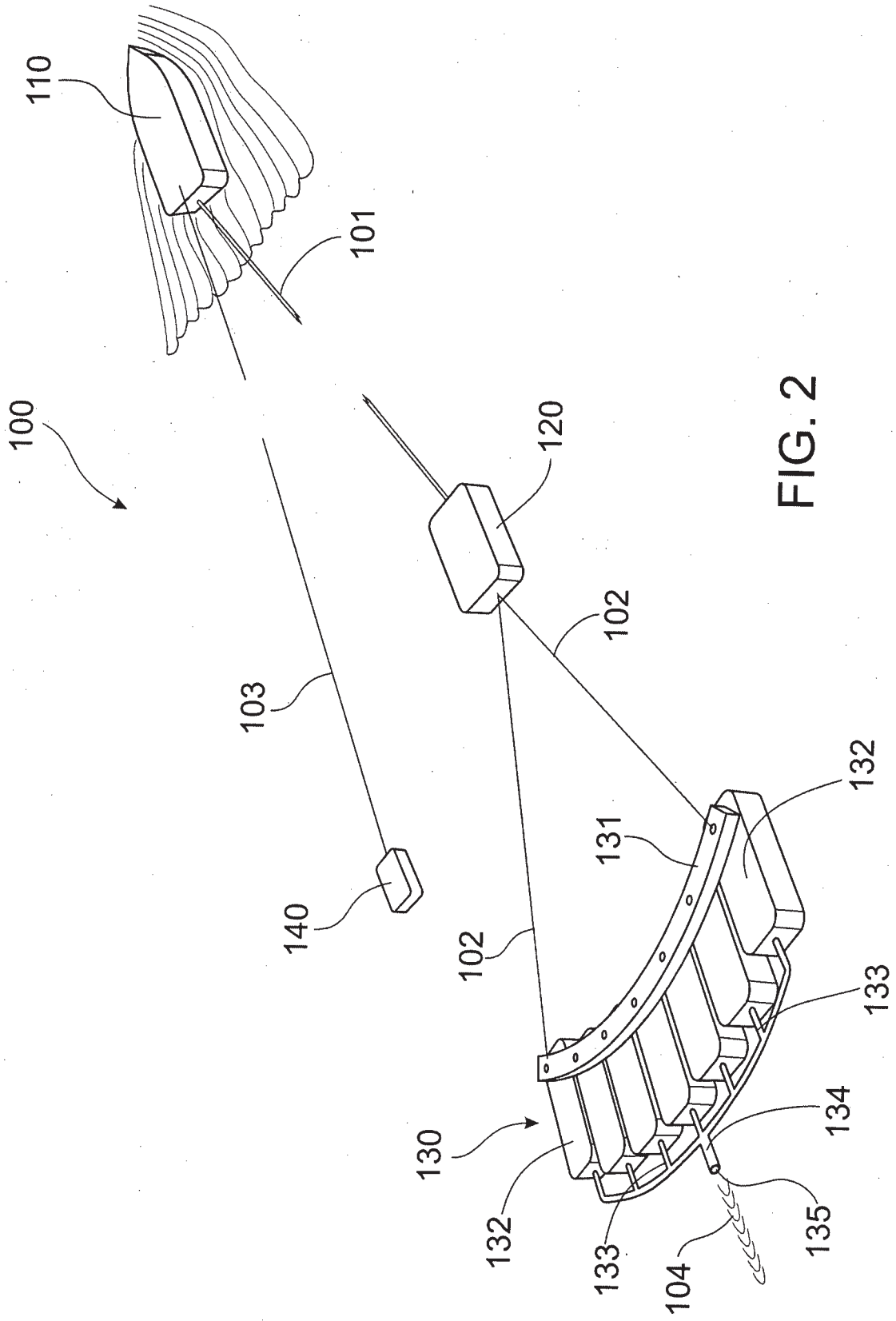
modifier la direction du véhicule sous-marin (120) pour modifier la direction de l'appareil (130) de recueil de nodules pour ramener l'appareil (130) de recueil de nodules sur le parcours prédéterminé. 35

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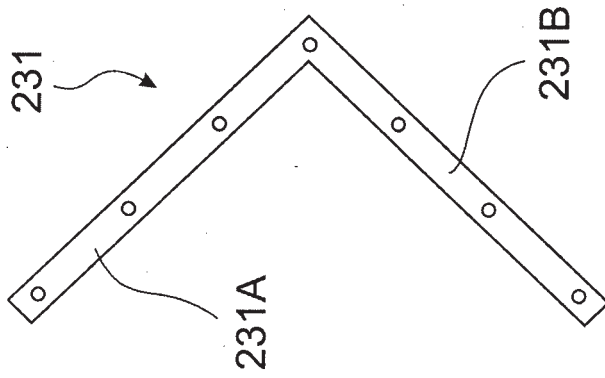


FIG. 3A

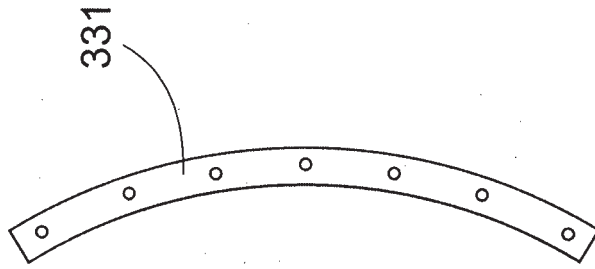


FIG. 3B

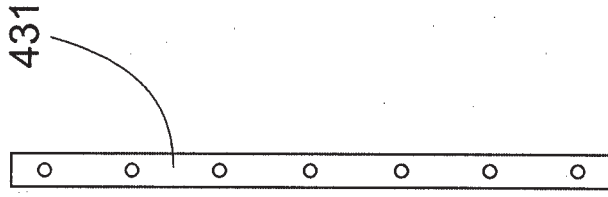


FIG. 3C

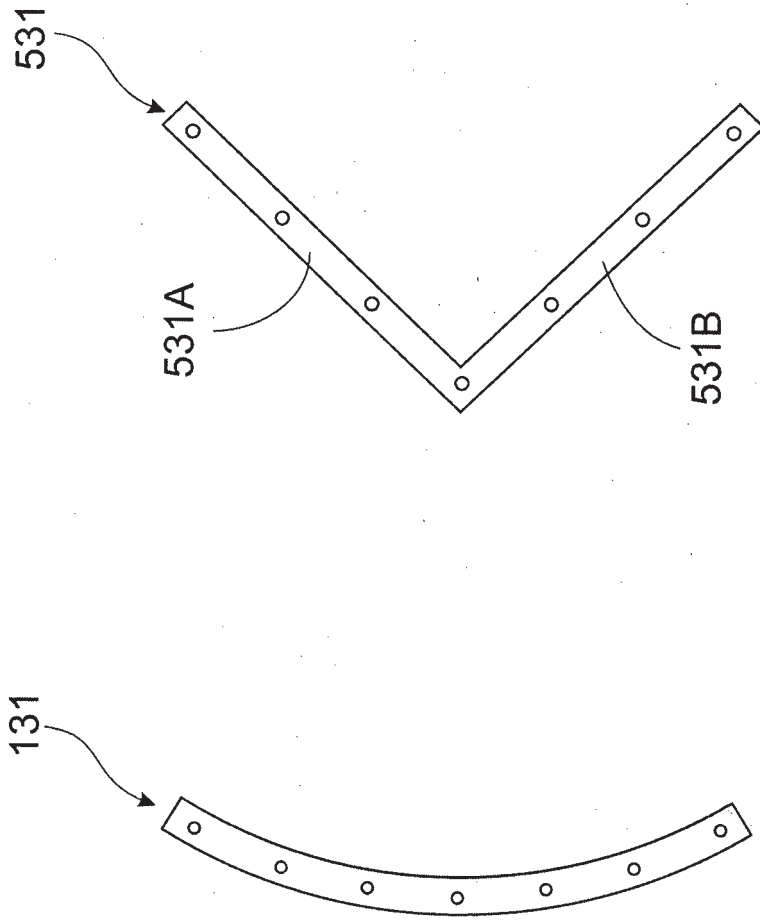


FIG. 3E

FIG. 3D

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(12) **United States Patent**
Parianos et al.

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(45) **Date of Patent:** **Jan. 5, 2021**

(54) **SEAFLOOR HAULAGE SYSTEM**

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Sean Michael Plunkett, Milton (AU)

(73) Assignee: **Nautilus Minerals Singapore Pte Ltd.**,
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(2013.01); **B65G 17/36** (2013.01); **E02F**
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(58) **Field of Classification Search**

CPC **E02F 7/005**; **E02F 7/065**; **E02F 9/2016**;
E02F 9/205; **B65G 17/126**; **B65G 17/36**;
E21C 50/00

See application file for complete search history.

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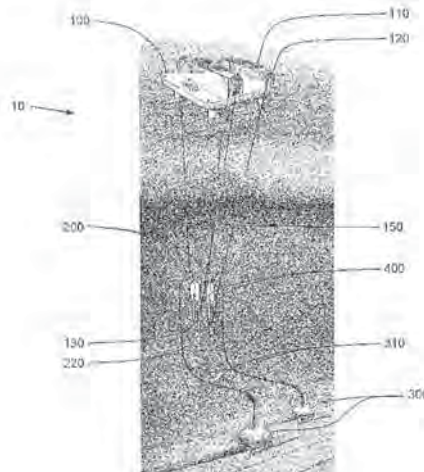
Primary Examiner — Tara Mayo-Pinnock

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(57) **ABSTRACT**

A seafloor haulage system (10), for lifting seafloor materials from the seafloor to the surface, that has a line member (150), preferably synthetic rope, that extends at least partially between the seafloor and the surface and a container (400), preferably a plurality of containers, capable of carrying a load connected to the line member (150). The containers have a steerable element (410), such as a rudder, that enables the container to manoeuvre as it is propelled, typically towed by the line member, through the water.

44 Claims, 4 Drawing Sheets



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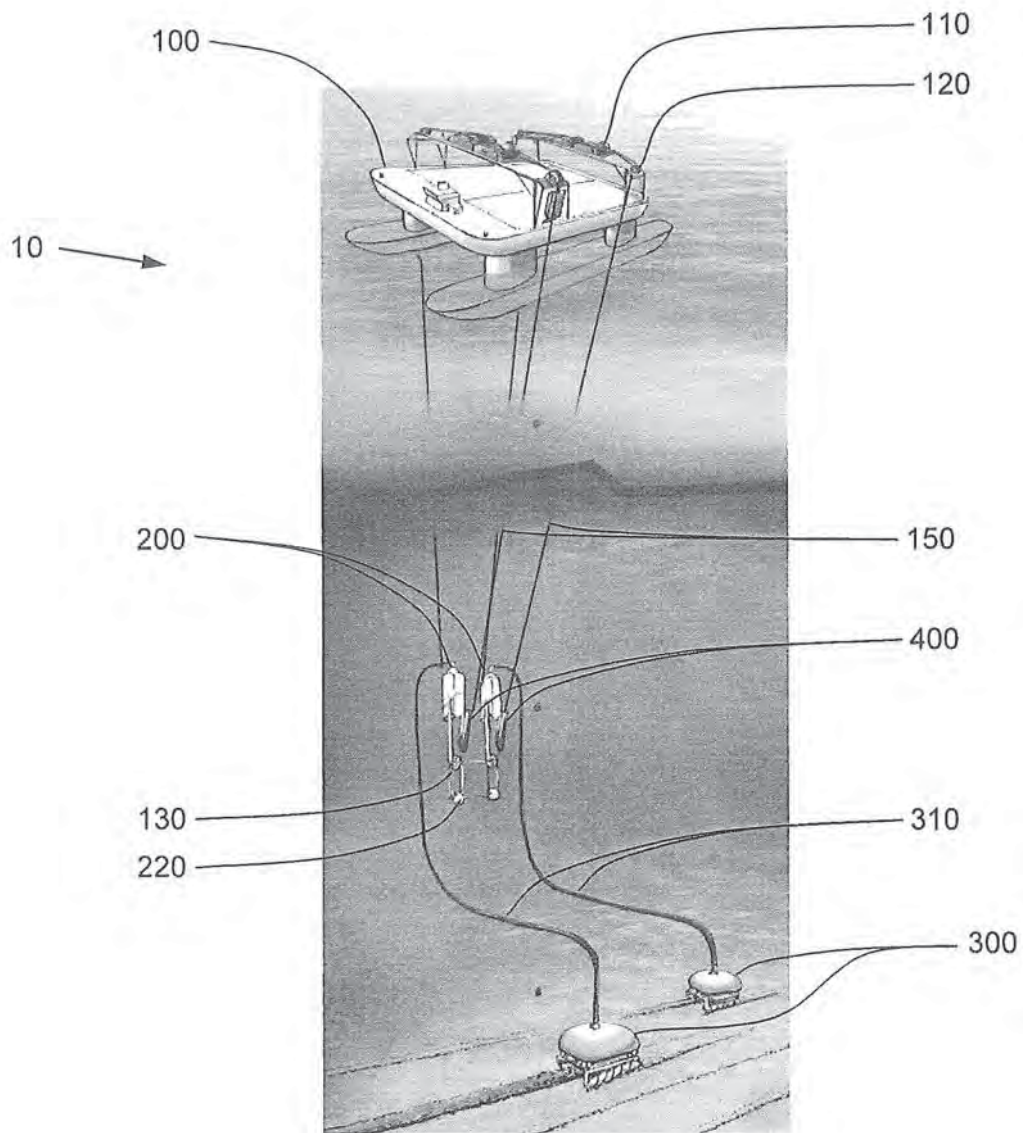


FIGURE 1

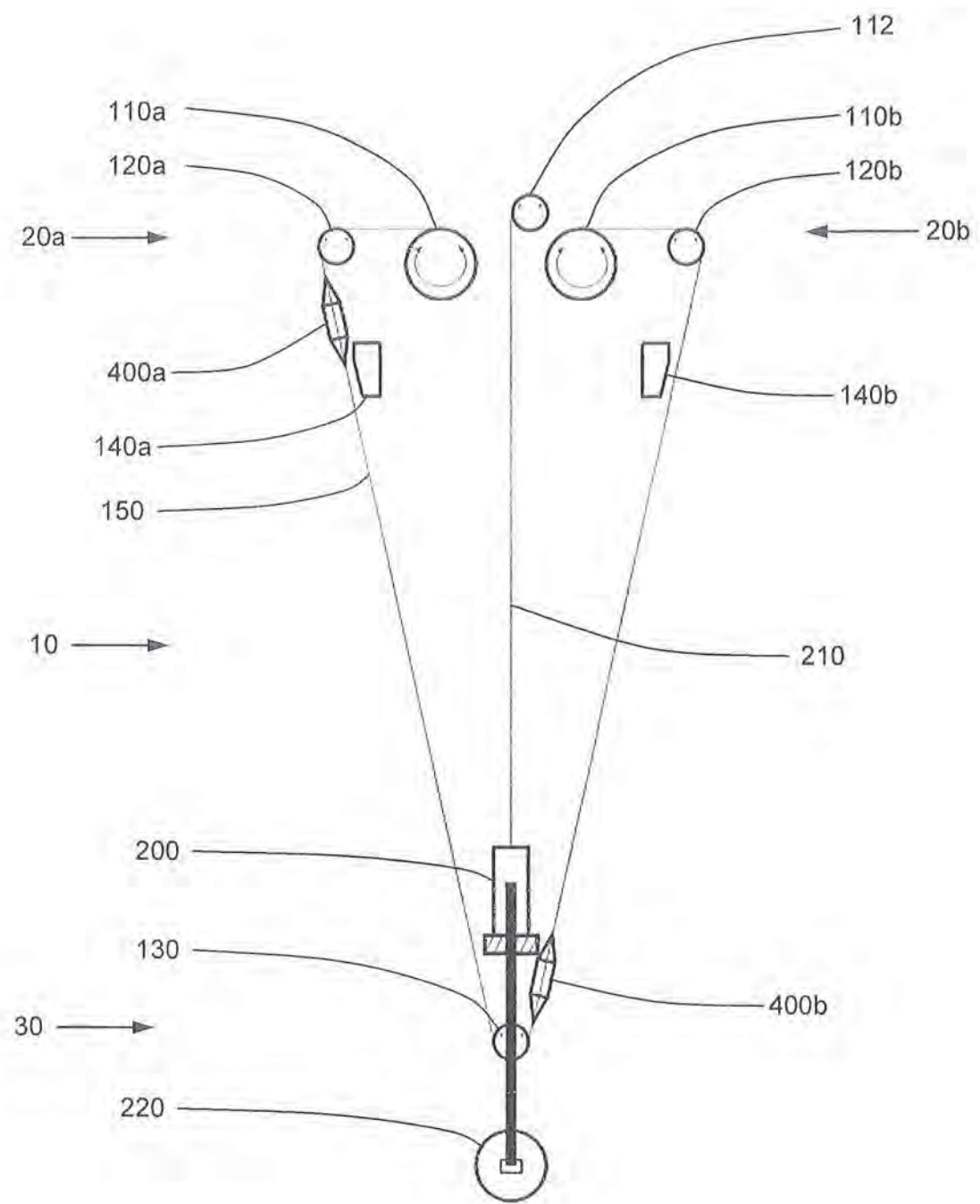


FIGURE 2

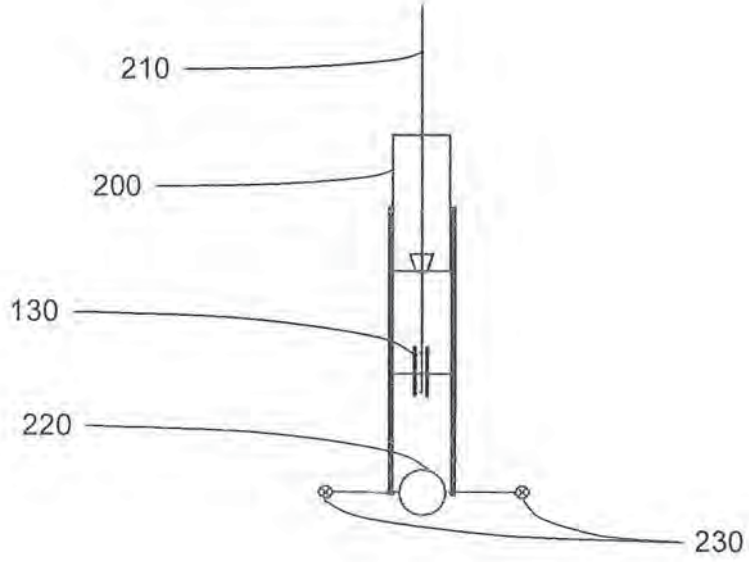


FIGURE 3

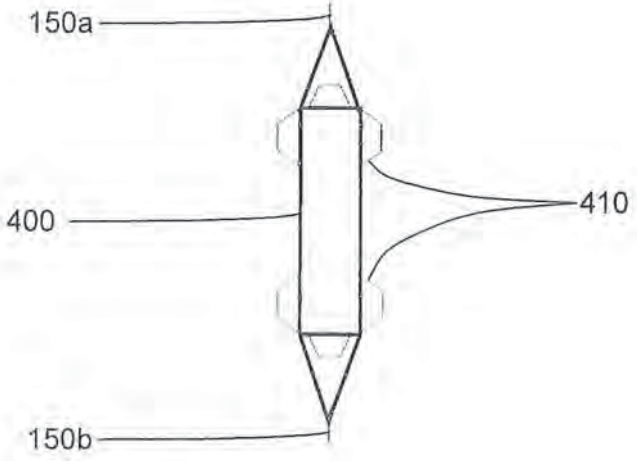


FIGURE 4

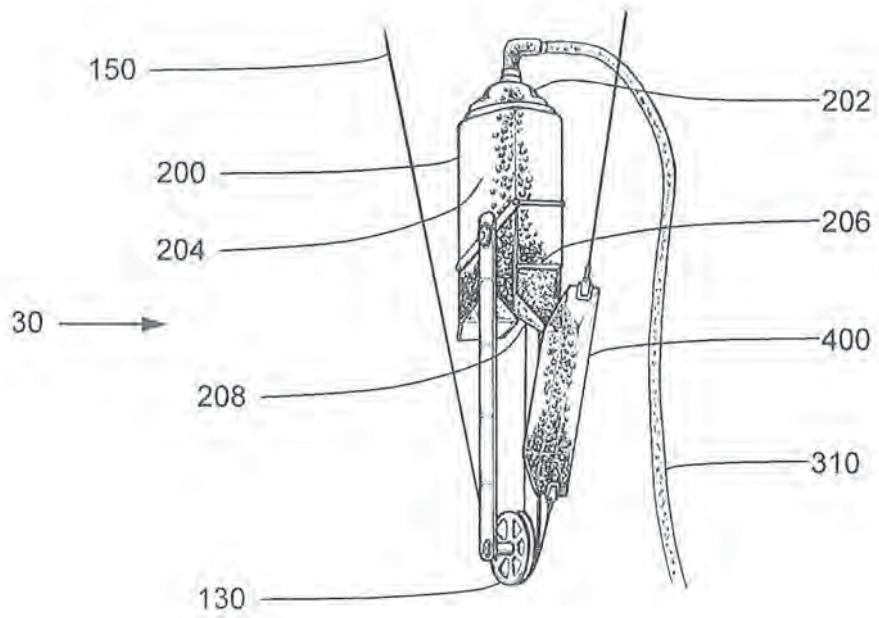


FIGURE 5

SEAFLOOR HAULAGE SYSTEM**FIELD OF THE INVENTION**

The invention relates to a haulage system preferably a seafloor haulage system operating underwater. In particular, the invention relates, but is not limited, to a mechanical seafloor haulage system with guided containers

BACKGROUND TO THE INVENTION

Reference to background art herein is not to be construed as an admission that such art constitutes common general knowledge.

In various locations in the ocean valuable seafloor materials, such as sulphide precipitates or polymetallic nodules, exist in a surface layer on the seafloor at water depths of between around 300 to 6,000 metres, often around 5,000 metres.

There have been various attempts to develop commercially viable mining systems that collect and then convey the nodules from the seafloor. One important aspect of seafloor mining systems relates to haulage systems that raise collected seafloor material to the surface. One of the key factors affecting operational costs, and hence commercial viability, is energy consumption, particularly in relation to hauling seafloor material from the seafloor to the surface.

One haulage system design is to hydraulically haul seafloor materials using some form of riser which pumps seafloor material from the seafloor to a surface vessel or platform. In one such design, a riser is provided which contains and conveys a fluid with suspended minerals therein. The riser material is typically transported in slurry form via subsea pumps and/or compressed air injected into the riser.

Although functional, these systems are energy inefficient, particularly the airlift systems where the majority of the energy loss is a result of slippage of solid particles downwards through the fluid column. Furthermore, as the seafloor materials are lifted in slurry form, they need to be dewatered at the surface requiring further processing and equipment.

Mechanical haulage systems that lift containers by a cable, such as a single drum hoist, double drum hoist or friction (Koepe) hoist as used in some underground terrestrial mines, have potential to be considerably more energy efficient. In terrestrial mines cable driven storage bins or skips winch loads of material to the surface, and make use of a plurality of guiderails to keep the storage bins in alignment. However, when applied underwater over long distances the added complexity required to compensate for the absence of a rigid support structure, using guide wires for example, these designs potentially suffer from serious entanglement and deployment issues.

Particularly, several additional guidewires are required to be located between a surface vessel and an anchor location at or near the seafloor. Over long distances underwater with varying water currents the potential for the wires to twist or tangle or for two or more bins to collide is very high. The risk of twisting or tangling, particularly when further cables are provided for other seafloor infrastructure (e.g. an umbilical for seafloor operations), is typically considered to be prohibitively high.

Additionally, in terrestrial applications the haulage systems are typically in a fixed location for the life of the mine. In seafloor mining operations the haulage system needs to be moved frequently or continuously in order to be able to collect seafloor materials, such as manganese nodules, over

a very large area. Lateral drags and/or raising or lowering of the system caused by such movement further increase the likelihood of tangling of the wires or collision of the bins.

Some mitigating procedures have been considered but they all have significant operational downsides. For example, one approach to reduce the likelihood of collisions is to slow the bins down during intervals of overlap, but this slowdown reduces the operating efficiency of the system. Another approach is to enclose the bins in tubes or pipes, but in addition to the constructions required this effectively creates a pumped system, creating large frictional energy losses caused by the entrained fluids and the surrounding structures. Additional guide wires in an attempt to exert lateral control from the surface vessel has also been considered, but this significantly increases complexity of the system and leads to higher risks of operational downtime and additional maintenance requirements.

Object of the Invention

It is an aim of this invention to provide a seafloor haulage system which overcomes or ameliorates one or more of the disadvantages or problems described above, or which at least provides a useful alternative.

Other preferred objects of the present invention will become apparent from the following description.

SUMMARY OF INVENTION

In one form, although it need not be the only or indeed the broadest form, there is provided a seafloor haulage system for lifting seafloor materials from the seafloor to the surface, the seafloor haulage system comprising:

at least one line member that extends at least partially between the seafloor and the surface; and

at least one container capable of carrying a load, the container being connected to the line member;

wherein the container has a steerable element that enables the container to manoeuvre as it is propelled through the water.

Preferably the steerable element comprises at least one adjustable surface. The steerable element may comprise a rudder, flap, and/or at least one adjustable hydrofoil. Preferably the steerable element is controlled to guide the container along a path. The steerable element may be controlled remotely but is preferably controlled autonomously. Preferably the steerable element is controlled by actively trimming the steerable element.

Preferably the container is a skip. Preferably the container further comprises a position determination system, even more preferably an inertial navigation system that provides a position estimate based on inertial measurements. Alternatively, the position determination system may include magnetic compass, attitude, and/or depth sensors, with potential additional input from acoustic navigation equipment such as Ultra Short Base Line systems. Preferably the steerable element is controlled with respect to the position estimate from the position determination system. Preferably the container is programmed to follow a predetermined path.

The line member may be made of cable, rope, or wire. Preferably, the line member is made of rope, even more preferably synthetic rope, even more preferably two synthetic ropes running parallel so to spread load and reduce the consequences of failure of a single rope. The line member may be integral or may comprise a plurality of line member

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segments that collectively define the line member. Preferably at least some of the line member segments are connected via a container.

Preferably the line member extends from a first surface location located towards or at the surface to a deep sea location located towards or at the seafloor. Preferably the line member further extends from the deep sea location located towards or at the seafloor to a second surface location located towards or at the surface. Preferably the first surface location and the second surface location are located substantially the same distance from the deep sea location. Preferably the first surface location and the second surface location are located at substantially the same level with respect to sea level. Preferably the first surface location and the second surface location are located on opposite ends or sides of a surface vessel, e.g. ship or boat or other type of floating device.

Preferably the line member is received by a sheave at or near the first surface location, the second surface location, and/or the deep sea location. Preferably the system further comprises at least one drive element that pulls on the line member. Preferably the drive element includes a winch that receives at least a portion of the line member. Preferably the winch comprises a rotatable spool around which the line member can be wound.

Preferably the system comprises two winches, preferably in a double drum configuration. Preferably the winches are configured such that potential energy from a down-going container can be recovered by an up-going container. Preferably a first winch is located adjacent the first surface location and the second winch is located adjacent the second surface location. Preferably the first and second winches are located above the surface, but they could be located below the surface. Preferably the line member extends from the first winch to the second winch. Preferably as the line member is wound onto one winch it is unwound from the other winch. Preferably the line member is under tension between the two winches, preferably via a sheave located at or near the deep sea location.

Preferably the line member extends from the first winch to the second winch, preferably via a sheave at or near the first surface location, a sheave at or near the deep sea location, and/or a sheave at or near the second surface location. Preferably a first container is connected to the line member between the first surface location and the deep sea location, and preferably a second container is connected to the line member between the second surface location and the deep sea location. Preferably the first container and second container are spaced apart on the line member such that when one container is located at or near the deep sea location the other container will be located at or near its respective surface location.

Preferably the system further comprises a counterweight. Preferably the counterweight is located at or near the deep sea location. Preferably the counterweight is configured to ensure that the buffer is statically stable and resists the tendency to overturn. Preferably the system further comprises a buffer. Preferably the buffer is located at or near the deep sea location. Preferably the counterweight is connected to the buffer.

Preferably the buffer is suspended above the seafloor. Preferably the buffer is suspended above the seafloor by a buffer line extending from at or near the surface. Preferably the buffer line is an umbilical cable which provides services, such as power and/or data transfer, to the buffer and/or seafloor machines.

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Preferably the buffer has a storage compartment for storing gathered seafloor materials. Preferably the buffer has at least one inlet for receiving gathered seafloor materials and at least one outlet for dispensing gathered seafloor materials. Preferably the inlet is connected to an inlet pipe, preferably a slurry hose inlet pipe. Preferably the outlet or outlets comprises a chute or chutes. Preferably the chutes selectively release seafloor materials when actuated. The chutes may have dosers to dispense a predetermined quantity of seafloor materials when actuated.

The buffer preferably comprises thrusters. Preferably the thrusters actively control orientation, preferably azimuthal orientation relative to a surface vessel, preferably configured to counteract twisting of the subsea rigging. The buffer preferably comprises a seafloor processing system. Preferably the seafloor processing system separates desirable seafloor materials, such as nodules, from slurry.

The container may traverse the line member, but preferably the container is affixed to the line member and is propelled by being towed by the line member. Preferably the container is affixed to at least two segments of the line member, a first line member segment for towing the container in a first direction and a second line member segment for towing the container in a second direction.

Preferably the seafloor haulage system further comprises a surface vessel. Preferably the at least one winch is mounted to the surface vessel. Preferably the line members are supported in the water by the surface vessel. Preferably a plurality of line members, preferably with respective winches, containers and/or buffers, are arranged in parallel from the surface vessel. Preferably the seafloor haulage system further comprises at least one seafloor material collection apparatus. Preferably the at least one seafloor material collection apparatus is connected by a seafloor material transfer pipe to the buffer.

In another form, there is provided a container for hauling seafloor materials from the seafloor to the surface, the container comprising:

- a line member attachment assembly;
- a cavity for carrying a load of seafloor material; and
- at least one steerable element that enables the container to manoeuvre as it is propelled through the water.

In yet another form, there is provided a method of hauling seafloor materials from the seafloor to the surface, the method comprising the steps of:

- gathering seafloor material;
- transferring gathered seafloor material to at least one container located at or near the seafloor;
- guiding the container from at or near the seafloor to at or near the surface using at least one steerable element; and
- unloading the container to a surface vessel.

Preferably the step of gathering seafloor material comprises operating at least one seafloor material collection apparatus to gather seafloor materials. The gathered seafloor materials are preferably transferred from the at least one seafloor material collection apparatus via a pipe, preferably in slurry form.

Preferably the step of transferring gathered seafloor material to at least one container located at or near the seafloor further comprises the step of transferring the gathered seafloor material to a buffer located at or near the seafloor and then dispensing gathered seafloor material from the buffer to the at least one container. The method may further comprise the step of processing the incoming seafloor material, preferably by separating desirable seafloor materials, such as seafloor nodules, from incoming slurry, at the buffer.

Preferably the step of guiding the container from at or near the seafloor to at or near the surface comprises controlling the at least one steerable element. Preferably the container is autonomously controlled. Preferably at least two containers are provided and as one container travels towards the surface the other container travels towards the seafloor. Preferably the two containers are connected by a single line member. Preferably each container is guided to avoid collision with the other container as they pass each other, preferably by controlling the at least one steerable element. The method preferably comprises simultaneously guiding a first container towards the surface and a second container towards the seafloor.

The step of unloading the container to a surface vessel preferably comprises releasing the contents of the container into an unloading bin located at or near the surface vessel.

Preferably the method further comprises the step of towing the container with a line member. Preferably the step of towing the container with a line member comprises actuating a winch that winds the line member onto a spool. Preferably the line member is connected between two winches, preferably via a sheave at a deep sea location, and is simultaneously unwound from a first winch as it is wound onto the second winch to tow the container in a first direction, and is unwound from the second winch and wound onto the first winch to tow the container in a second direction. Preferably a first container travels between the first winch and the sheave located at or near a deep sea location and a second container travels between the second winch and the sheave located at or near a deep sea location.

Further features and advantages of the present invention will become apparent from the following detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

By way of example only, preferred embodiments of the invention will be described more fully hereinafter with reference to the accompanying figures, wherein:

FIG. 1 is a perspective view of a seafloor haulage system;

FIG. 2 is a diagrammatic side elevation representation of a seafloor haulage system;

FIG. 3 is a diagrammatic side elevation representation of a buffer;

FIG. 4 is a diagrammatic side elevation representation of a container; and

FIG. 5 is a close-up perspective view of a buffer unloading material into a container.

DETAILED DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates a seafloor haulage system 10 comprising a surface vessel 100, two buffers 200 located near, but suspended above, the seafloor, two seafloor material collection apparatus 300, and two (or four) containers 400 with a cavity therein to carry a load of seafloor material. The surface vessel 100 has winches 110 and sheaves 120 which are engaged with lines members 150. Winches 110 are preferably in the form of hydrographic or drum winches which may include heave compensation systems.

Containers 400 are preferably skips. Each container 400 is connected to a respective line member 150. Each seafloor material collection apparatus 300 is connected via flexible pipe in the form of a slurry hose 310 to a buffer 200. Although not shown in FIG. 1, it is preferable for the buffer to have its own power, control and communication umbilical cable. Power, control, and communication is then also

provided to the seafloor material collection apparatus 300 from the buffer 200. Alternatively, the seafloor material collection apparatus 300 could be powered and/or controlled using umbilicals from another entity (e.g. the surface vessel 100). Although one seafloor collection apparatus 300 is shown per buffer 200, it will be appreciated that each buffer 200 could be connected to multiple seafloor collection apparatus 300 or multiple seafloor collection apparatus 300 could be connected to a single buffer 200.

FIG. 2 illustrates further details of haulage system 10. As seen in FIG. 2 buffer 200 is suspended by a buffer line 210 which is preferably in the form of an umbilical cable providing power, control, and/or data communications to the buffer 200 from the surface vessel 100 (not shown in FIG. 2) via a buffer winch 112. The buffer 200 is weighted by a counterweight 220 at a deep sea location 30 located towards, preferably near, the seafloor.

A line member 150, which is preferably made substantially of synthetic rope, extends from a first surface location 20a down to the deep sea location 30 and back up to a second surface location 20b which is located adjacent the first surface location 20a. Specifically, the line member 150 extends from a first winch 110a to a first surface sheave 120a to a deep sea sheave 130 located adjacent the buffer 200 to a second surface sheave 120b to a second winch 110b. The winches 110a, 110b and surface sheaves 120a, 120b are typically located on the surface vessel 100 (as shown in FIG. 1).

A first container 400a is located between the first surface sheave 120a and the deep sea sheave 130. A second container 400b is located between the second surface sheave 120b and the deep sea sheave 130. The first container 400a and the second container 400b are connected to the same line member but on opposite sides of the deep sea sheave 130. The two winches 110a and 110b are arranged such that as one winds wire onto its respective spool the other unwinds wire from its respective spool, and vice versa. The first container 400a and second container 400b are each affixed to the line member 150 by a line member attachment assembly such that connects the containers 400a, 400b between two adjacent segments of the line member 150.

A first unloading bin 140a and a second unloading bin 140b are located at the first surface location 20a and second surface location 20b, respectively. The first unloading bin 140a and second unloading bin 140b are both configured to receive material from the first container 400a and the second container 400b, respectively, when their respective container 400a, 400b is alongside. The unloading bins 140a, 140b may have a large storage capacity, possibly a shared storage capacity, or may transfer the seafloor materials to one or more silos of the surface vessel 100 for storage.

FIG. 3 illustrates a buffer 200 suspended by buffer line 210 and weighted down by counterweight 220. The buffer 200 has azimuth thrusters 230. Although the thrusters 230 are illustrated as extending from the counterweight 220, it will be appreciated that they could also be located on other parts of the buffer 200. The thrusters 230 serve to provide azimuth and lateral maneuverability of the buffer 200.

In particular, the thrusters 230 can be used to actively control orientation of the buffer 200, primarily azimuthal orientation relative to the surface vessel 100. This enables the buffer 200 to maintain correct orientation relative to the surface vessel to prevent any entanglement caused by twisting of any of the lines (e.g. line member 150, buffer line 210, and any other lines extending from the surface vessel 100). The thrusters 230 of the buffer 200 are preferably controlled autonomously or remotely from the surface vessel 100.

FIG. 4 illustrates a container 400 connected between a first segment 150a and a second segment 150b of the line member 150. The container 400 has steerable elements in the form of adjustable flaps 410 which enable the container 400 to manoeuvre as it is pulled through the water by the lines members. The container 400 is programmed to autonomously or via remote control to direct the container 400 on a path that avoids entanglement or collision with any lines or other containers operating in the area as it is pulled by the line member 150.

The container 400 has a position determination system, preferably in the form of an inertial navigation system, that provides control systems for the container 400 with position estimates. The position determination system preferably includes a plurality of sensors including at least one or more of, heading, pitch, roll, position and depth sensors. The flaps 410 are then trimmed with respect to the position estimate and sensor outputs to direct the container 400 along a substantially predetermined path.

The container 400 preferably has a power storage system, typically including a battery, which provides the necessary power for control systems and the adjustable flaps 410 to be trimmed. Preferably the power storage system is interchangeable or charged when the container 400 is located at its surface position 20a, 20b. Alternatively, with an appropriate line member 150 the container 400 could be powered and/or controlled from the surface vessel 100 via the line member 150.

The container 400 is preferably connected to two line members 150 above and two line members below (e.g. in a Blair multi-rope configuration of a double drum hoist system). The two line members 150 above the container 400 allow the container 400 to be azimuthally oriented, without the need for hydrodynamic steering, when the container 400 slows down as it approaches the unloading bin of the surface vessel 100. Likewise, the two line members 150 below the container 400 allow the container 400 to be azimuthally oriented, without the need for hydrodynamic steering, when the container 400 slows down as it approaches the buffer 200 near the seafloor.

FIG. 5 illustrates a close up view of a buffer 200 when unloading seafloor materials into a container 400. Buffer 200 has an inlet 202 that receives gathered seafloor materials from seafloor collection apparatus 300 via slurry hose 310. The gathered seafloor materials are then stored in storage compartment 204 of the buffer 200 ready to be unloaded to a container 400. The storage compartment 204 preferably has a capacity sufficient to at least fully load a single container 400 without having to wait for further materials to be received over slurry hose 310. The seafloor material contained in storage compartment 204 of the buffer 200 assists the counterweight 220 (not shown in FIG. 5) to weigh the buffer 200 down in the water. The counterweight 220 (not shown in FIG. 5) located below the sheave 130 assists to weigh the buffer 200 down and also acts to prevent overturning of the buffer 200.

When container 400 is located at deep sea location 30 as illustrated in FIG. 5 the seafloor materials are transferred from the storage compartment 204 of the buffer 200 to the container 400 via outlet 206 of the buffer 200. Outlet 206 of the buffer 200 is located at an upper end of the storage compartment 204 to enable gravity feeding of the storage materials down chute 208. Alternatively, or additionally, the seafloor materials may be urged toward the container 400 using an appropriate mechanism such as, for example, an Archimedes screw feeder.

Chute 208 is preferably actuated to open outlet 206 when the container 400 arrives to the deep sea location 30 (as shown in FIG. 5) and to close outlet 206 when the container 400 leaves the deep sea location 30 to prevent loss of seafloor materials from inside the storage compartment 204. Chute 208 may be actuated by any suitable means such as mechanically or hydraulically by the storage container 400 or electronically either automatically or via control from the surface vessel 100.

As shown in FIG. 1, the seafloor haulage system 10 can be expanded from a single line member 150 system (as shown in FIG. 2) to have multiple line members 150 (e.g. two adjacent line members 150 as shown in FIG. 1) working adjacent each other, each with respective containers 400 and buffers 200. Larger arrays of line members 150 with associated containers 400 and buffers 200 could also be used to scale the system as needed.

In use, seafloor materials are gathered by seafloor collection apparatus 300 and pumped in slurry form over slurry hose 310 to the buffer 200. The buffer 200 may optionally process the received seafloor material, and collects the gathered seafloor material in temporary storage compartment 204. First container 400a is lowered to the buffer 200 by actuating second winch 110b which pulls the first container 400a via the line member 150. Once the first container 400a arrives at the buffer 200, gathered seafloor material is transferred from the buffer 200 to the container 400a. Once the buffer 200 has dispensed the required seafloor material, the first container 400a is pulled, via line member 150, back to the surface by actuating the first winch 110a.

As the first winch 110a is actuated the second container 400b is simultaneously pulled down, via line member 150, to the buffer 200. The first container 400a and second container 400b are spaced apart on the line member such that when the first container 400a is at the surface the second container 400b is at the buffer 200 and vice versa. Once the first container 400a arrives at the surface and the second container 400b arrives at the buffer the first container then unloads the seafloor material to the surface vessel 100 via unloading bin 140a. At, or at least around, the same time, the buffer 200 transfers gathered seafloor material to the second container 400b. Second container 400b is then pulled the surface to second unloading bin 140b, which in turn pulls first container 400a back down to the buffer 200, and the process repeats.

Advantageously the seafloor haulage system 10 provides, a mechanical haulage system that is energy efficient compared to hydraulic riser systems while also reducing the likelihood of entanglement of subsea lines or collision of passing containers. Furthermore, it is easily relocatable by raising the deep sea components towards the surface, moving them to a new location, and then lowering them at the new location. This reduces relocation costs and set up times which ultimately increases productivity as the seafloor mining system covers large areas of the seafloor.

While the figures illustrate the distance between the surface and the seabed as being relatively close, this is for convenience only and it will be appreciated that the present invention will typically be used in deep sea applications where the seabed is over 2,000 m, typically around 5,000 m, deep. References herein to the seafloor, seabed, subsea, or the like are for convenience only and could equally be applied to other bodies of water such as, for example, a lake with a lakebed, etc.

In this specification, adjectives such as first and second, left and right, top and bottom, and the like may be used solely to distinguish one element or action from another

element or action without necessarily requiring or implying any actual such relationship or order. Where the context permits, reference to an integer or a component or step (or the like) is not to be interpreted as being limited to only one of that integer, component, or step, but rather could be one or more of that integer, component, or step etc.

The above description of various embodiments of the present invention is provided for purposes of description to one of ordinary skill in the related art. It is not intended to be exhaustive or to limit the invention to a single disclosed embodiment. As mentioned above, numerous alternatives and variations to the present invention will be apparent to those skilled in the art of the above teaching. Accordingly, while some alternative embodiments have been discussed specifically, other embodiments will be apparent or relatively easily developed by those of ordinary skill in the art. The invention is intended to embrace all alternatives, modifications, and variations of the present invention that have been discussed herein, and other embodiments that fall within the spirit and scope of the above described invention.

In this specification, the terms 'comprises', 'comprising', 'includes', 'including', or similar terms are intended to mean a non-exclusive inclusion, such that a method, system or apparatus that comprises a list of elements does not include those elements solely, but may well include other elements not listed.

What is claimed is:

1. A seafloor haulage system for lifting seafloor materials from the seafloor to the surface, the seafloor haulage system comprising:

at least one line member that extends at least partially between the seafloor and the surface;

at least one container capable of carrying a load, the container being connected to the line member; and

a buffer located at or near a deep sea location wherein the buffer has: a storage compartment for storing gathered seafloor materials; at least one inlet connected to an inlet pipe for receiving gathered seafloor materials; and at least one outlet comprising a chute to selectively release seafloor materials when actuated for dispensing gathered seafloor materials from the buffer, wherein the storage compartment is connected to the inlet pipe and the chute;

wherein the container has a steerable element that enables the container to maneuver as it is propelled through the water,

wherein the steerable element comprises at least one adjustable surface, and

wherein the container comprises a position determination system adapted to provide a position estimate.

2. The seafloor haulage system of claim 1, wherein the steerable element comprises a rudder, flap, and/or at least one adjustable hydrofoil.

3. The seafloor haulage system of claim 1, wherein the steerable element is controlled to guide the container along a path.

4. The seafloor haulage system of claim 1 wherein the steerable element is controlled autonomously.

5. The seafloor haulage system of claim 1, wherein the steerable element is controlled remotely.

6. The seafloor haulage system of claim 1, wherein the steerable element is controlled by actively trimming the steerable element.

7. The seafloor haulage system of claim 1, wherein the container is a skip.

8. The seafloor haulage system of claim 1 wherein the position determination system comprises an inertial navigation system that provides a position estimate based on inertial measurements.

9. The seafloor haulage system of claim 1, wherein the position determination system includes magnetic compass, attitude, and/or depth sensors.

10. The seafloor haulage system of claim 1, wherein the position determination system includes input from acoustic navigation equipment.

11. The seafloor haulage system of claim 1, wherein the steerable element is controlled with respect to the position estimate from the position determination system.

12. The seafloor haulage system of claim 1 wherein the container is programmed to follow a predetermined path.

13. The seafloor haulage system of claim 1, wherein the line member is made of cable, rope, or wire.

14. The seafloor haulage system of claim 13, wherein the line member is at least substantially made of synthetic rope.

15. The seafloor haulage system of claim 14, wherein the line member comprise two synthetic ropes running parallel.

16. The seafloor haulage system of claim 13, wherein the line member is integral.

17. The seafloor haulage system of claim 13, wherein the line member comprises a plurality of line member segments that collectively define the line member.

18. The seafloor haulage system of claim 17, wherein at least some of the line member segments are connected via a container.

19. The seafloor haulage system of claim 1, wherein the line member extends from a first surface location located towards or at the surface to a deep sea location located towards or at the seafloor.

20. The seafloor haulage system of claim 19, wherein the line member further extends from the deep sea location located towards or at the seafloor to a second surface location located towards or at the surface.

21. The seafloor haulage system of claim 20, wherein the first surface location and the second surface location are located substantially the same distance from the deep sea location and at substantially the same level with respect to sea level.

22. The seafloor haulage system of claim 20, wherein the first surface location and the second surface location are located at opposite ends or sides of a surface vessel.

23. The seafloor haulage system of claim 20, wherein the line member is received by a sheave at or near the first surface location, the second surface location, and/or the deep sea location.

24. The seafloor haulage system of claim 1, further comprising at least one drive element that pulls on the line member.

25. The seafloor haulage system of claim 24, wherein the drive element includes a winch that receives at least a portion of the line member.

26. The seafloor haulage system of claim 25, wherein the drive element comprises two winches arranged in a double drum configuration such that potential energy from a down-going container can be recovered by an up-going container.

27. The seafloor haulage system of claim 25, wherein a first winch is located adjacent a first surface location and the second winch is located adjacent a second surface location and the line member extends under tension from the first winch to the second winch via a sheave located at or near a deep sea location.

28. The seafloor haulage system of claim 27, wherein the line member extends from the first winch to the second

winch via a sheave at or near the first surface location, a sheave at or near the deep sea location, and a sheave at or near the second surface location.

29. The seafloor haulage system of claim 27, wherein a first container is connected to the line member between the first surface location and the deep sea location and a second container is connected to the line member between the second surface location and the deep sea location.

30. The seafloor haulage system of claim 29, wherein the first container and second container are spaced apart on the line member such that when one container is located at or near the deep sea location the other container will be located at or near its respective surface location.

31. The seafloor haulage system of claim 1, further comprising a counterweight connected to the buffer.

32. The seafloor haulage system of claim 1 wherein the buffer is suspended above the seafloor by a buffer line extending from at or near the surface.

33. The seafloor haulage system of claim 1, wherein the chutes have dosers to dispense a predetermined quantity of seafloor materials when actuated.

34. The seafloor haulage system of claim 1, wherein the buffer comprises thrusters.

35. The seafloor haulage system of claim 1, wherein the thrusters actively control orientation of the buffer relative to a surface vessel.

36. The seafloor haulage system of claim 1, wherein the buffer comprises a seafloor processing system that separates seafloor materials from slurry.

37. A method of hauling seafloor materials from the seafloor to the surface, the method comprising the steps of: gathering seafloor material;

transferring gathered seafloor material to at least one container located at or near the seafloor;

guiding the container from at or near the seafloor to at or near the surface using at least one steerable element; and

unloading the container to a surface vessel, wherein the container comprises a position determination system adapted to provide a position estimate;

wherein the at least one steerable element comprises at least one adjustable surface; and

wherein the step of transferring gathered seafloor material to at least one container located at or near the seafloor further comprises the step of transferring the gathered seafloor material to a buffer located at or near the seafloor and then dispensing gathered seafloor material from the buffer to the at least one container, wherein the buffer has: a storage compartment for storing gathered seafloor materials; at least one inlet connected to an inlet pipe for receiving gathered seafloor materials; and at least one outlet comprising a chute selectively release seafloor materials when actuated for dispensing gathered seafloor materials from the buffer, wherein the storage compartment is connected to the inlet pipe and the chute.

38. The method of claim 37, wherein the step of gathering seafloor material comprises operating at least one seafloor material collection apparatus to gather seafloor materials.

39. The method of claim 37, wherein the gathered seafloor materials are transferred from the at least one seafloor material collection apparatus via a pipe in slurry form.

40. The method of claim 37, further comprising the step of processing the incoming seafloor material, by separating seafloor materials from incoming slurry, at the buffer.

41. The method of claim 37, wherein the step of guiding the container from at or near the seafloor to at or near the surface comprises controlling the at least one steerable element.

42. The method of claim 37, wherein at least two containers are provided and as one container travels towards the surface the other container travels towards the seafloor.

43. The method of claim 42, wherein the two containers are connected by a single line member and each container is guided to avoid collision with the other container as they pass each other.

44. The method of claim 37 further comprising the step of towing the container with a line member connected between two winches via a sheave at a deep sea location such that the line member is simultaneously unwound from a first winch as it is wound onto the second winch to tow the container in a first direction, and is unwound from the second winch and wound onto the first winch to tow the container in a second direction.

* * * * *



Nodule Lateral Conveyor - A Full-Scale Test

Nautilus Minerals – Tonga Offshore Mining Limited

Polymetallic Nodule Concentrator:

Lateral Conveyor – A Full-Scale Test

Rev no.	Date	Reason for Issue	Prepared	Checked	Approved
A	3/03/2020	Draft for internal review	Anthony Manocchio, Gordon Yu	John Parianos	John Parianos
0	18/03/2020	Final	Anthony Manocchio, Gordon Yu	John Parianos	John Parianos

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BMS-NMI-BMA-TEM-0000-001

List of References

Ref. No	Document Name	Document Number
1	Nautilus Nodule Concentrator: Lateral Conveyor - Numerical Simulation of Flows	TBD
2	NI 43-101 Technical Report TOML Clarion Clipperton Zone Project, Pacific Ocean. 2016 AMC	AMC Project 315039 Nautilus Document Number CCZ-TOM-DEV-RPT-2200-002
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5		

1 Summary

Nautilus' Decoupled Underwater Collection System design currently consists in part of a Concentrator Array (CA), led by a Concentrator Steering Unit (CSU), in turn towed from a surface vessel via towing umbilical. While this concept has survived critical review to date and is largely based on proven technology, it has not yet been fully tested at pilot scale. The collector sub-component in the CA was pilot tested in 1978 using a collection width of 2 and 3 m. The Nautilus full scale Concentrator Array (CA) design involves coupling up to 7 several such modules for an effective collection width of 21m. In the design, once the nodules are collected, they are deposited into a concentrated windrow on the seafloor for later reclamation.

To achieve this, nodules collected along the length of the CA need to be conveyed to the centre for windrow at a sufficient rate to meet the volumes required for full production. Nodules along the width of the CA, but particularly from the outer extremities need to be moved at relatively high speeds to prevent accumulation. Given that this type of conveying is not known to have ever been done before at these rates and velocities, we set about doing a numerical simulation. This numerical simulation has identified critical velocities capable of conveying particles to satisfy the required production rate. However, the numerical results needed to be validated by real world data. We decided we could do a full-scale test to both prove the concept in a test environment but also substantiate the model for future design.

A full-scale test program was developed and undertaken 31st Jan – 3rd Mar 2020, in a purpose-built water filled test tank at Nautilus Minerals/TOML warehouse in East Brisbane. Some 55 tests were conducted involving:

- Setup and calibration runs
- 1st set of tests with 6 m long array over 0° incline
- 2nd set of tests with 6 m long array over 3° incline
- 3rd set of test with 9 m long array over 0° incline

The authors were primarily responsible for the development of the test equipment, performing the testing, processing and validating the data with the numerical simulation.

The testing achieved the primary objective of demonstrating that nodules can be transferred at the velocities required to meet full production. The key findings are as follows:

1. The test program has shown the Concept of Lateral Conveyor is effective in conveying nodules at the desired production rates. In all test program cases, with a Flow Velocity over 2 m/s, *all* nodule particles can be transported through the full-scale Conveyor Tube with a length up to 9 m (300 mm diameter), given a nodule feeding rate of 6 kg/s or higher.
2. The recommended Flow Velocity for is 4 m/s. Extensive tests were carried out using Flow Velocity of 3 m/s for a 6-m Tube and proved to be sufficient. For a design Tube length of 9 meters, the numerical simulation, which has been validated by the Test, shows a Flow

Velocity of 4 m/s will ensure a low nodule volume concentration throughout the Tube (<15%) to avoid a potential “backlog” of the Conveyor Tube.

3. With a recommended Flow Velocity of 4 m/s, *Shaft Power* P_1 required to generate the flow rate is estimated to be 11.88 kW and the required *Pump Power* P_2 is 14.25 kW (See Section 2.3 of *Ref. 1*). A high-flow and low-head Impeller is recommended for this Operation, applicable to those commonly used in Axial Flow Pumps.
4. This Test has played an important role in validating the numerical work detailed in *Ref. 1*. A Drag Coefficient of 0.4 is used throughout the numerical simulation as commonly recommended in the literature.

A full-scale Lateral Conveyor will be incorporated into the future Pilot Testing in the CCZ with actual nodules to test the “steady-state” conveying, which is impractical to achieve in a test environment.

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2 Background

Polymetallic nodules are found in a thin layer on the seafloor (abundance of ~10-15 kg/m²; ref 2). Nautilus has a patented decoupled underwater collection system includes

- Concentrator Array (CA)
- Concentrator steerage unit
- Towing umbilical
- Sensor and feedback and control system.

The collection system concentrates the nodules from this thin layer into a windrow (holding ~200-300 kg/m) using a towed array of primary collector devices, called a Concentrator Array (CA). The number of Concentrator Units (CUs) that are arrayed together can thus be varied to provide the required collection width for each development / operational phase. For example:

1. Pilot phase will use a single 3 m wide module
2. Demo-phase will likely use 3 ea. modules, forming a 9 m wide array
3. Mining test phase might use 3 or 5 modules for a 9 to 15 m wide array
4. Material handling modelling and mining planning suggests that the commercial phase use up to 7 ea modules into a 21 m wide collection array.

A tow bridle will be designed such that each 3 m collector system can track the seafloor independent of one another as they are towed across the seafloor depositing nodules into a highly concentrated windrow.

The concentrator array (CA) works by collecting nodules from the seafloor and placing them into a single nodule windrow located behind the centre of the CA (e.g. Figure 1).

This means of primary nodule collection, sediment rejection, nodule transport within the system, and nodule discharge into the windrow is all based on the hydraulic collector design developed and implemented by Ocean Management Inc (OMI) during the mid-70's.

Each concentrator unit (CU) in the array will incorporate its own high volume, low pressures pumps to pick up the nodules and deliver them to lateral conveyors that will transport and deposit the nodules into the windrow. The system is modular, and the number of CUs can be varied depending on application and deposit characteristics. Each CU "floats" semi-independently over the seabed optimising primary collection and accommodating irregularities.

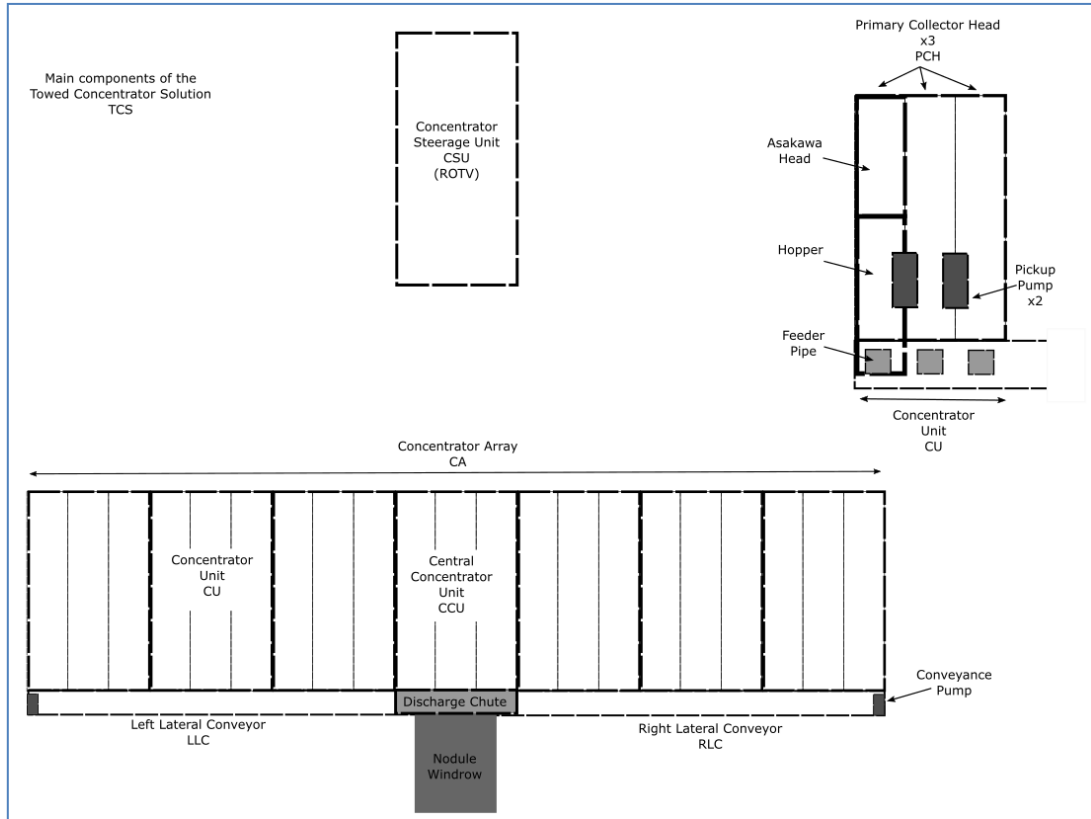


Figure 1: Main Components in the towed concentrator solution

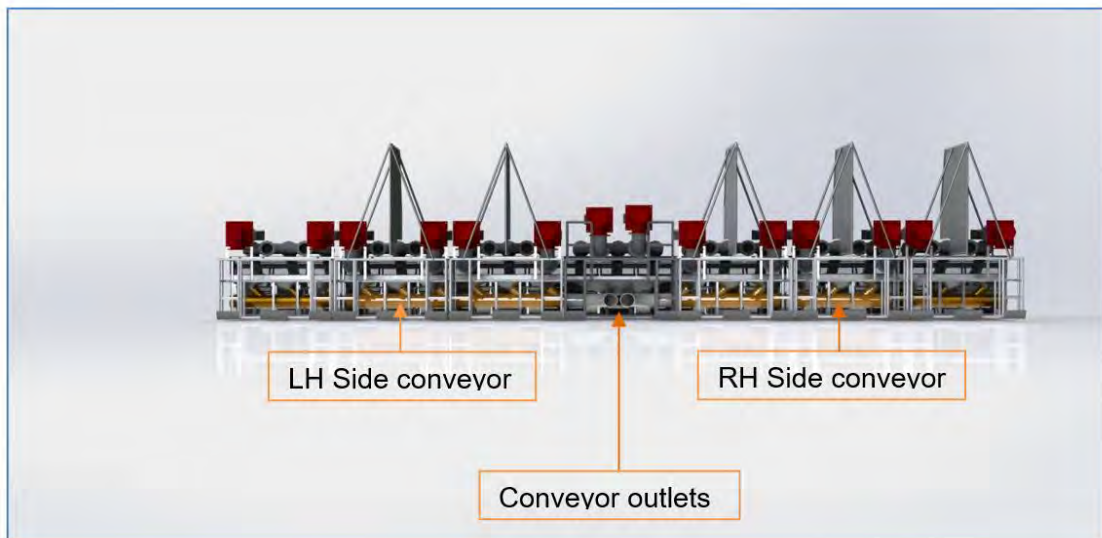


Figure 2: Rear view of 21m wide concentrator SW model

Both sides of the conveyor can be seen in the SolidWorks model, shown in orange above.

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Other key benefits with this technology are

- Proven during the 1970s OMI pilot testing program
- Proven sediment rejection during the OMI testing
- Proven nodule separation and recovery during the OMI testing
- Our CU width = OMI Collector width, so hydraulic design is fully scaled
- Flexible, modular design

We have incorporated critical data obtained from the OMI testing in the 70s for various aspects of the CA, but lateral conveying was not tested, so we have started from scratch on this concept, with any relevant recommendations from this testing.

3 Test Program

This test program looks at a single side 9m long conveyor (Figure 3). The test was setup as full scale but only 1 side. Both Left Lateral Conveyor (LLC) and Right Lateral Conveyor (RLS) are identical.

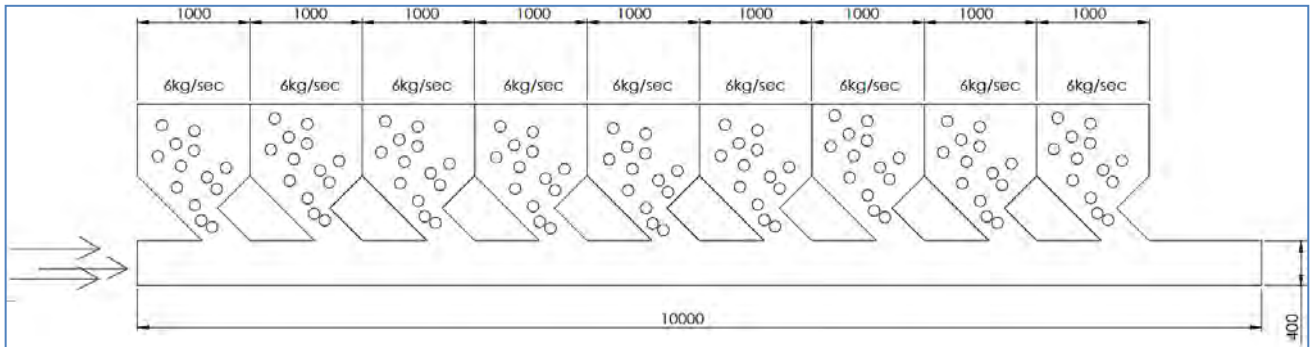


Figure 3: Schematic of lateral conveyor (1 side only)

Some 55 different tests were conducted including:

- Setup and calibration runs
- 1st set of tests with 6 m long array over 0° incline
- 2nd set of tests with 6 m long array over 3° incline
- 3rd set of test with 9 m long array over 0° incline

A full list of tests is included in Appendix A.

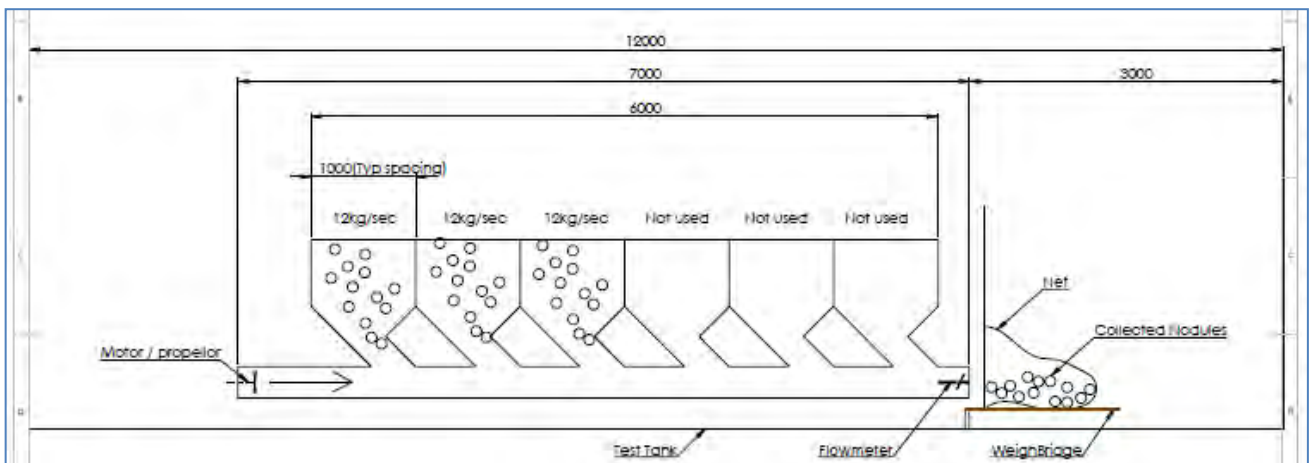


Figure 4: Schematic of test conveyor 6m (1 side only)

The 1st set of tests were configured as per Figure 4: Schematic of test conveyor 6m (1 side only) above, it includes a 12 m test tank, 6 m long conveyor' 6ea feeder units were configured but only

the first 3 were used with a standard 12 kg per dose. Total nodules conveyed for each test was thus 36 kg

A 2nd set of test were configured as per Figure 4: Schematic of test conveyor 6m (1 side only). But set at a 3° incline, all other test parameters were not changed.

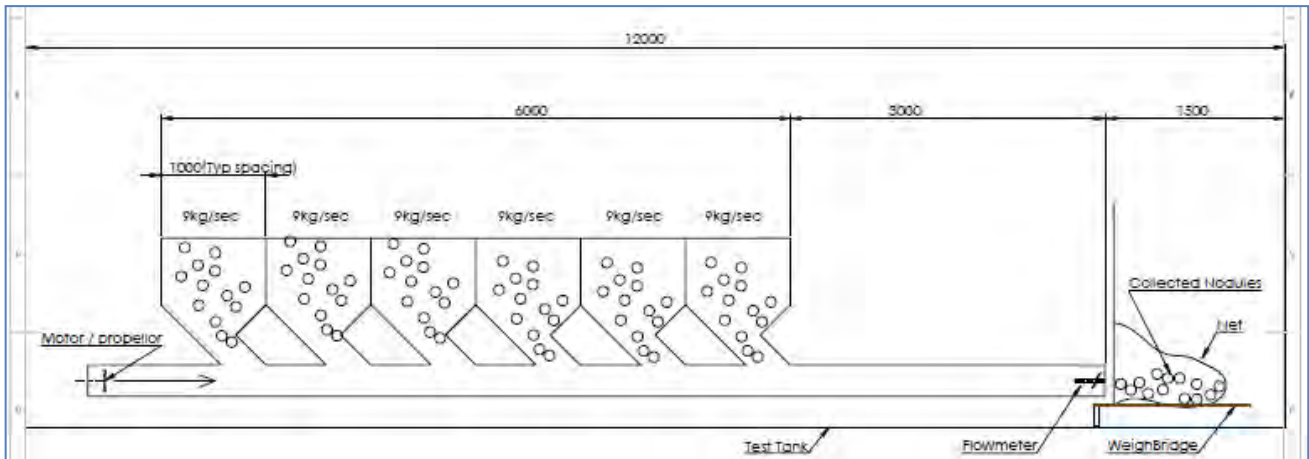


Figure 5: Schematic of test conveyor 9m (1 side only)

The 3rd set of tests were configured as per Figure 5 above, it included a 12m test tank, 9m long conveyor, 6ea feeder units were configured, 9kg per dose. Total nodules conveyed for each test was 54kg. Note that in the full scale CA design the central 3 m sled discharges directly so each side is 9 m long i.e. 9 m LLC + 3 central sled +9 m RLC = 21 m operating width.

The key areas considered during the testing were as follows

- Conveyor water / nodule velocity. This aspect of the testing needed to confirm that production volumes can be conveyed at the required speed
- Conveyor power. This aspect of the testing was needed to confirm power requirements, but also allowed for optimisation
- Model validation
- Understand the propeller / impeller dynamics and future design requirements.

3.1 Objectives

The critical factors considered in this test were

1. To demonstrate the effectiveness of the Concept of Lateral Conveyor.
2. To validate the results of numerical simulations, which was run in conjunction to define and supplement the Test.
3. To determine the minimum “Critical Flow Velocity”, capable of conveying *all* nodule particles through the Conveyor Tube, given the required production rate. Subsequently the power of the conveyor can be determined.

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4. To determine / define follow-up work

3.2 General Comments

The testing was conducted between the 31st Jan to the 3rd Mar 2020, inside Nautilus Minerals warehouse in East Brisbane.

The equipment worked quite well overall, although some aspects deviated from the original plan due to unforeseen circumstances.

- The original plan to measure nodule velocity was to use video cameras ported through the side of the conveyor pipe. Turbulence in the water prevented this solution for working so an alternative solution was developed.
 - A flow meter was incorporated into the end of the conveyor to measure the water velocity
 - A weighbridge was incorporated into the conveyor outlet to indicate when the nodules arrived at the outlet
 - A synchronised method for feeding the nodules at each inlet to measure the time it takes for the nodules to travel along the conveyor

3.3 Equipment

The main test equipment used was as follows.

- 12 m long test tank
- 9 m long conveyor (300 mm diameter)
- Drive motor and propeller / impeller

The full-scale testing solution included a real time logging system for post processing of the data.

3.3.1 Test tank

The test tank was designed and constructed to minimise the cost of the build while ensuring the test was not constrained. The tank was 12 m long x 1.2 m wide x 1.2 m high and was manufactured from RHS "C" frame sections and Form ply. Originally two layers of heavy-duty builders' plastic was used to waterproof the tank, a third layer was added when we reconfigured for 3deg incline.

The size of the tank was determined by the volume of water required to return uninhibited to the propeller inlet. Most of the testing was conducted with a 6 m conveyor, providing 3 m at the discharge, and 3 m at the intake. We found the volumes to be sufficient for all our test velocities. Later in the testing we increased the conveyor length to the full 9 m as per the full-scale system, which only provided us with 2 m at the discharge and 1m at the intake. In this configuration we did experience some back pressure on the conveyor outlet due to its proximity to the end of the tank which did partially impede the testing.

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Figure 6: 12m test tank as built at various stages of the build

3.3.2 Conveyor

As per the tank design, the conveyor was constructed to minimise the cost of the build while ensuring the test was not significantly constrained in any way. Our original modelling considered an internal pipe diameter for the conveyor of 400 mm. The largest pipe size is constrained by the physical dimensions of the CA system; the largest we could have considered was 450 mm. As part of optimisation we also wanted to test the minimum conveyer ID. This was simply derived by multiplying the maximum particle size of 100 mm x 3, and the initial numerical simulations indicated 300 mm would probably work without blockage. We configured the first test using 300mm ID pipe because it was significantly cheaper than the larger 400 mm option in the hope (duly realised) that it would be suitable, and we would save some money in the testing.

The first set of tests were configured with 6 feed points spaced 1 m apart providing a total conveyor distance of 6 m. This length was considered adequate to demonstrate the concept. The pipe and 45° “Ts” were clamped onto a modular frame which coupled the conveyor to the motor / impellor.



Figure 7: 300 mm x 6m conveyor as built, “Ts” are spaced 1m apart

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3.3.3 Motor / impellor

The motor / impellor were selected based on availability and cost, but also closeness to the parameters assumed in the initial numerical modelling. A 20 hp motor was thought to be adequate for the test based on this modelling and a long leg was required for maximum water depth while in the tank. Our final selection was

1. Motor – 25 hp Johnston long leg outboard.
2. Propeller – 4 blade, 254 mm diameter, 15° pitch (high flow propeller)



Figure 8: 25hp Johnston outboard and test propeller

The motor / propeller were mounted onto the conveyor frame so that the propeller was shrouded into the entrance of the pipe. This arrangement was considered the most appropriate approach during the initial design.



Figure 9: – Motor / propeller arrangement

3.3.4 Nodule feeder system

A system of feeding the conveyor with the appropriate weight of nodules was designed to simulate production rates for a single instance, not a continuous or steady state as in the actual production environment. Feeder tubes were loaded with wet nodules of the appropriate weight before each test. A flashing strobe set at the desired flash rate was used to synchronize and time the release for each test, with one person positioned at each tube to manually release the nodules accordingly.



Figure 10: – Initial test setup showing the manual feeder system

The feeder system was designed to take up to 12 kg per dose and angled to allow for easy loading and provide a steady release rate of under 1 second for up to 12 kg. The majority of the testing was performed from the first three feeder points using 12 kg for each dose. In full production, the conveyor will need to transport 6 kg / meter / second to the windrow.

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Braces were installed across the tank once all the equipment was installed and prior to filling with water. These were designed to prevent the tank from spreading with the weight of the water.

3.3.5 Main test sensors

Various sensors were used throughout the testing, the critical ones being

1. Flow meter – This was positioned near the exit of the conveyor to measure the water velocity during each test. The flow meter data was logged as single counts and converted to RPM for both logging and for local LCD display. During processing this count was used in conjunction with sample timing to calculate the water velocity.
2. Weighbridge – This was positioned on the exit of the conveyor to measure instantaneously the moment the nodules exited the conveyor. Data from a couple load cells connected to each end side of the weighbridge was logged and then processed to calculate the time it took for the nodule to travel the length of the conveyor.

Critical sensor calibration

1. Flow meter – The flow meter was calibrated using a hand-held laser RPM counter and a battery drill. The reading on the handheld counter was compared with the reading on the LCD display. Incidentally the LCD display is printed from the serial data being logged.



Figure 11: – Flow meter calibration

2. Weighbridge – The weighbridge was used primarily to determine when the nodules were exiting the conveyor. Initially we tried using cameras to observe the nodules but due to the turbulence in the water nodules were not observable in the video.

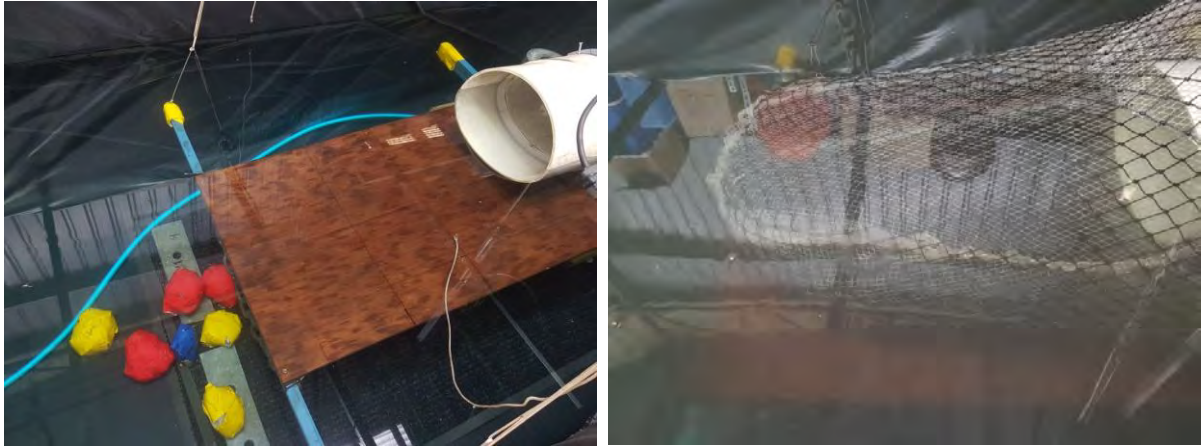


Figure 12: – Weighbridge left, net in place right

A net was used to catch the nodules (Ref Figure 4) as they exited the conveyor to stop them getting lost in the tank and allowed us to easily recover them for reuse. The net would also trap the nodules on the weighbridge for detection.

Load cells attached to the weighbridge for logging were used to synchronise the feeding of nodules during the test by tugging one of them as the countdown was called out. As can be seen in Figure 13, the synchronised countdown started at 10, with feeding starting at 1, then 2, then 3. Nodules can be seen arriving at the weighbridge approximately 7.5 seconds from releasing the first nodules.

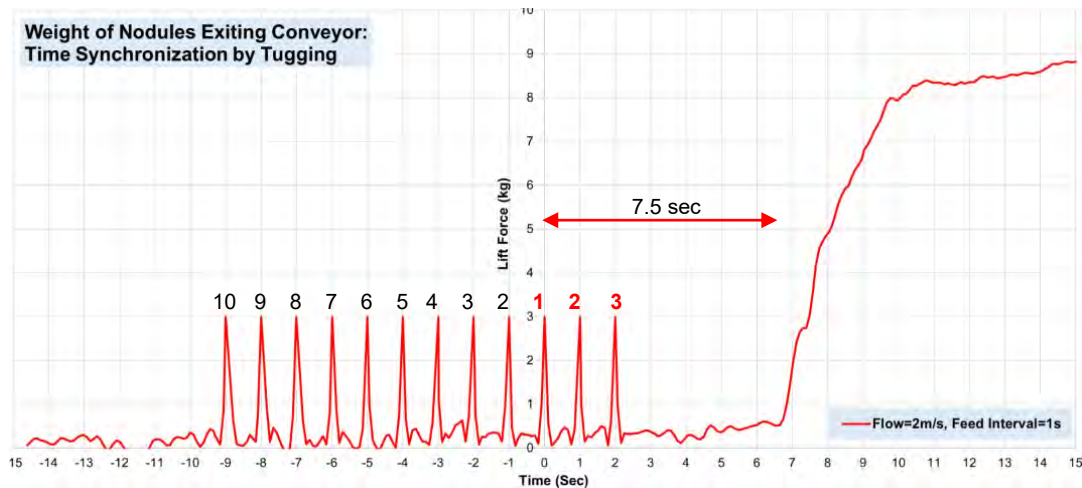


Figure 13: – Time synchronisation by “tugging”

The weighbridge was physically calibrated using a known weight at various places (refer Figure 14). These results were fed into the numerical model.

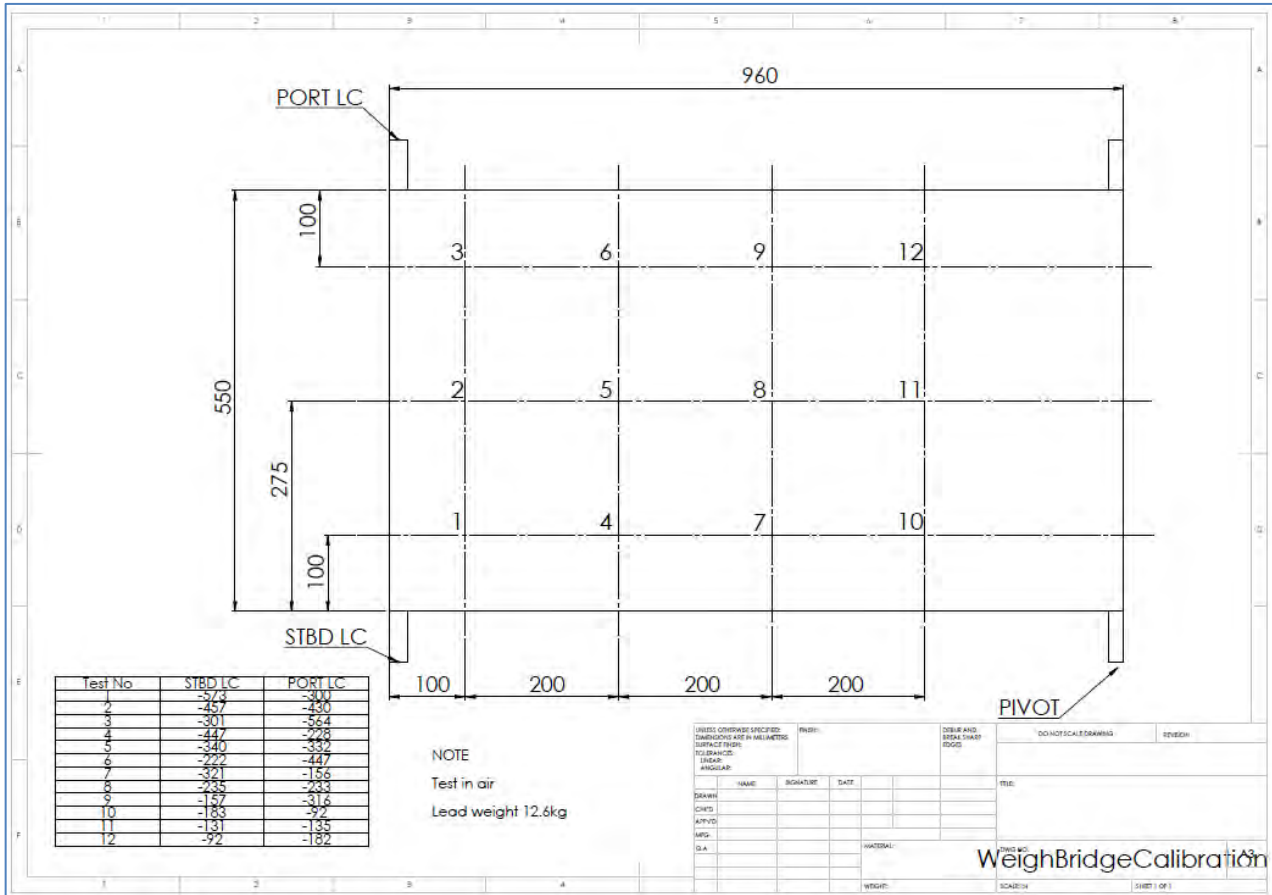


Figure 14: – Weighbridge calibration layout

3. Propeller speed

The propeller speed was measured using a handheld Laser RPM counter directly on the magneto / starter flywheel. This measurement was not logged in real time; it was only used for verification. The propeller speed was then derived by dividing motor speed with the gear box ratio, in our case 2.15.

Figure 16 shows the relation between RPM of the Propeller and the Flow Meter. For a practical Flow Velocity of 3 m/s, the Flow Meter RPM is about 655 (See section 4.2), corresponding to a Propeller RPM of 1244 and a Motor RPM of 3111. For a Flow Velocity of 4 m/s, the Propeller and Motor RPMs are 1658 and 4145. These RPM values are all within the expected range, giving validation to the current selection of Test equipment and providing guidance to future Impeller and Motor selection for the Operation.

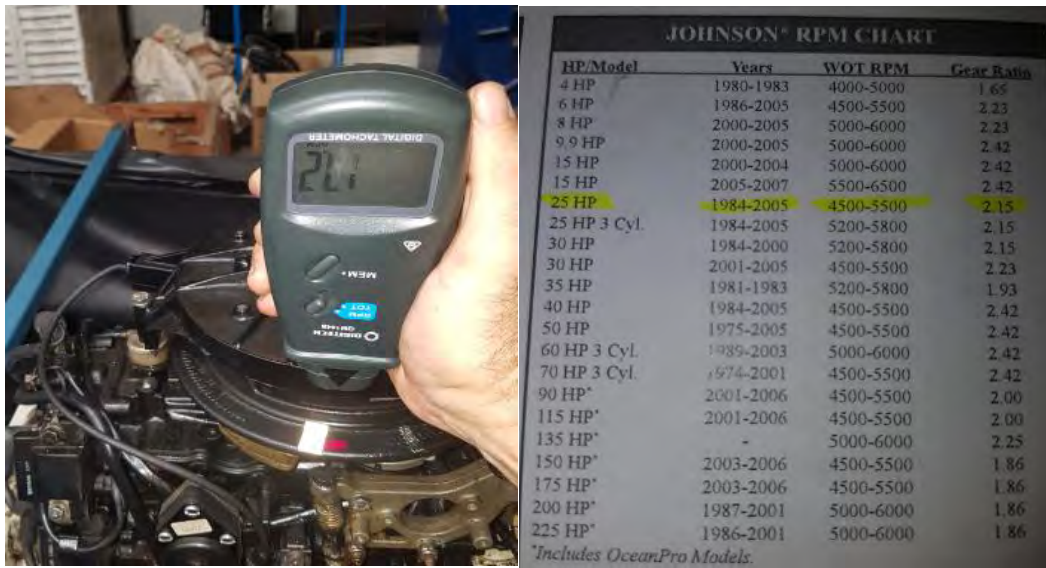


Figure 15: – Propeller speed measurement and motor spec

The table below was used to calculate the propeller speed in the range we were using during the testing.

LCD Display Reading	Calculated Propeller RPM	Motor RPM Counter Reading			Spec Gear Ratio
		Upper	Last	Lower	
228	453	1006	974	923	2.15
336	652	1456	1402	1352	2.15
408	774	1708	1664	1633	2.15
492	944	2063	2029	2003	2.15

Table 1: – Propeller speed table V actual water flow meter reading

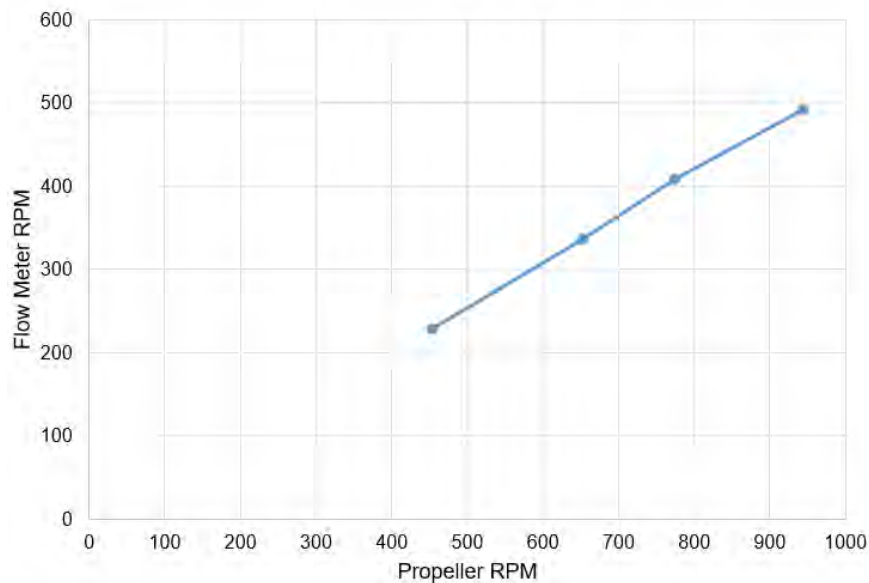


Figure 16: – Propeller RPM vs. Flow Meter RPM

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4 Test Results and Discussion

4.1 Logged Raw Data

Data for each test was logged to laptop using (Putty) serial plotter and then copied to excel for processing. Each file was stamped with actual date and time in the following format.

===== PuTTY log 2020.02.24 11:06:38 =====

We used two configurations during the testing, one was data logged NO weighbridge and the second with was logged data with weighbridge.

Logged data format with NO weighbridge.

Each column of the log represented the following data

1. Time in m/s from start of logging
2. Pulses / revolution / 2
3. Pulses / revolution
4. Calculated raw RPM

Logged data format with weighbridge.

1. Time (M/s) from start of logging
2. Event indicator count
3. Cumulative count / 2
4. Cumulative count
5. Calculated raw RPM
6. LC1 – Actual
7. LC1 – Low
8. LC1 – High
9. LC2 – Actual
10. LC2 – Low
11. LC2 - High

Refer Appendix 1 – Compilation of all the data logged during the testing

4.2 Calibration for Flow Velocity

Flow Velocity is one of the key parameters of the test, which, as described in (section 3.3.5) above, is measured by the Flow Meter and its Revolution Counts are logged in milliseconds. The RPM of the Flow Meter can be calculated from the Revolution Counts and the corresponding time stamps.

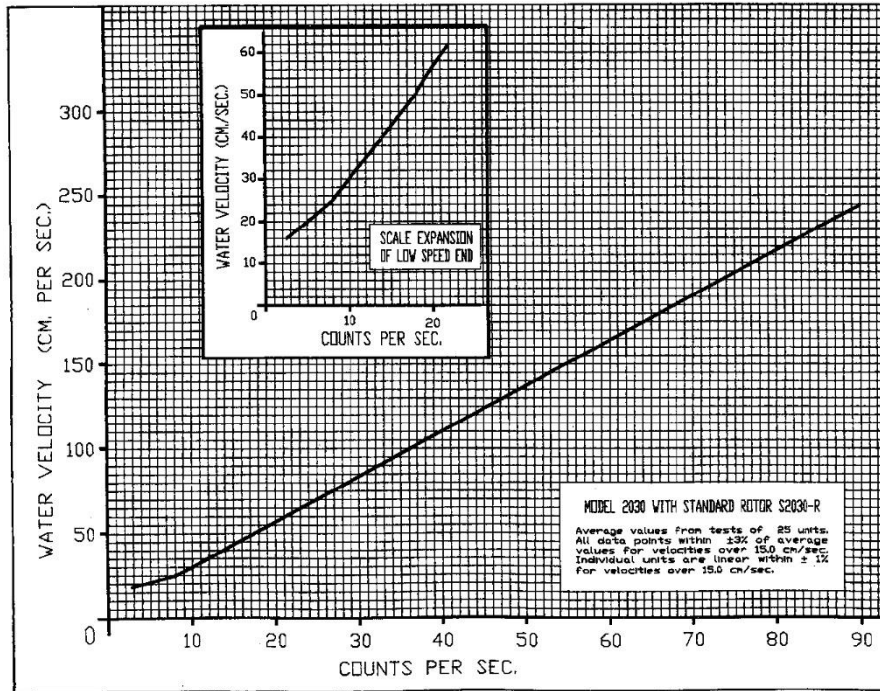


Figure 17: Flow Meter Revolution Count vs. Flow Velocity

The Flow Velocity is calculated from the RPM using a conversion factor (See Figure 17) provided by the Flow Meter manufacturer, which is 218.18 RPM for 1.0 m/s for this model of Flow Meter. This was also checked during calibration (Refer Figure 11: – *Flow meter calibration*)

Figure 18 shows the process and logged and RPM on top and the processed Flow Velocity at the bottom.

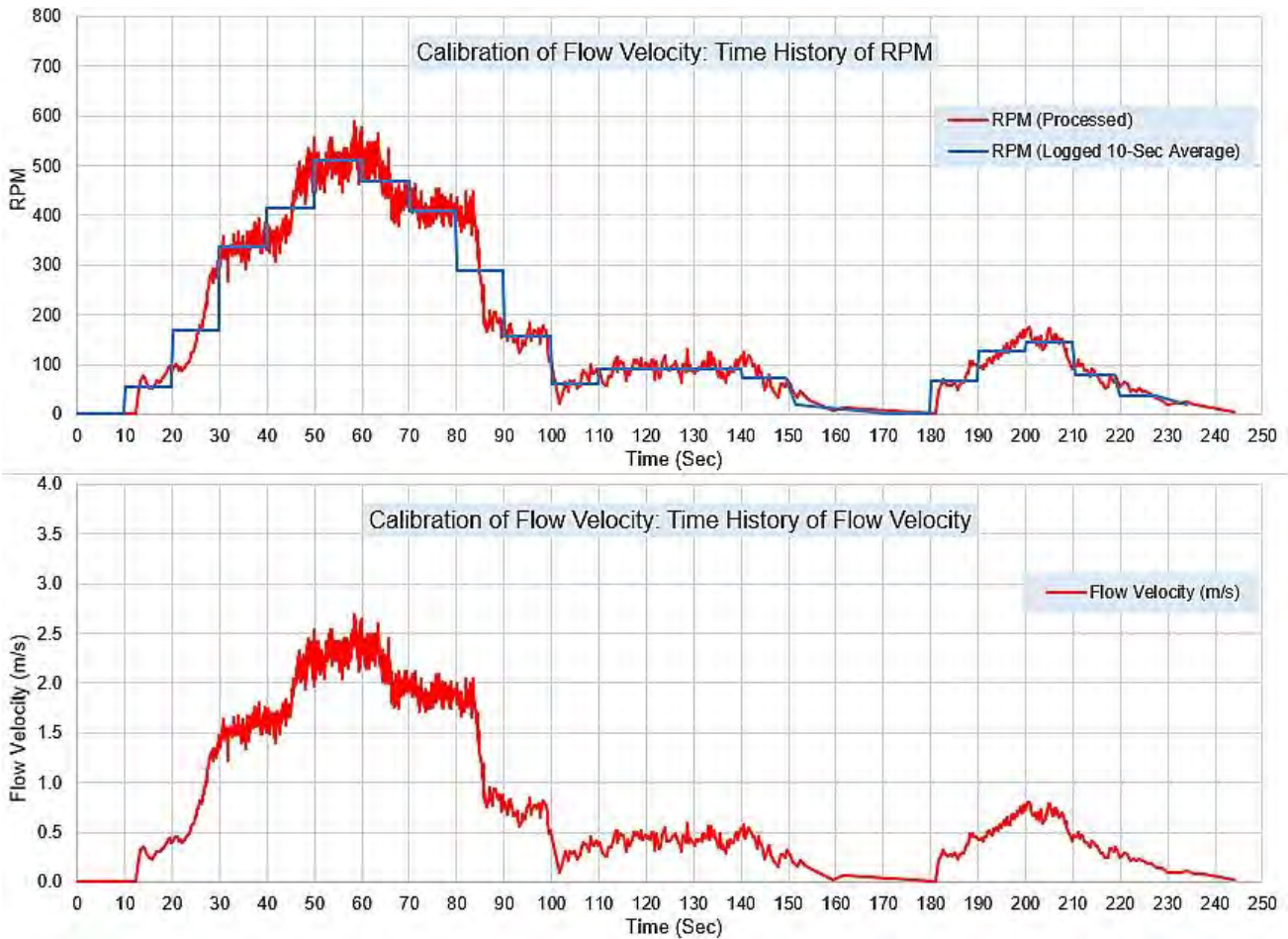


Figure 18: Calibration of Flow Meter: RPM Measured by Flow Meter (Top) and Calculated Flow Velocity (Bottom)

4.3 Calibration of the Weighbridge

The effectiveness of a Conveyor is measured by how soon and how complete it can transport the nodules. In this test, we would evaluate the performance of the Conveyor by measuring how fast and how much of the nodules fed through the feeders will exit the outlet of the Conveyor. While visual was very difficult due to water turbulence, real-time measurement of the weight of particles exiting the Conveyor turned out to be quite an appropriate method.

The following procedure is used to calibrate the Weighbridge, described in (Section 3.3.5) above.

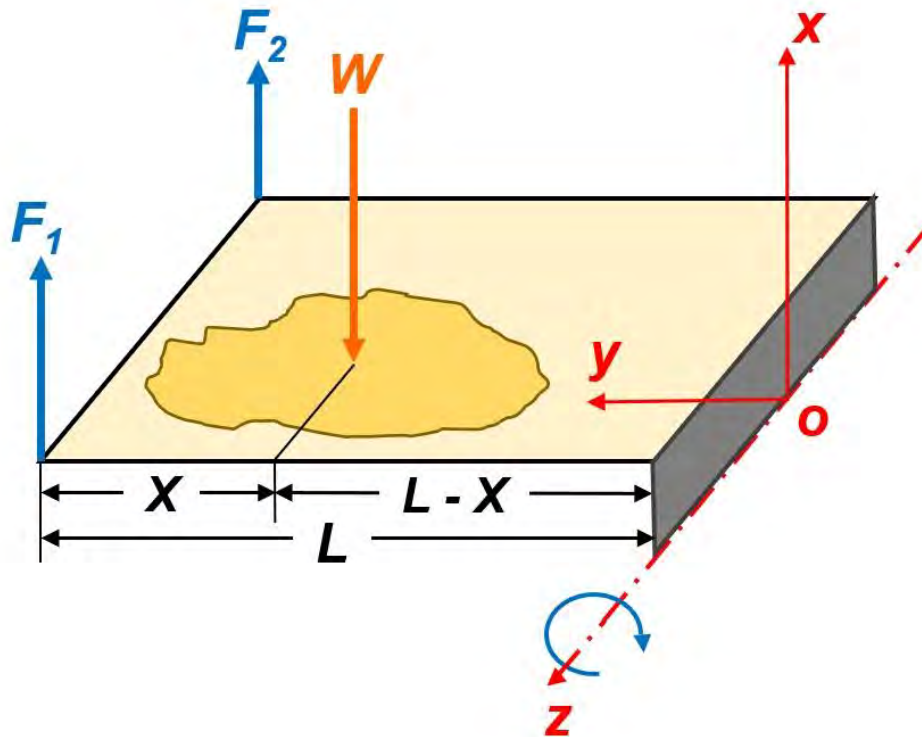


Figure 19: – Moments Equilibrium of the Weighbridge

The Moment equilibrium of the Weighbridge about the z-axis requires (See Figure 20 above):

$$(F_1 + F_2) * L = W * (L - X)$$

Where W is the Total Weight of the Particle resting on the Weighbridge, F_1 and F_2 the Loads holding the Bridge, L the Length of the Bridge, and X indicating the Centre of Gravity of the Particles. The location of the Centre of Gravity of the Particles can be calculated by:

$$X = (1 - \frac{F_1 + F_2}{W}) * L$$

The calibration factor α between the total Loads $F_1 + F_2$, and their raw measurements by the load cells $R_1 + R_2$ can be determined using array of test data as shown in Figure 14. A weight was placed at 12 locations on the Weighbridge and the corresponding measurements from the two load cells were recorded. The data is shown in Table 2 below. As the Weight W is known to be 11.5 KG, the value of α can be calculated by:

$$\alpha = \frac{F_1 + F_2}{R_1 + R_2} = \frac{W(1 - \frac{X}{L})}{R_1 + R_2} = \frac{W * (L - X)}{(R_1 + R_2) * L}$$

Based on a mean $\alpha = -0.01151$ KG, the Coefficient of Variation is about 1.46%, which shows a value above is reliable.

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Test No.	Location of Weight (mm)		Weight (Kg)	Load Cell Readings		α	Coefficient of Variation
	X	Y		Starboard	Port		
1	100	100	11.35	-573	-300	-0.01165	1.75247E-08
2	100	275	11.35	-457	-430	-0.01146	2.64688E-09
3	100	450	11.35	-301	-564	-0.01175	5.76468E-08
4	300	100	11.35	-447	-228	-0.01156	2.08909E-09
5	300	275	11.35	-340	-332	-0.01161	9.47011E-09
6	300	450	11.35	-222	-447	-0.01166	2.23160E-08
7	500	100	11.35	-321	-156	-0.01140	1.27518E-08
8	500	275	11.35	-235	-233	-0.01162	1.13075E-08
9	500	450	11.35	-157	-316	-0.01150	2.72406E-10
10	700	100	11.35	-183	-92	-0.01118	1.13197E-07
11	700	275	11.35	-131	-135	-0.01156	1.74354E-09
12	700	450	11.35	-92	-182	-0.01122	8.74105E-08
				Mean α =		-0.01151	-1.458%

Table 2: Calculation of Calibration Factor for Forces on Weighbridge

4.4 Velocity Loss due to Impingement by Nodule Particles

As discussed in *Ref. 1*, due to the presence of nodule particles being fed through the Feeders in the Conveyor Tube, the “*Impingement effect*” of the particles causes the increases of flow density and pressure, and loss of flow velocity along the Conveyor Tube. Along the tube length, kinematic energy of the flow is being transferred to the nodule particles. The process “conveys” the nodules through the tube, while reducing the flow velocity.

The process is simulated numerically in *Ref. 1* and this test will confirm the process and its parameters.

Figure 20 shows Flow Velocity Loss due to Impingement of Nodule Particles at the end of Conveyor Tube. The Tube exit is 7 meters from the Impeller. 12 KG of nodule particles are fed into 3 feeders, namely Feeders No. 1, 2 and 3, located 1, 2 and 3 meters from the Impeller respectively. Feeder No. 1 is fed first, followed by Feeders No. 2 and 3, at 3 timed intervals of 1/3, 1/2 and 1 Sec, to simulate various impingement scenarios. The worst impingement scenario occurs when the particles fed into the feeders are superimposed on to each other causing the maximum impingement effect. Impingement of flow by the introduction of nodules was checked at 2 m/s and 3m/s with the following effect

- 2m/sec – velocity drop of 0.15m/s in 1 second is observed
- 3m/sec – velocity drop of 0.33m/s in 1 second is observed

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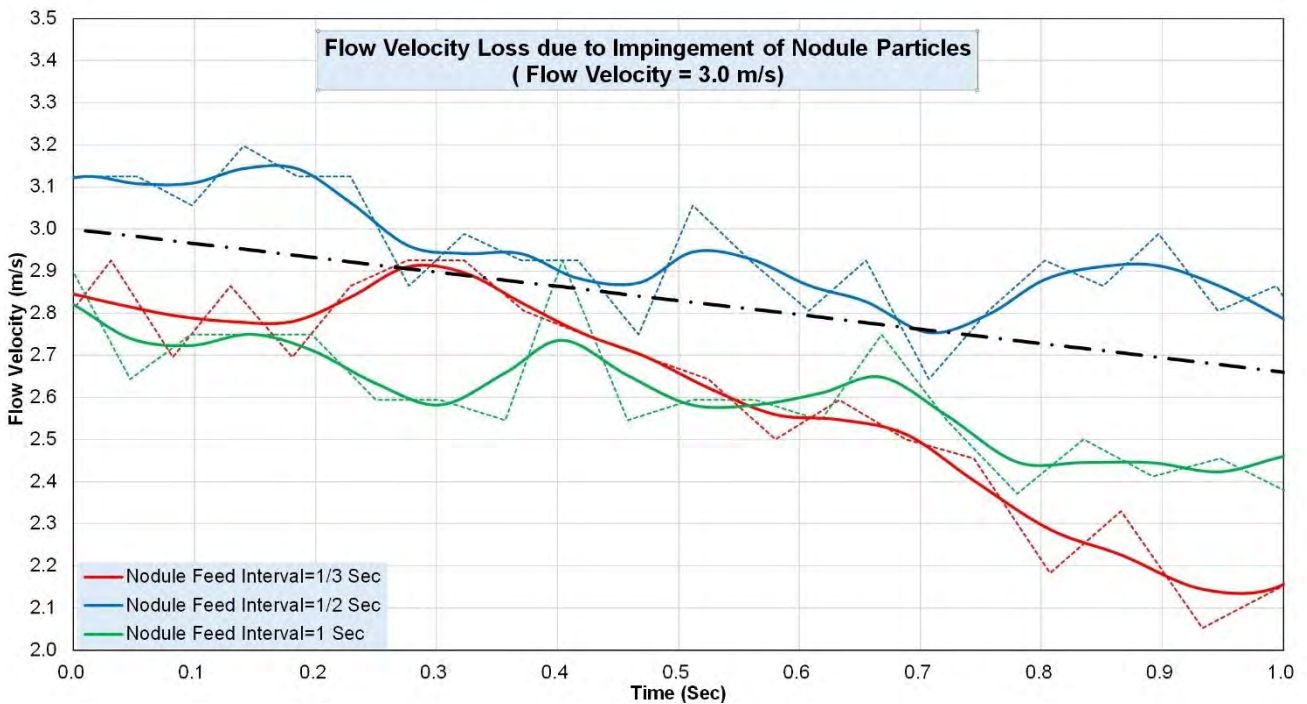
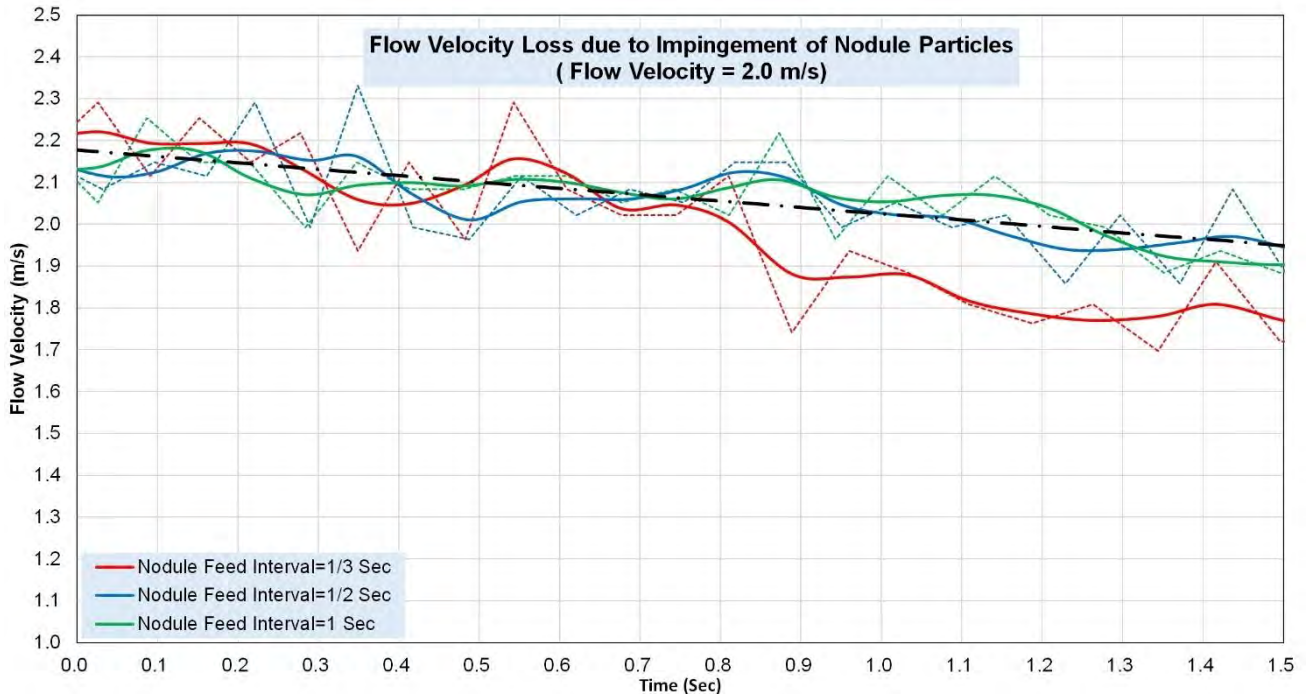


Figure 20: Flow Velocity Loss due to Impingement of Nodule Particles

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Only temporal variation of flow velocity is measured here due to the limited availability of flow meters, and the spatial variation shall be measured in the future pilot test work.

4.5 Critical Flow Velocity and Conveyor Performance

The key objective of the Test is to determine the minimum “Critical Flow Velocity”, which is capable of “conveying” all nodule particles through the Conveyor Tube, given the required particle feeding rate. Based on the initial results of numerical simulation in *Ref. 1*, Flow Velocities of 2 and 3 m/s were selected for majority of the Testing.

A Tube of 6 m in length was used for most of the Tests (See layout in Figure 4). 12 kg of nodules were fed into feeders 1, 2 and 3, at various timed intervals for these tests. The Weighbridge, installed at the Exit of the Tube, measures and logs in real time the weight of particles exiting the Tube and landing on the weighbridge. The logged data indicates the start and ending time of nodule particles exiting the Tube, as well as the Weight distribution of particles. The exited particles are collected by a net installed at the Tube exit. The captured particles were weighed manually and compared with the weight of particles fed into the Conveyor.

Typical test data are shown in Figure 21 for Flow Velocities of 2 and 3 m/s and for particles feed intervals of 1/3, 1/2, 1 and 1-1/2 seconds. As expected, for both Flow Velocities, the starting times for the particles to exit the Tube are similar. However, the different feeding intervals do create discrepancies in finishing time. It is observed that for higher Flow Velocity of 3 m/s, the particles arrive earlier and finishes sooner. The higher rate of transportation of nodules is demonstrated by a steeper slope in the curve.

According to the analysis in *Ref. 1*, smaller particles are travelling faster and exiting sooner than the larger ones, driven by the same Flow Velocity. For Flow Velocities of 2 and 3 m/s, the total time window for delivering the same amount of particles (between the time when the *smallest* nodules start exiting and the time when the *largest* finish exiting) is about 5 and 2 Seconds. This significantly smaller time windows of 2 Sec driven by higher Flow Velocity of 3 m/s indicates nodules of various sizes are being “conveyed” in a *timelier* fashion, in which the difference in times for the smallest particle (fastest) and the largest particle (slowest) to pass through the Tube is smaller, making a “backlog” and a subsequent “blockage” less likely.

It is worthwhile to point out that in *all* the Test cases above, *all* nodule particles are conveyed out of the Tube. This is confirmed by weighting the particles collected at the Tube exit. Except for a small expected attrition of nodule particles, the weight loss for each Test is minimal.

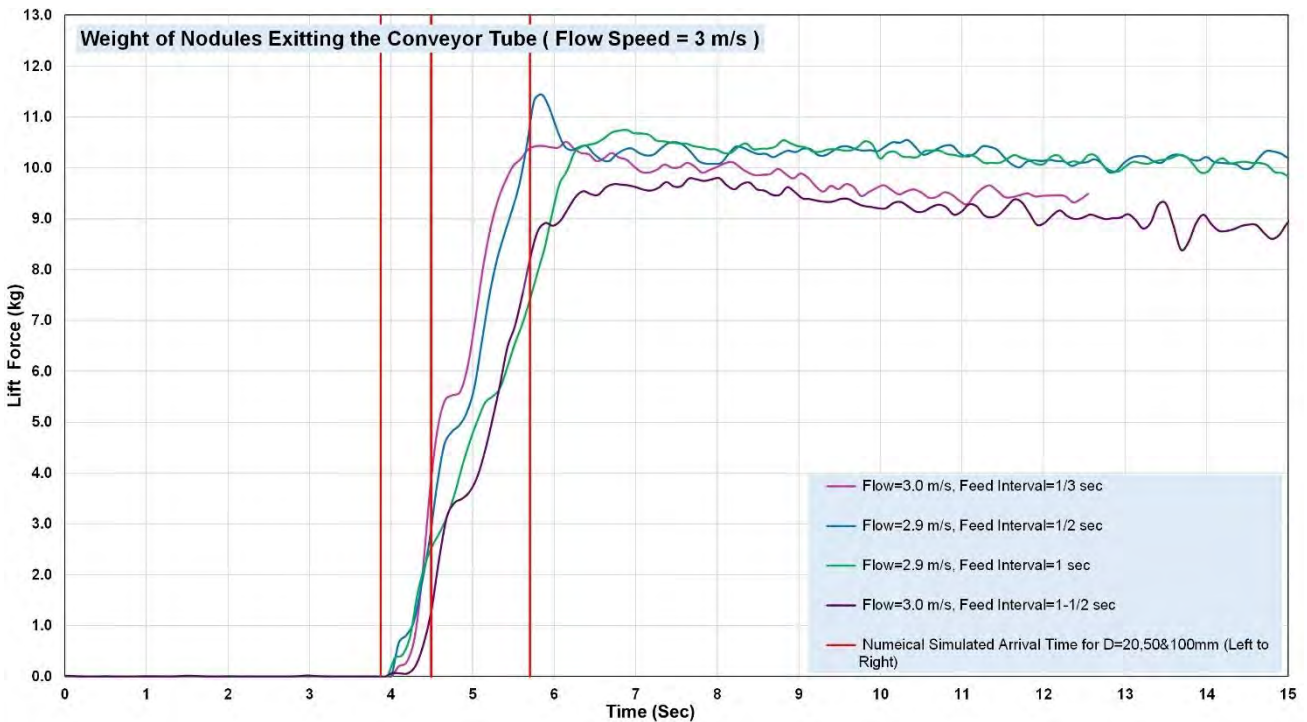
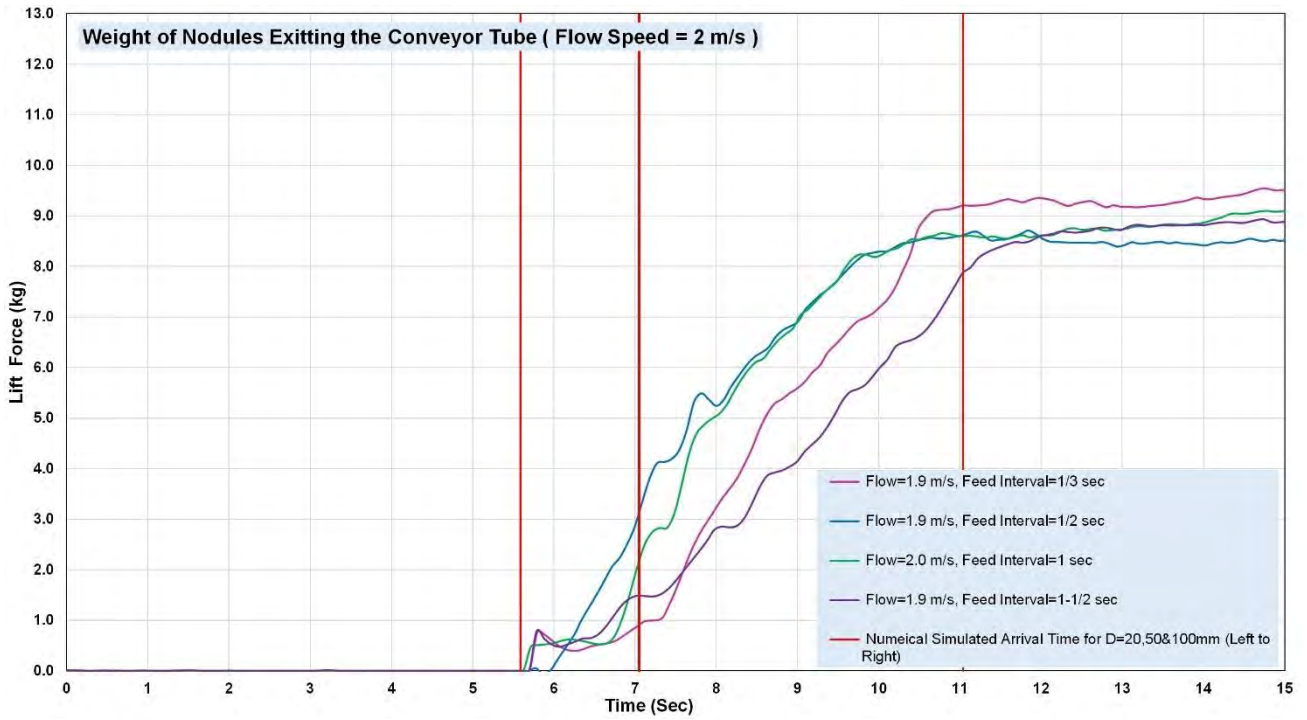


Figure 21: Time History of Weight of Nodule Particles Exiting the 6 m Conveyor: For Flow Velocities = 2 and 3 m/s (Top and Bottom)

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It can be observed from Figure 21, for Flow Velocities of 2 and 3 m/s, the Life Forces reach steady states at about 8.5 and 9.5 kg respectively. Using the Equation in Section 3.3, it is easy to calculate the X-coordinate of the Centre of Gravity of the nodules after they have rested on the Bridge. For example, in the case of Flow Velocity equals 2 m/s, $F_1 + F_2 = 8.5 \text{ KG}$,

$$X = \left(1 - \frac{F_1 + F_2}{W}\right) * L = \left(1 - \frac{8.5}{18}\right) * 960 = 506.67 \text{ (mm)}$$

Where 18 kg is the submerged weight of nodules particles which weights 36 KG in the air when fed through the Feeders.

For Flow Velocity equals 3 m/s, $F_1 + F_2 = 9.5 \text{ KG}$, then

$$X = \left(1 - \frac{F_1 + F_2}{W}\right) * L = \left(1 - \frac{9.5}{18}\right) * 960 = 453.33 \text{ (mm)}$$

For higher Flow Velocity of 3 m/s, a smaller X value indicates the particles are pushed further away from the Tube exit.

Also shown in Figure 21 are results from numerical simulations of exiting times for particles with diameters of 20, 50 and 100 mm, which cover with range of *significant* nodule sizes. Assuming the exiting of the smaller particles (20 mm in diameter) indicates the *start* of the particle congregation exiting the Test Tube, and the exiting of the larger ones (100 mm in diameter) indicating the *finish*, the numerical results agree well with Test data. Details of the numerical simulation are presented in *Ref. 1*.

Figure 22: Time History of Weight of Nodule Particles Exiting the 6 m Conveyor with an Inclination of 3° : For Flow Velocities = 2 and 3 m/s (Top and Bottom) shows similar results as in Figure 21, except the Conveyor Tube was inclined by 3 degrees, with a higher Exit end. As shown in the Appendix of *Ref. 1*, a small inclination of Tube is equivalent to a small increase of Friction Coefficient between the nodule and the Tube surface. Except for a small slow-down of particle transportation, the results are consistent with the previous Test with inclination. The results from numerical simulations for particle diameters of 20, 50 and 100 mm are also shown, and they agree well with test data.



Figure 22: Time History of Weight of Nodule Particles Exiting the 6 m Conveyor with an Inclination of 3° : For Flow Velocities = 2 and 3 m/s (Top and Bottom)

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The 3rd set of tests were carried out using a Tube Length of 9 m (See layout in Figure 5), but these were limited due to the length of the Tank. The longer conveyor placed the Tube outlet too close to the end wall of the Tank, causing significant “back flow”. Figure 23 shows these Test results. In this case, 9 kg of nodules were fed from 6 consecutive Feeders (from No.1 to No.6); with 3 feed intervals of 1, 1.5 and 2 s. Despite the larger amount of nodules fed into the Conveyor (9x6=54 kg) and longer Tube, the Conveyor still delivered *all* nodules particles through the entire length of Tube, as observed. However, the net couldn’t hold all the nodules exiting the Tube and an amount of nodules escaped to bottom of the Tank in the first 2 cases. The dropped particles in both cases were collected manually and weighed and it was found *all* nodules particles were delivered except for a small amount of attrition (expected).

The results from numerical simulations of exiting times for particle diameters of 20, 50 and 100 mm are also shown. The numerically simulated time instance when the particles start exiting the Tube (about 5.4 s after nodules is dropped into Feeder No.1) agrees well with the Test data, with the 2 s feed case bounding the results nicely.

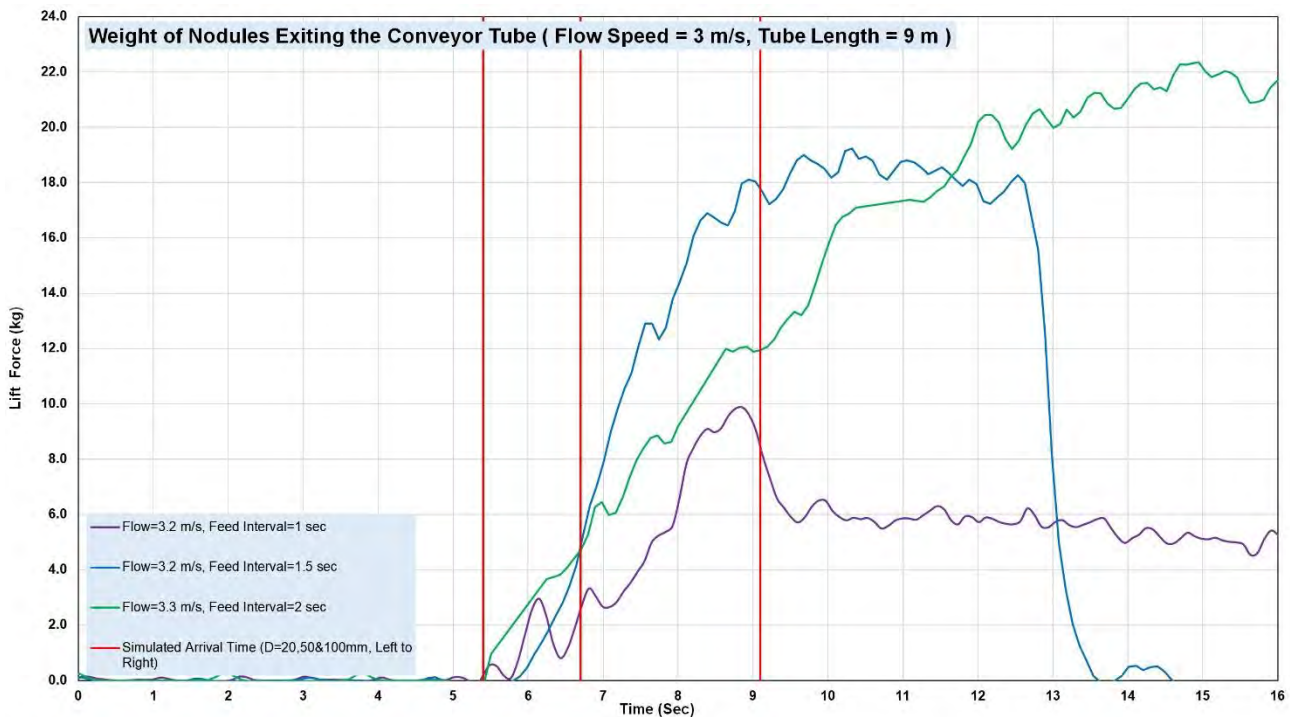


Figure 23: Time History of Weight of Nodule Particles Exiting the Conveyor: For Flow Velocities = 3 m/s and Tube Length = 9 m

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5 Conclusion and Future Work

The test program was carried out for a full-scale Nodule Lateral Conveyor, which is a key component of the Nodule Concentrator Array (CA). The purpose of the test program was to observe the effectiveness of the Concept of Lateral Conveyor and to select key parameters as the basis for future Design. This test program is carried out in junction with work on a numerical simulation. While the test program validates the numerical simulation, the latter can also examine cases which are difficult to implement in a Lab test program environment. Based on the results and analyses presented above, the following conclusions can be made:

5. The test program has shown the Concept of Lateral Conveyor is effective in conveying nodules at the desired production rates. In all test program cases, with a Flow Velocity over 2 m/s, *all* nodule particles can be transported through the full-scale Conveyor Tube with a length up to 9 m (300 mm diameter), given a nodule feeding rate of 6 kg/s or higher.
6. The recommended Flow Velocity for is 4 m/s. Extensive tests were carried out using Flow Velocity of 3 m/s for a 6-m Tube and proved to be sufficient. For a design Tube length of 9 meters, the numerical simulation, which has been validated by the Test, shows a Flow Velocity of 4 m/s will ensure a low nodule volume concentration throughout the Tube (<15%) to avoid a potential “backlog” of the Conveyor Tube.
7. With a recommended Flow Velocity of 4 m/s, *Shaft Power* P_1 required to generate the flow rate is estimated to be 11.88 kW and the required *Pump Power* P_2 is 14.25 kW (See Section 2.3 of *Ref. 1*). A high-flow and low-head Impeller is recommended for this Operation, applicable to those commonly used in Axial Flow Pumps.
8. This Test has played an important role in validating the numerical work detailed in *Ref. 1*. A Drag Coefficient of 0.4 is used throughout the numerical simulation as commonly recommended in the literature.

A full-scale Lateral Conveyor will be incorporated into the future Pilot Testing in the CCZ with actual nodules to test the “steady-state” conveying, which is impractical to achieve in a test environment.

Nautilus Minerals – Tonga Offshore Mining Limited

Nautilus Nodule Concentrator:

Lateral Conveyor - Numerical Simulation

Rev no.	Date	Reason for Issue	Prepared	Checked	Approved
A	18/03/2020	Draft for review	Gordon Yu, Anthony Manocchio	Glen Jones, John Parianos	John Parianos
0	18/03/2020	Final	Gordon Yu, Anthony Manocchio	Glen Jones, John Parianos	John Parianos

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Summary

The Lateral Conveyor is a key element of the Concentrator Array (CA), which carries the nodules picked up by each Concentrator module from the seafloor to the centre of the Concentrator Array to form a windrow. A new conveying concept was devised, which uses water flow in a conveyor tube, generated by an impeller at one end. The tube is fed from overhead feeders spaced equally along the tube.

A numerical model was developed to simulate the operation of such a Lateral Conveyor. The movements of nodule particles in the conveyor tube was modelled using a “*section-wise*” approximation, which assumes flow parameters remain the same in the *section* between two feeders and a flow steady state has been reached (i.e. the flow parameters are no longer varying with time). The numerical procedure consists of:

1. Firstly, the flow velocity loss along the tube is estimated by applying the principal of “conservation of energy” to the transferring of kinematic energy from the flow to the nodule particles.
2. Secondly, various differential equations governing modes of particle movements in a uniform flow are derived and solved.
3. Finally, the nodule particles movements are simulated, *section by section* along the tube, using the previously solved equations of particle movements (solved in 2 above), with the reduced “*section-wise*” flow velocity (estimated in 1 above) as boundary conditions.

The numerical results were calibrated and compared with the results of a full-scale lab test program (reported separately), which was carried out in conjunction. The calibrated numerical method was then used to analyse the nodule conveying process, which is impractical to test in a lab environment. The results of the analyses are to provide design parameters for the future Project.

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1 Introduction

The Lateral Conveyor is a key element of the Concentrator Array (CA), which carries the nodules picked up by each Concentrator modules from the seafloor to the middle of Concentrator Array to form a windrow.

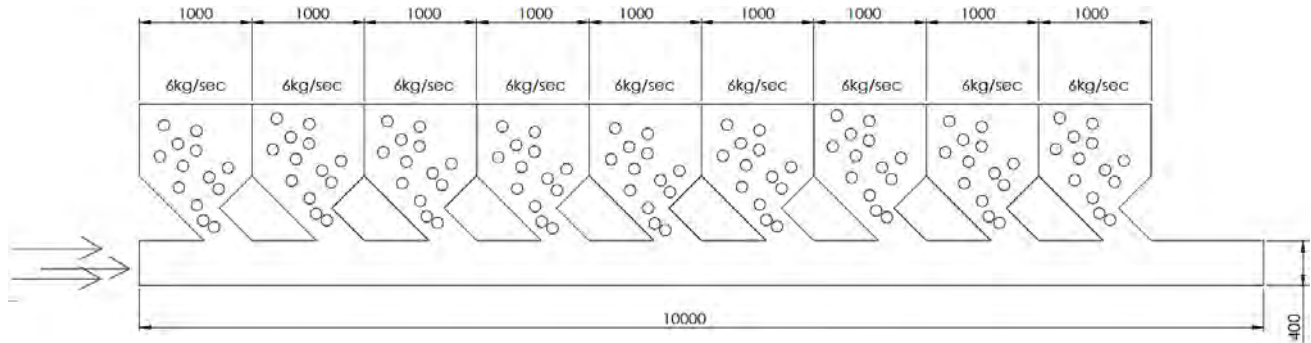


Figure 1: Schematics of a Lateral Conveyor

Figure 1 shows the schematics of a Conveyor Tube. A flow, driven by an impeller or a propeller, enters from the left while the nodules are being fed from the vertical feeders, and the nodules and the flow exit at the right end.

Due to the relatively large size of nodules (with diameter up to 100 mm), an adequate flow rate is required to carry all nodule through to the exit, and to prevent a blockage in the Tube. This report proposes a practical numerical model for simulating the “two-phase” flow in the Conveyor Tube and certain criteria for defining the conditions under which a blockage would or would not occur. The results of the analyses will provide design parameters for the future projects.

A separate full-scale lab test program has been carried out to calibrate and verify the numerical analyses in this Report. This program is reported separately.

2 Flow in Lateral Conveyor Tube: A Section-Wise Approach

2.1 Numerical Modelling

The flow in the Lateral Conveyor Tube is modelled using a “section-wise” approximation, in which the flow field is divided into a total of 11 sections, with the nodule feeders as the dividing points. It is further assumed the flow parameter remains the same within each section, and a flow steady state has been reached (the flow parameters are no longer varying with time). The numerical simulation starts at the 1st section where a uniform flow with a speed of V_0 entering the tube and ends with the 11th section where the flow is discharged.

The flow simulation involves 4 steps, as described below. It provides a procedure to estimate the variation of flow velocity along the length of the conveyor due to the presence of nodule particles. Once flow velocity is calculated for each tube section. The equations derived in the Appendix can be used to calculate the detailed movements of particles.

At this initial stage of analysis, no numerical convergence of flow parameters is attempted, and a iterative procedure can be implemented in the future to achieve higher accuracy.

(1) Flow density ρ increase along the conveyor tube: due to adding nodules

In a small duration of time Δt , nodule weight $A \Delta t$ is added through a feeder and is dispersed on a volume equal to $V_1 \Delta t S$, with a weight of $\rho_1 V_1 \Delta t S$, where A is the rate of the weight of nodules being fed into the flow, V_1 the flow velocity and ρ_1 the flow density before the nodules are added into this section. The added nodule will displace $A \Delta t / \rho_n$ volume of water, which weights $(A \Delta t / \rho_n) \rho_w$, where ρ_n and ρ_w are densities of nodules and water respectively. The flow density ρ_2 after the nodules are added is:

$$\rho_2 = \frac{A \Delta t - \left(\frac{A}{\rho_n}\right) \rho_w \Delta t + \rho_1 V_1 \Delta t S}{V_1 \Delta t S} = \rho_1 + \frac{A(1 - \frac{\rho_w}{\rho_n})}{V_1 S}. \quad \text{Eq.(1)}$$

The above equation is used to calculate the flow density along the tube, section by section in the flow direction, with the section being the tube between two consecutive nodule feeders.

(2) Volume Concentration C_v increase along the tube: due to adding nodules

In a small duration of time Δt , nodule volume $B \Delta t$ is added through a feeder and is dispersed on a volume equal to $V_1 \Delta t S$, where B is the rate of the volume of nodules being fed into the flow. The added nodule will displace $A \Delta t / \rho_n$ volume of water, which weights $(A \Delta t / \rho_n) \rho_w$, where ρ_n and ρ_w are densities of nodules and water respectively. The nodule volume concentration $C_{v 2}$ after the nodules are added is:

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$$C_{v2} = C_{v1} + \frac{B \Delta t}{V_1 \Delta t S} = C_{v1} + \frac{B}{V_1 S} \quad \text{Eq.(2)}$$

The above equation is used to calculate the flow density along the tube, section by section in the flow direction, with the section being the tube between two consecutive nodule feeders.

It can be shown that Eq.(1) and Eq.(2) agree with each other, related by the equation below:

$$\rho = (1 - C_v)\rho_w + C_v\rho_n, \quad \text{Eq.(3)}$$

where ρ is flow density with the presence of nodules.

(3) Flow Pressure increase along the conveyor tube: due to the impingement by the nodules

When a nodule particle is fed into the conveyor tube, it will first fall to the bottom of the tube due to gravity (See Section (1) of the Appendix) and at the same time driven forward by the flow (See Section (2) of the Appendix). Once it has landed on the bottom of tube, it will be driven forward by flow while sliding under friction with the tube surface. The movement of particles in this stage is dictated by Eq.(A30a) and Eq.(A30b) in Section (3) of the Appendix. The hydrodynamic force driven the particle is

$$D_x = \frac{1}{2} C_d \rho_w S (V_0 - V_x)^2, \quad \text{Eq.(3)}$$

where V_0 and V_x are flow and particle velocities, while C_d , ρ_w and S are drag coefficient, water density and cross-section area of nodule particle.

From Eq.(A31a) in the Appendix, when time t is large, $V_0 - V_x$ will approach a constant β . As it will be shown in the actual calculation later, $V_0 - V_x$ will approach β *quickly* after the particle has landed on the bottom of the tube. The equation

$$V_0 - V_x = \beta, \quad \text{Eq.(4)}$$

is accurate for *most* part of the “sliding” stage of the particle. Eq.(3) then gives:

$$D_x = \frac{1}{2} C_d \rho_w S (V_0 - V_x)^2 = \frac{1}{2} C_d \rho_w S \beta^2 = \frac{1}{2} C_d \rho_w S \left[\frac{4gd\mu}{3C_d} \left(\frac{\rho_n}{\rho_w} - 1 \right) \right] = \frac{2gd\mu}{3} (\rho_n - \rho_w) S. \quad \text{Eq.(5)}$$

The average pressure P_{ave} on cross-section of the conveyor tube is calculated by averaging the area occupied by particles (C_v percentage) and the area occupied by water ($1-C_v$ percentage) :

$$P_{ave} = C_v \frac{D_x}{S} + (1 - C_v) * 0 = C_v \frac{D_x}{S} = C_v \frac{2gd\mu}{3} (\rho_n - \rho_w), \quad \text{Eq.(6)}$$

where C_v is given by Eq.(2).

(4) Flow Velocity loss along the conveyor tube: due to the impingement by the nodules

Assuming P_{ave} and P_0 are flow Pressures at two sections of the tube, one in an area with nodule present, and one at the inlet of the tube. The *Bernoulli Equation* (Conservation of Energy in the flow) gives:

$$P_{ave} + \frac{1}{2} \rho_{ave} V_{ave}^2 = P_0 + \frac{1}{2} \rho_w V_0^2 \quad Eq.(7)$$

It is without losing generality to assume $P_0=0$, as the pressure is measured in relative terms. Using Eq.(7), we have:

$$P_{ave} + \frac{1}{2} \rho_{ave} V_{ave}^2 = 0 + \frac{1}{2} \rho_w V_0^2$$

$$V_{ave} = \sqrt{\frac{\rho_w V_0^2 - 2P_{ave}}{\rho_{ave}}}, \quad Eq.(8)$$

where ρ_{ave} and P_{ave} are given by Eq.(1) and Eq.(6) respectively.

2.2 Results and Discussion

Numerical simulations are carried out for various input parameters. The results below are based on input parameters in *Table 1* below. The nodule is assumed to be in a spherical shape with a diameter of 50 mm.

Input Parameters	Value	Unit
Tube Internal Diameter d	300	mm
Nodule Density ρ_n	2	Ton/m^3
Rate of Weight of Nodule being Added A	6	Kg/sec
Flow Velocity at Tube Entrance	3	m/sec

Table 1: Input Parameter for Simulation of Flow in Conveyor Tube

Figure 2 below shows the increase of flow density and pressure, and loss of flow velocity along the Conveyor Tube, due to the presence of nodule particles being fed through the Feeders. Along the tube length, kinematic energy of the flow is being transferred to the nodule particles. This process “conveys” the nodules through the tube, while reducing the flow velocity.

After the overall flow parameters are calculated, the velocity components and trajectory of a nodule particle after fed into the flow can be calculated using equations developed in the Appendix.

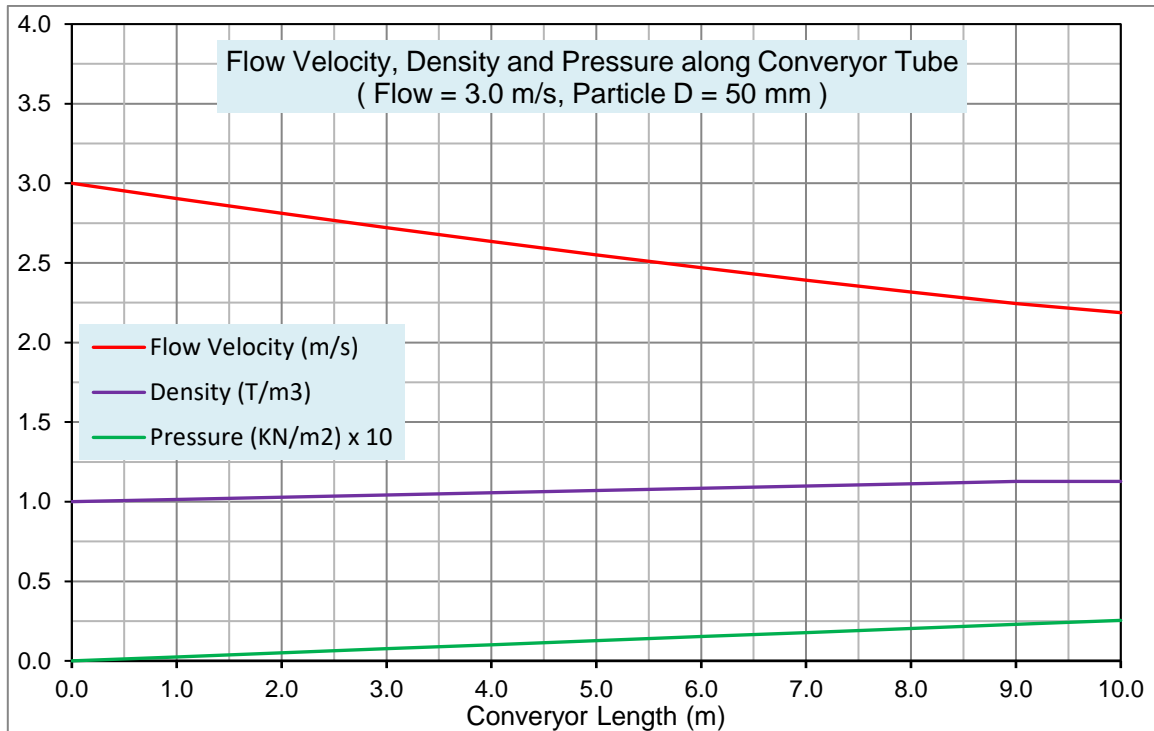


Figure 2: Variations of Flow Velocity, Density and Pressure along the Length of the Conveyor Tube Due to Impingement of Nodule Particles

When a nodule particle is dropped into the flow in the Conveyor, it will undertake two stages of movement, before exiting the tube, namely:

- (1) The “falling” stage: The particle is *falling* to the bottom of the tube due to gravity and at the same time being driven forward by the flow. At this stage, the movement of the particle can be determined by Eq.(A7) in Section (1) of the Appendix in the lateral X-Direction, and by Eq.(A19a) or Eq.(A19b) in Section (2) in the vertical Y-Direction.
- (2) The “sliding” stage: Once the particle has landed on the bottom of the tube, it remains driven forward by the flow while *sliding* under friction on the tube surface. The movement of the particle at this stage is dictated by Eq.(A30a) and Eq.(A30b) in Section (3) of the Appendix. The final particle lateral velocity as it lands on the tube bottom (as calculated at the “falling” stage) is used as initial velocity for the “sliding” stage.

Results are shown in Figure 3, Figure 5 and Figure 6. The Nodule Diameter is set to be 50 mm and Drag Coefficient is 0.4.

Figure 3 below shows the flow velocity and three particle velocities as the particles travel in the Conveyor Tube. The particles are dropped at three different locations on the conveyor (i.e. at 1 m, 5m and 10m). For the particle velocities, the dash-line indicates the “falling” stage while the solid-line for the “sliding” stage.

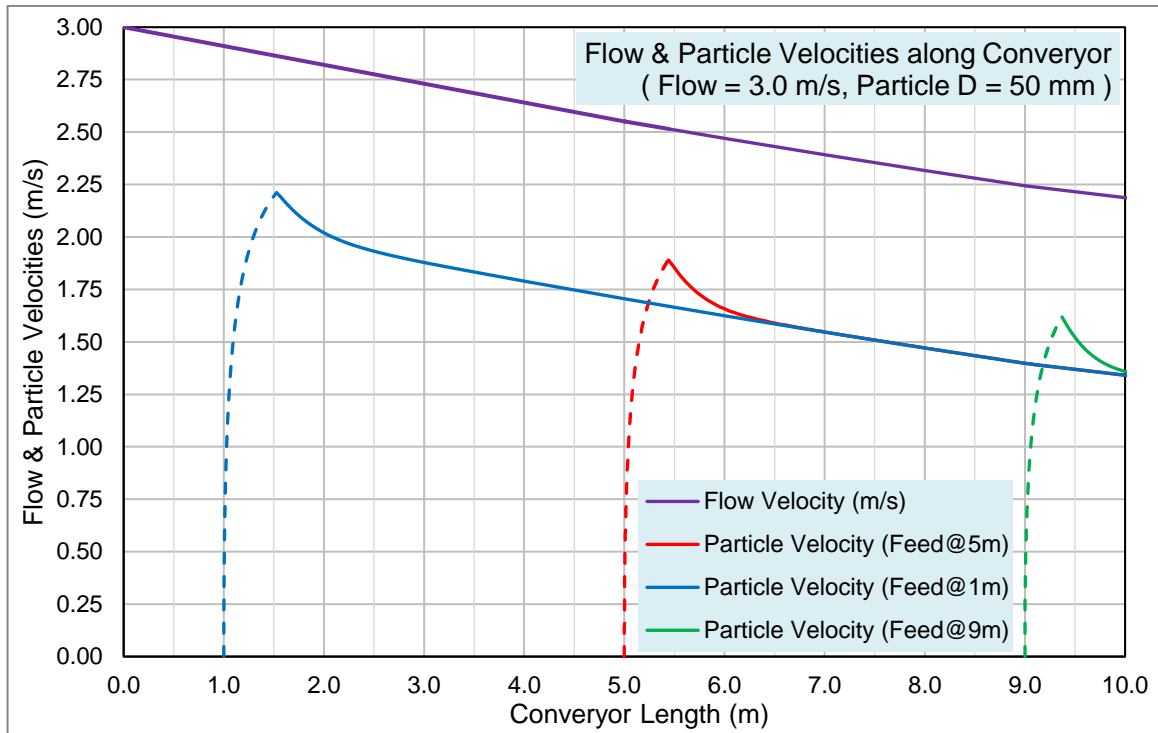


Figure 3: Flow & Nodule Particle Velocities along Conveyor Tube (Different Particle Entry Positions)

It is easy to observe from Figure 3 above, at the “sliding” stage, the particles will quickly reach a “steady” state, where the particle velocity becomes parallel to the flow velocity. This is clearly manifested in Eq.(A31) in Section (3) of the Appendix, and gives justification for the approximation made above in Eq.(4) in Paragraph (3) of Section 2.1. When particles are scarce in the flow, the flow velocity loss as discussed above (e.g. in Eq.(8)) is minimal. In this case, the particle velocity when it travels in the conveyor can be estimated by:

$$V_x = V_0 - \beta_x = V_0 - \sqrt{\frac{4gd\mu}{3C_d}(\rho_n - 1)} \tag{Eq.(9)}$$

Eq.(9) was used to calculate exit time for a manganese nodule and a SMS nodule travelling through the Conveyor. The numerical prediction matches well with the lab test (See Figure 4 below).

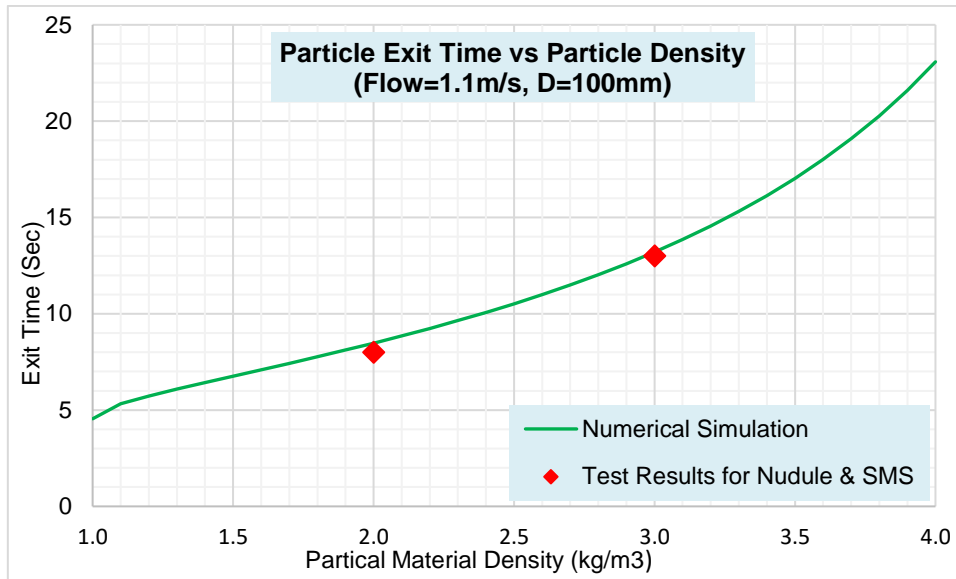


Figure 4: Time When Particles (Nodule & SMS) Exiting the Tube vs. Particle Material Density

Figure 5 below shows the time history of particle velocities as it travels in the Conveyor tube. For the same particle dispatched at different locations along the Conveyor, the time it takes for to fall to the bottom is the same, but the lateral speed it reaches at the end of the “falling” stage is different, due to the flow velocity variation along the Conveyor tube. Particle dispatched nearer the entrance of the Conveyor with higher flow velocity is to land further away in the “falling” stage, achieving higher lateral velocity going into the “sliding” stage, and moving continually at higher velocity.

Figure 6 below shows the time history of the position of particles dispatched at different locations along the Conveyor. It can be observed that it takes about 2.2 sec for a particle started in Feeder No.1 (1 m) to travel 4 m to reach laterally to Feeder No.5 (5 m). The same distance will take about 2.8 sec for a particle started in Feeder No.5. It can also be observed that particles started in Feeder No.1, No.5 and No.9 will take about 5.5 sec, 3.4 sec and 0.76 sec to exits the tube.

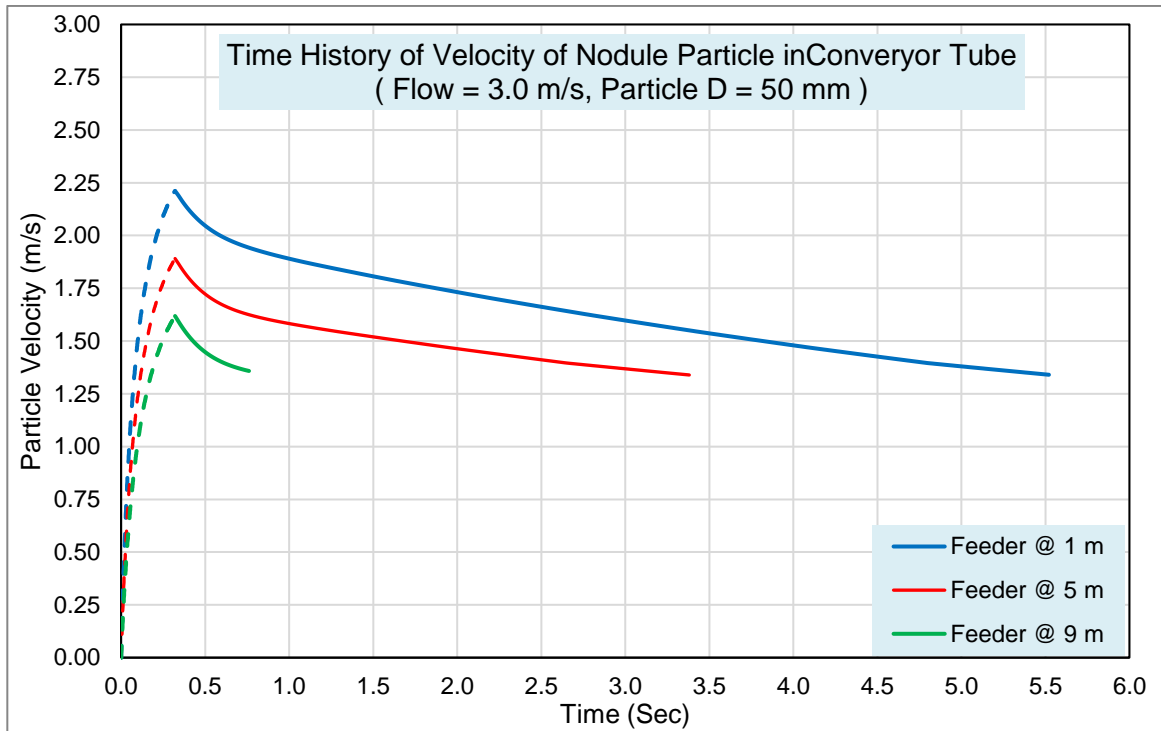


Figure 5: Time History of Nodule Velocities in Conveyer (Different Particle Entry Positions)

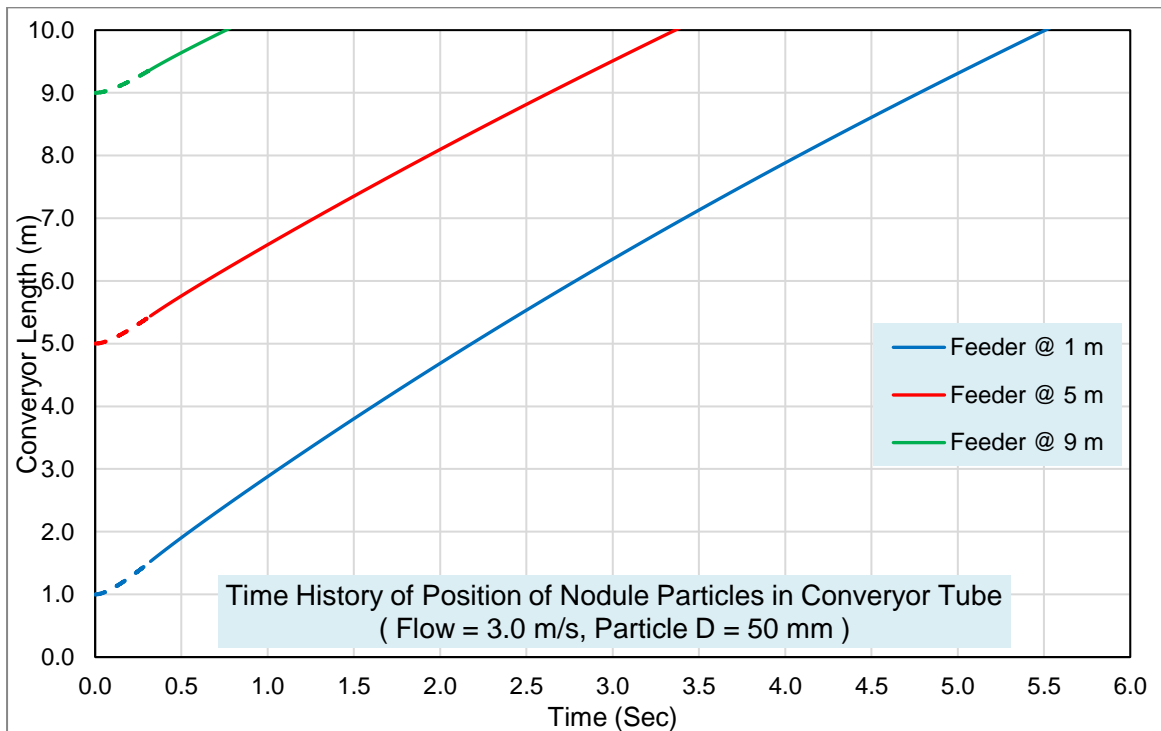


Figure 6: Time History of Position of Particles in Conveyer (Different Particle Entry Positions)

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Figure 7 below shows trajectories of particles dispatched at different locations along the conveyor. As observed in Figure 4, particle dispatched nearer the entrance of the conveyor is to land further away in the “falling” stage, due to the less flow velocity loss occurring along the Conveyor length.

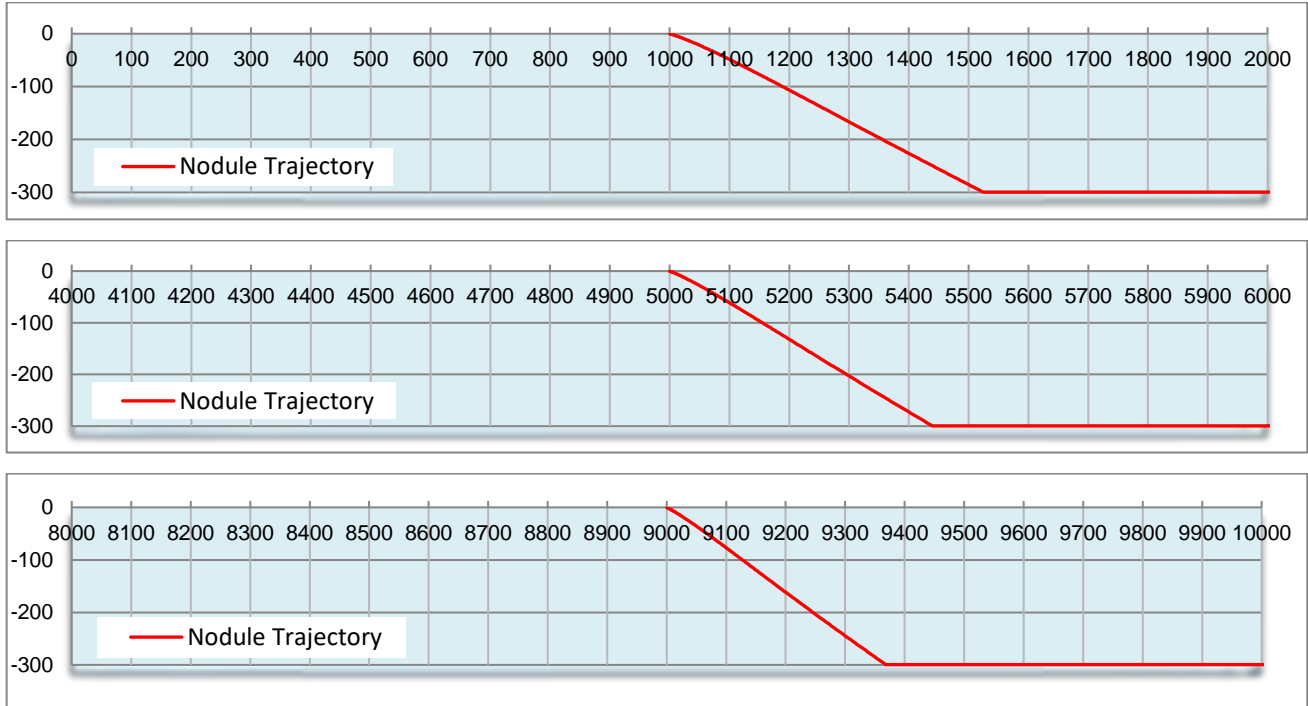


Figure 7: Trajectory of Nodule in Conveyor Tube (From Top to Bottom: Nodules Fed at 1.0 m, 5.0m and 10.0 m)

Figure 8 to Figure 10 below shows the behaviours of particles of different sizes under the same initial flow velocity. It can be observed that under the same flow velocity, the smaller particles take longer time to fall to the tube bottom, achieving higher lateral velocity at the end of the “falling” stage. They also travel faster laterally at the “sliding” stage and exit the Conveyor Tube sooner.

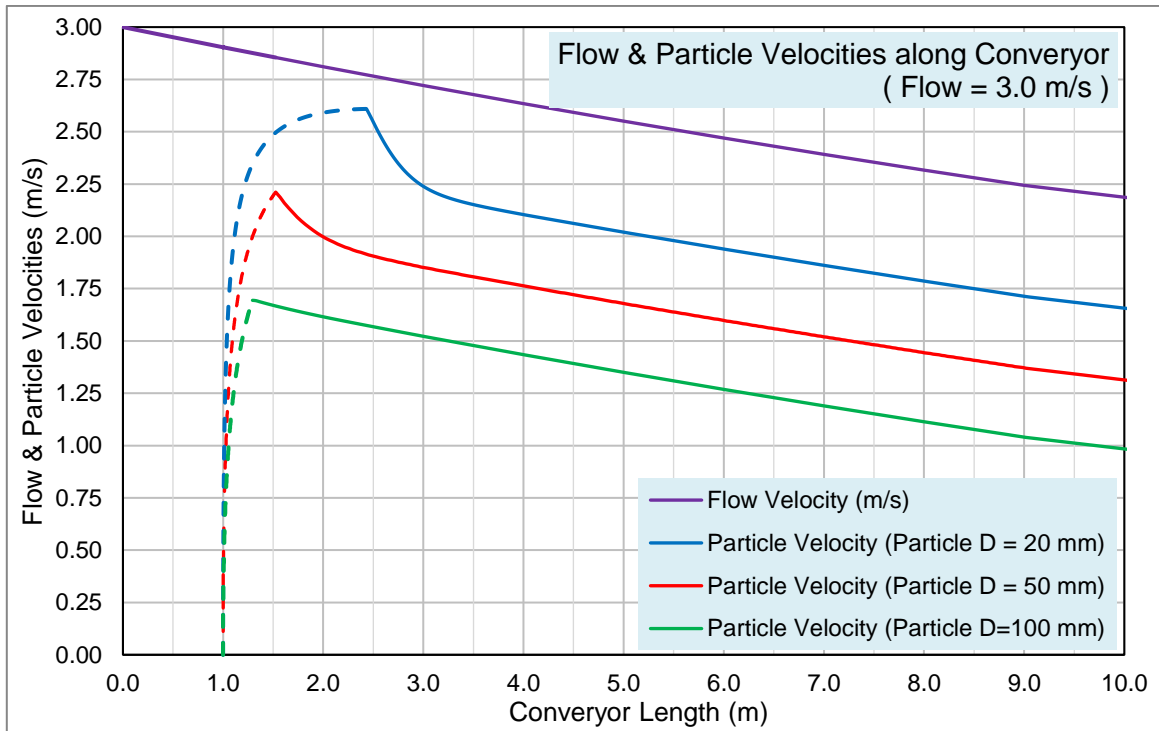


Figure 8: Flow & Nodule Particle Velocities along Conveyor Tube (Different Particle Sizes)

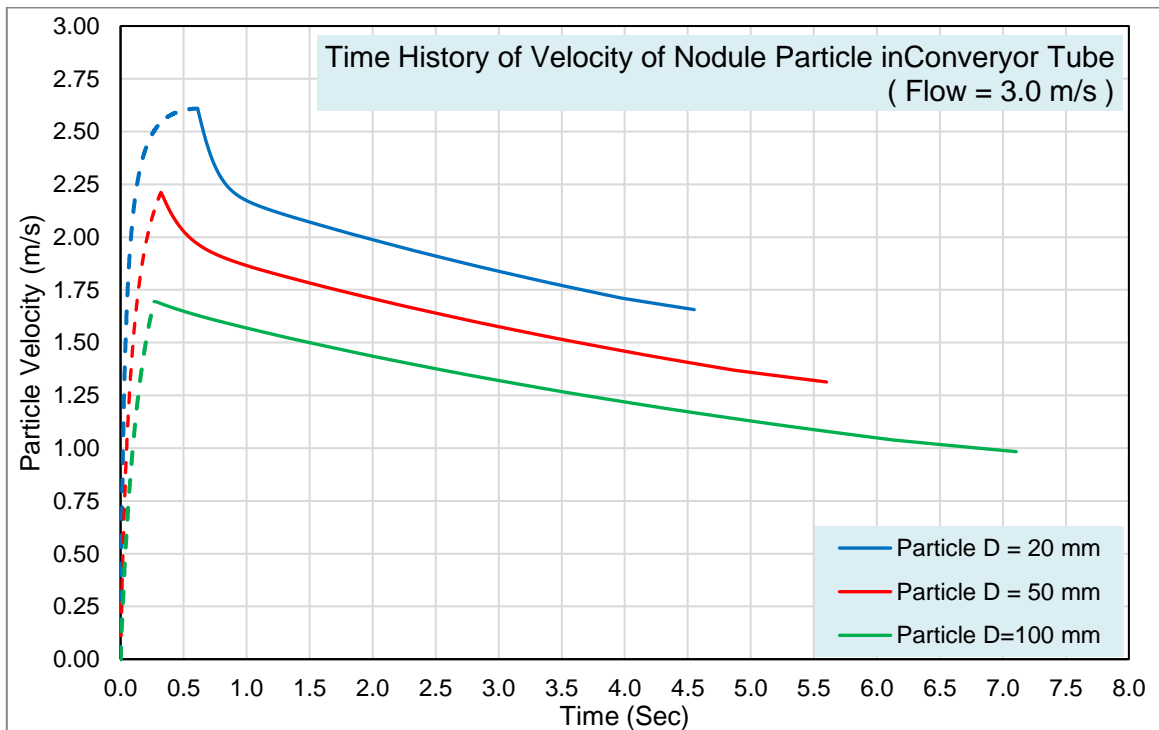


Figure 9: Time History of Nodule Velocities in Conveyor Tube (Different Particle Sizes)

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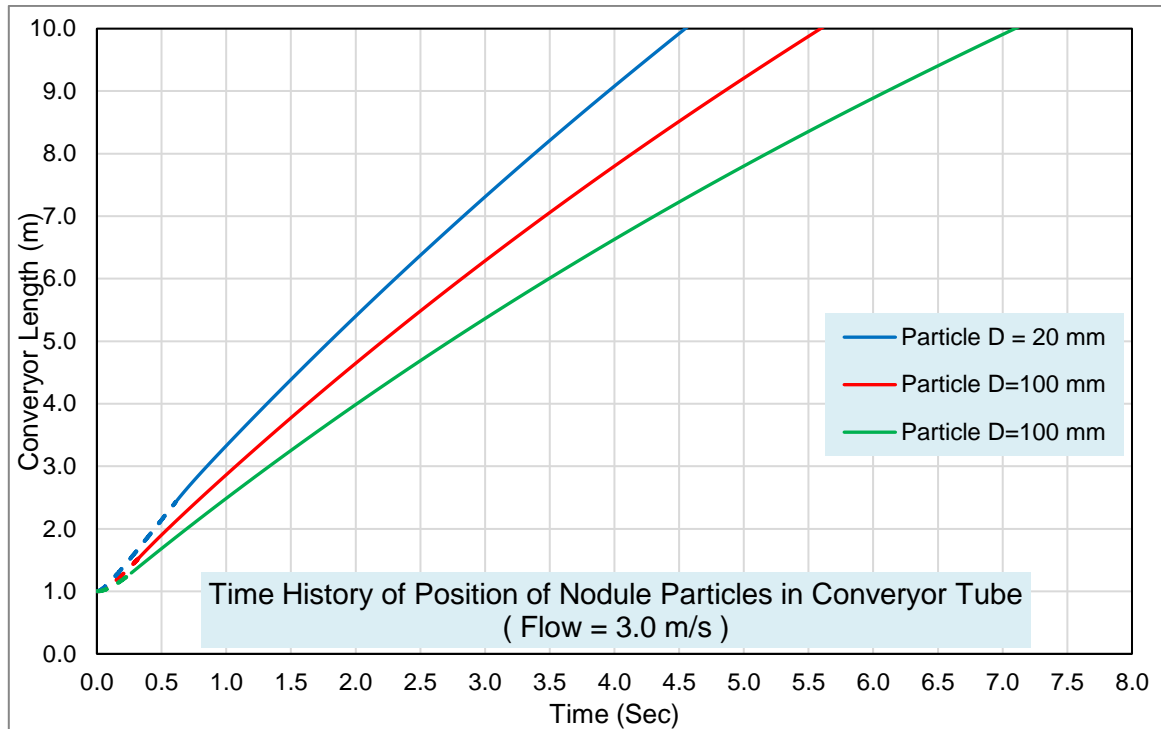


Figure 10: Time History of Position of Particles in Conveyor Tube (Different Particle Sizes)

Figure 11 to Figure 14 below shows the behaviours of flow velocities and particles velocities for three different nodule feeding patterns. In these three cases, the nodules are fed from Feeders No. 1-9, Feeders No. 1-6 and Feeders No. 1-3 respectively. It can be seen from Figure 11 the effects of different nodule patterns on the *flow* velocities, which reduce in different manners along the conveyor length and, in turn, affect the *particles* velocities differently (also in Figure 12 and Figure 13). Given the same initial Flow Velocity (i.e. 3 m/s), different nodule feed patterns affect the nodule volume/weight concentration along the conveyor length (Figure 14). Among these three cases, in the first case, more nodule particles are fed into the conveyor in a given period of time. This faster feeding rate has given rise to higher volume/weight concentration at the end of the conveyor.

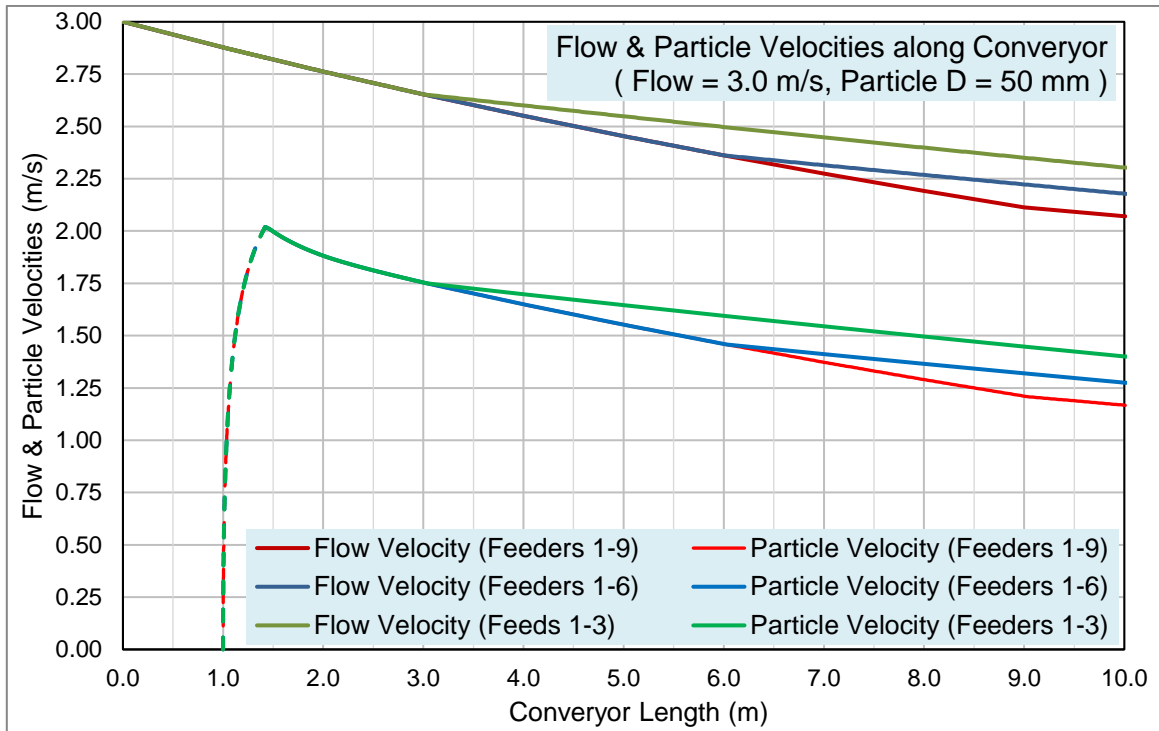


Figure 11: Flow & Nodule Particle Velocities along Conveyor Tube (Different Nodule Feed Patterns)

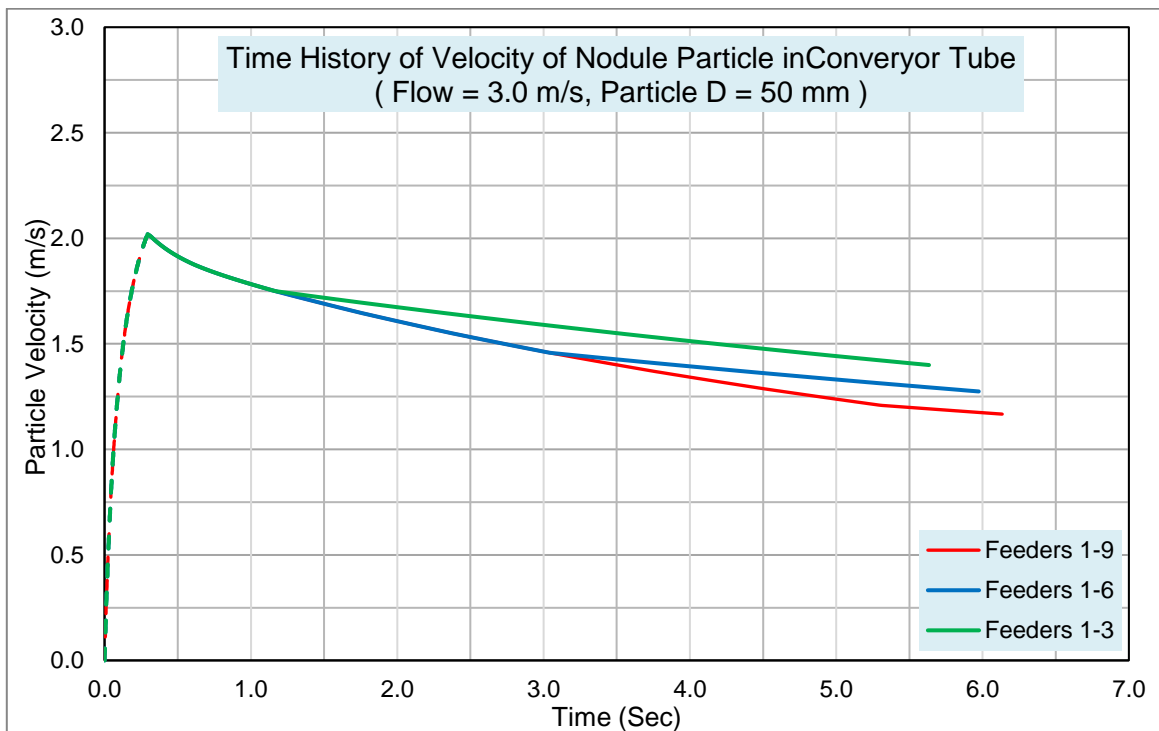


Figure 12: Nodule Particle Velocities along Conveyor Tube (Different Nodule Feed Patterns)

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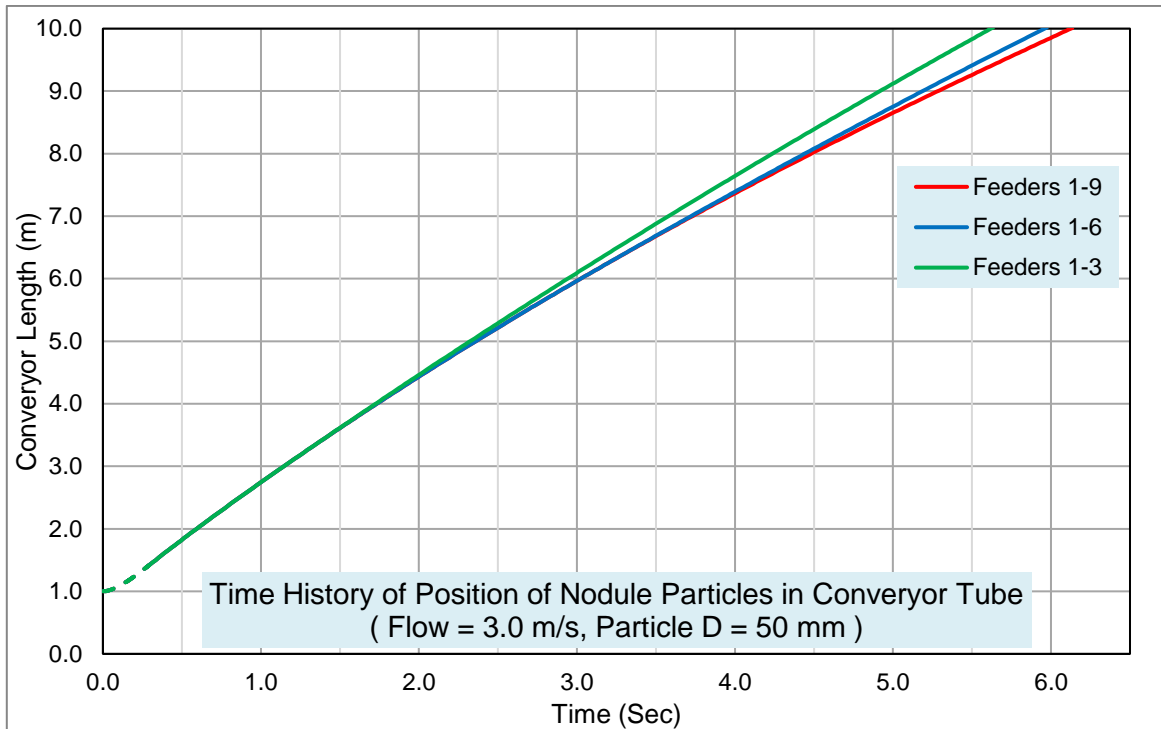


Figure 13: Time History of Position of Particles in Conveyor Tube (Different Nodule Feed Patterns)

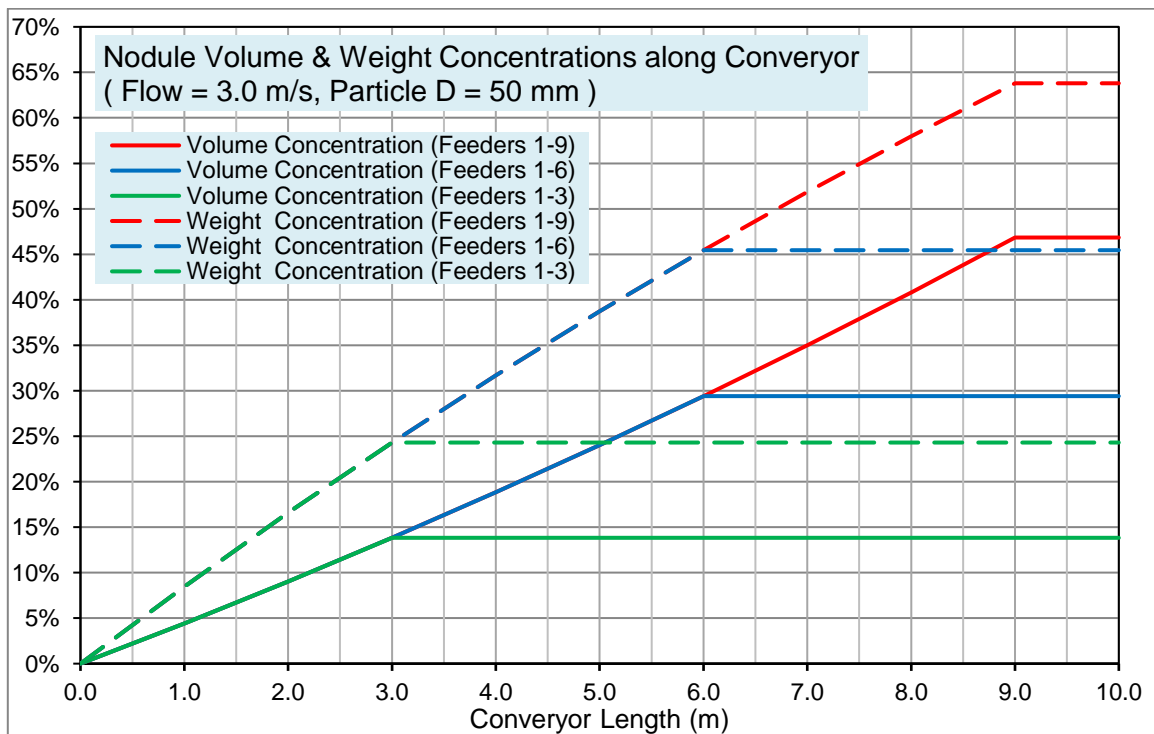


Figure 14: Nodule Weight and Volume Concentrations along Length of Conveyor (Different Nodule Feed Patterns)

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2.3 Assessment of Nodule Blockage in Conveyor Tube

As its basic functionality, the Conveyor needs to be able to carry nodule particles through to the tube exit without blockage. The flow entry velocity V_0 is a key parameter, and an optimized value will ensure smooth operation of the Conveyor while keeping the cost down.

A key parameter effecting the blockage of nodule particles is the volume concentration C_v , which is in turn, effected by the flow velocity V_0 , for a given rate of particles volume/weight being dispatched into the Conveyor Tube. The higher flow velocity will lead to lower flow concentration, reducing the chance of blockage.

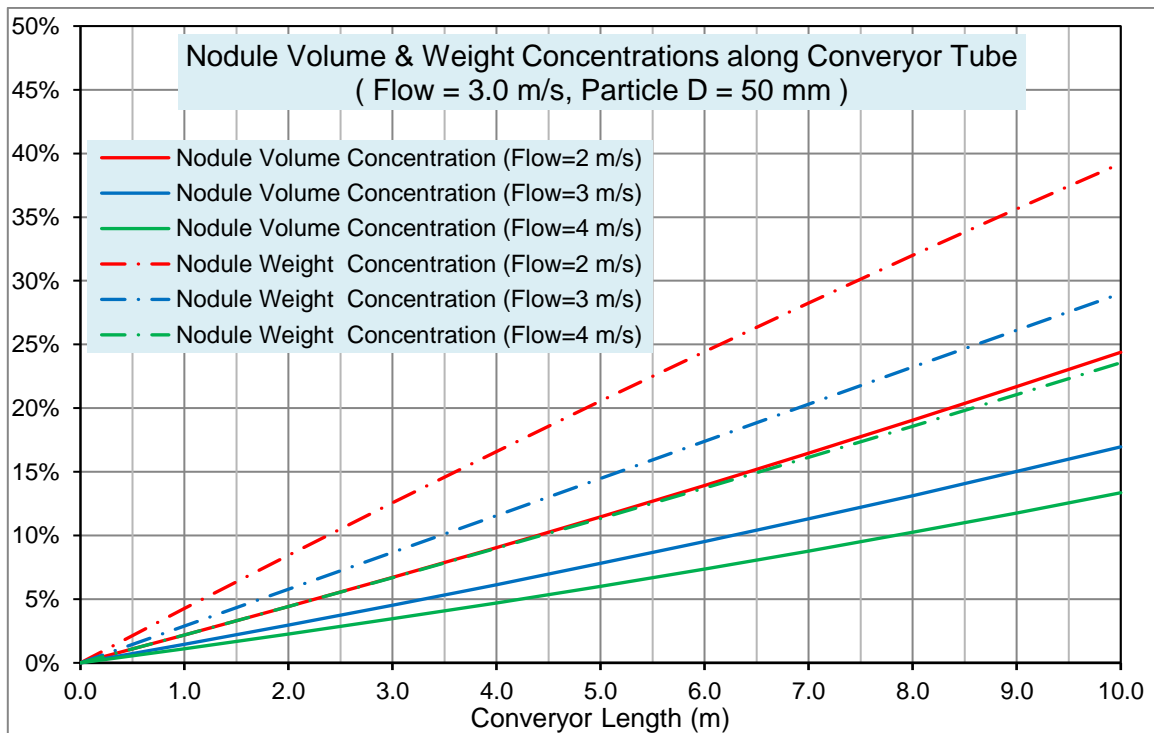


Figure 15: Nodule Weight and Volume Concentrations along Length of Conveyor Tube (Different Flow Velocities)

Figure 15 shows the nodule weight and volume concentrations along the length of the Conveyor Tube, for 3 flow velocities. It is evident that when the flow velocity increases, both volume and weight concentrations reduce. When entry flow velocity is at 2, 3 and 4 m/s, the highest volume concentration at the exit of the tube is about 24%, 17% and 13% respectively.

A full-scale lab test is being carried out to further our understanding of the requirement for the flow velocity and its resulting volume concentration.

Once the flow velocity and other dimensions of the Conveyor Tube are optimized, other key parameters of the Conveyor Array can be attempted. For an example, when the flow parameters are determined (e.g. *Tube Internal Diameter* $D = 300$ (mm) and *Flow Entry Velocity* $V_0 = 4$ (m/sec)), the *Shaft Power* P_1 required to generate the flow rate can be calculated as:

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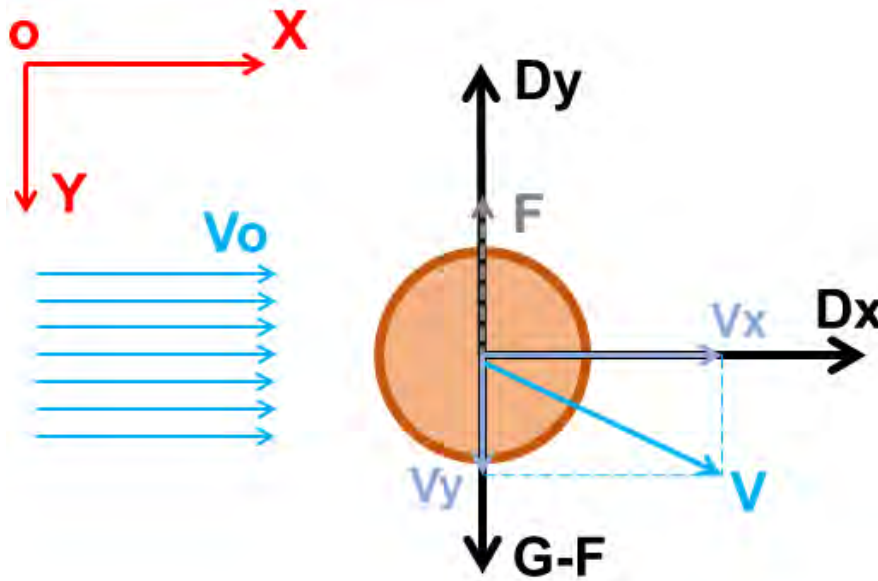
$$P_1 = \frac{\rho g Q H}{\eta} = 11.88 \text{ KW} ,$$

by assuming *Head* $H = 3$ (m) and *Pump Efficiency* $\eta = 0.7$. Further assuming a safety factor of 1.2, the required *Pump Power* P_2 is estimated to be 14.25 KW.

Appendix: “Falling” or “Sliding” of a Particle in Uniform Flow

A nodule particle, after being fed into the Lateral Conveyor, is exposed to the flow in the Conveyor tube. Assuming the velocity of the nodule is V (See Figure below), it can be decomposed into V_x and V_y in the horizontal X -Direction and vertical Y -Direction respectively. The Equations of Motion of the particle in the X - and Y - Directions can be deduced as follows.

(1) Particle Falling under the Gravity and Driven by a Uniform Flow (X -Direction)



Newton’s 2nd Law:

$$m \frac{dV_x}{dt} = D_x = \frac{1}{2} C_d \rho S (V_0 - V_x)^2 \quad \text{Eq.(A1)}$$

$$\frac{dV_x}{dt} = \frac{C_d \rho_w S}{2m} (V_0 - V_x)^2$$

then

$$\frac{dV_x}{dt} = \alpha (V_0 - V_x)^2 \quad \text{Eq.(A2)}$$

$$\text{where } \alpha = \frac{C_d \rho_w S}{2m} = \frac{C_d \rho_w \frac{\pi}{4} d^2}{2 \rho_n \frac{\pi}{6} d^3} = \frac{3 C_d \rho_w}{4 \rho_n d}, \quad \text{i. e. } \alpha = \frac{3 C_d \rho_w}{4 \rho_n d}. \quad \text{Eq.(A3)}$$

Eq.(A2) becomes:

$$\frac{dV_x}{(V_0 - V_x)^2} = \alpha dt \quad \text{Eq.(A4)}$$

Integrating Eq.(A4):

$$\int \frac{dV_x}{(V_0 - V_x)^2} = \int \alpha dt + C$$

gives:

$$(V_0 - V_x)^{-1} = \alpha t + C. \quad \text{Eq.(A5)}$$

Using Initial Condition when $t = 0$, $V_x = 0$,

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Eq.(A5) becomes:

$$(V_0 - 0)^{-1} = 0 + C$$

or

$$C = \frac{1}{V_0}. \quad \text{Eq.(A6)}$$

Inserting Eq.(A6) into (A5):

$$V_0 - V_x = \frac{1}{\alpha t + C} = \frac{1}{\alpha t + \frac{1}{V_0}}$$

or

$$V_x = V_0 - \frac{1}{\alpha t + \frac{1}{V_0}} = V_0 - \frac{V_0}{\alpha V_0 t + 1} = \frac{\alpha V_0^2 t}{\alpha V_0 t + 1}.$$

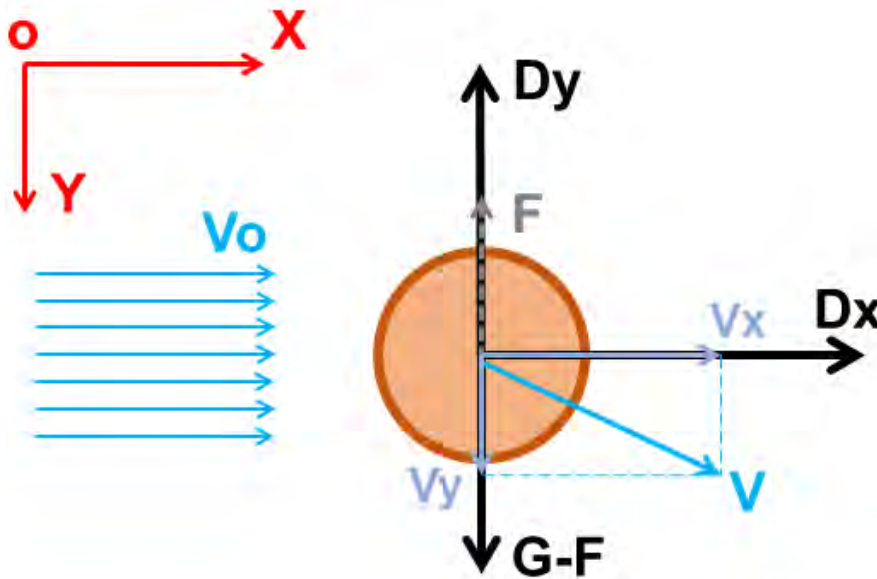
Finally

$$\frac{V_x}{V_0} = \frac{\alpha V_0 t}{\alpha V_0 t + 1}. \quad \text{Eq.(A7)}$$

For large t, Eq.(A7) gives:

$$V_x \rightarrow V_0 \quad \text{Eq.(A8)}$$

(2) Particle Falling under the Gravity and Driven by a Uniform Flow (Y-Direction)



Newton's 2nd Law:
$$m \frac{dV_y}{dt} = (G - F) - D_y = (mg - \rho_w V g) - \frac{1}{2} C_d \rho S V_y^2 \quad \text{Eq.(A11)}$$

or
$$\begin{aligned} \frac{dV_y}{dt} &= \left(g - \rho_w \frac{m}{\rho_n} g\right) - \frac{C_d \rho_w S}{2m} V_y^2 \\ &= g \left(1 - \frac{\rho_w}{\rho_n}\right) - \frac{C_d \rho_w S}{2m} V_y^2 \end{aligned} \quad \text{Eq.(A12)}$$

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then
$$\frac{dV_y}{dt} = \alpha \left[\frac{g(1 - \rho_w/\rho_n)}{\alpha} - V_y^2 \right] = \alpha(v^2 - V_y^2) \quad \text{Eq.(A13)}$$

where $\alpha = \frac{C_d \rho_w S}{2m} = \frac{3C_d \rho_w}{4\rho_n d}$, $v^2 = \frac{g(1 - \rho_w/\rho_n)}{\alpha} = \frac{g(1 - \rho_w/\rho_n)4\rho_n d}{3C_d \rho_w} = \frac{4g(\rho_n - \rho_w)d}{3C_d \rho_w}$

i. e. $\alpha = \frac{3C_d \rho_w}{4\rho_n d}$ and $v = \sqrt{\frac{4gd}{3C_d} \left(\frac{\rho_n}{\rho_w} - 1 \right)}$ **Eq.(A14)**

and $\alpha v = \sqrt{\alpha g \left(1 - \frac{\rho_w}{\rho_n} \right)} = \sqrt{\frac{3C_d \rho_w}{4\rho_n d} g \left(1 - \frac{\rho_w}{\rho_n} \right)} = \sqrt{\frac{3C_d g \rho_w}{4d} \left(1 - \frac{\rho_w}{\rho_n} \right)}$.

Eq.(A13) becomes:
$$\frac{dV_y}{(v - V_y)(v + V_y)} = \frac{1}{2v} \left[\frac{1}{(v - V_y)} + \frac{1}{(v + V_y)} \right] dV_y = \alpha dt \quad \text{Eq.(A15)}$$

Integrating Eq.(A15)
$$\int \frac{dV_y}{(v - V_y)} + \int \frac{dV_y}{(v + V_y)} = \int 2\alpha v dt + C$$

gives:
$$-\ln |v - V_y| + \ln |v + V_y| = 2\alpha v t + C. \quad \text{Eq.(A16)}$$

Using Initial Condition when $t = 0$, $V_y = 0$,

Eq.(16) becomes:
$$-\ln |v| + \ln |v| = 0 + C$$

or
$$C = 0. \quad \text{Eq.(A17)}$$

Inserting Eq.(A17) into (A16)
$$\ln \left| \frac{v + V_y}{v - V_y} \right| = 2\alpha v t \quad \text{Eq.(A18)}$$

(i) Assuming $V_y > 0$, and if $V_y < v$, Eq.(A18a) becomes:

$$\frac{v + V_y}{v - V_y} = e^{2\alpha v t} = \frac{e^{2\alpha v t}}{1}$$

or

$$\frac{v + V_y}{2v} = \frac{e^{2\alpha v t}}{1 + e^{2\alpha v t}}$$

then

$$V_y = 2v \frac{e^{2\alpha v t}}{1 + e^{2\alpha v t}} - v = v \frac{e^{2\alpha v t} - 1}{e^{2\alpha v t} + 1} = v \frac{1 - e^{-2\alpha v t}}{1 + e^{-2\alpha v t}}.$$

Finally,
$$\frac{V_y}{v} = \frac{1 - e^{-2\alpha v t}}{1 + e^{-2\alpha v t}} \text{ while } V_y < v \quad \text{Eq.(A19a)}$$

(ii) Assuming $V_y > 0$, and if $V_y > v$, Eq.(A18a) becomes:

$$\frac{V_y + v}{V_y - v} = e^{2\alpha v t} = \frac{e^{2\alpha v t}}{1}$$

or

$$\frac{V_y + v}{2v} = \frac{e^{2\alpha v t}}{e^{2\alpha v t} - 1}$$

then

$$V_y = 2v \frac{e^{2\alpha v t}}{e^{2\alpha v t} - 1} - v = v \frac{e^{2\alpha v t} + 1}{e^{2\alpha v t} - 1} = v \frac{1 + e^{-2\alpha v t}}{1 - e^{-2\alpha v t}}.$$

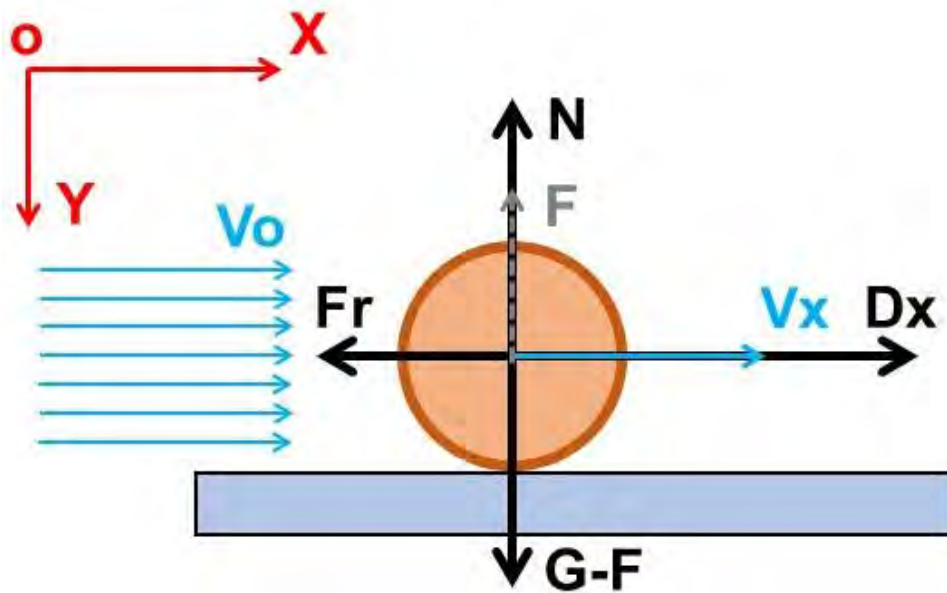
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Finally,
$$\frac{V_y}{v} = \frac{1 + e^{-2\alpha vt}}{1 - e^{-2\alpha vt}} \text{ while } V_y > v \quad \text{Eq.(A19b)}$$

For large t , both Eq.(A19a) & Eq.(A19b) become:

$$V_y \rightarrow v = \sqrt{\frac{4gd}{3C_d} \left(\frac{\rho_n}{\rho_w} - 1 \right)} \quad \text{Eq.(A20)}$$

(3) Particle Sliding on a Surface with Friction and Driven by a Uniform Flow



Newton's 2nd Law:

$$\begin{aligned} m \frac{dV_x}{dt} &= D_x - Fr = D_x - N\mu \\ &= \frac{1}{2} C_d \rho_w S (V_0 - V_x)^2 - (\rho_n - \rho_w) V g \mu \end{aligned} \quad \text{Eq.(A21)}$$

then

$$\frac{dV_x}{dt} = \frac{C_d \rho_w S}{2m} (V_0 - V_x)^2 - \frac{(\rho_n - \rho_w) V g \mu}{\rho_n V}$$

or

$$\begin{aligned} \frac{dV_x}{dt} &= \alpha \left[(V_0 - V_x)^2 - \left(1 - \frac{\rho_w}{\rho_n} \right) \frac{g\mu}{\alpha} \right] \\ \frac{dV_x}{dt} &= \alpha \left[(V_0 - V_x)^2 - \beta^2 \right] \end{aligned} \quad \text{Eq.(A22)}$$

$$\text{where } \alpha = \frac{C_d \rho_w S}{2m} = \frac{C_d \rho_w \frac{\pi}{4} d^2}{2\rho_n \frac{\pi}{6} d^3} = \frac{3C_d \rho_w}{4\rho_n d}, \quad \text{Eq.(A23)}$$

and

$$\beta^2 = \left(1 - \frac{\rho_w}{\rho_n}\right) \frac{g\mu}{\alpha} = \frac{4gd\mu}{3C_d} \left(\frac{\rho_n}{\rho_w} - 1\right)$$

or

$$\beta = \sqrt{\frac{4gd\mu}{3C_d} \left(\frac{\rho_n}{\rho_w} - 1\right)}. \quad \text{Eq.(A24)}$$

Assuming $V' = V_0 - V_x$, Eq.(A22) becoming:

$$\frac{dV'}{dt} = \alpha [\beta^2 - V'^2] \quad \text{Eq.(A25)}$$

then

$$\frac{dV'}{(\beta + V')(\beta - V')} = \alpha dt$$

or when $\beta \neq 0$,

$$\frac{1}{2\beta} \left[\frac{1}{\beta + V'} + \frac{1}{\beta - V'} \right] dV' = \alpha dt \quad \text{Eq.(A26)}$$

Integrating Eq.(A26):

$$\int \frac{dV'}{\beta + V'} + \int \frac{dV'}{\beta - V'} = \int 2\alpha \beta dt + C$$

results in:

$$\ln |\beta + V'| - \ln |\beta - V'| = 2\alpha\beta t + C.$$

or

$$\ln \left| \frac{\beta + V'}{\beta - V'} \right| = 2\alpha\beta t + C \quad \text{Eq.(A27)}$$

and

$$\left| \frac{\beta + V'}{\beta - V'} \right| = e^{2\alpha\beta t + C} \quad \text{Eq.(A28)}$$

Using Initial Condition when $t = 0$, $V' = V_0 - V_x = V_0 - V_{x0} = V'_0$,

Eq.(A27) becomes:

$$\ln \left| \frac{\beta + V'_0}{\beta - V'_0} \right| = 0 + C$$

or

$$C = \ln \left| \frac{\beta + V'_0}{\beta - V'_0} \right|. \quad \text{Eq.(A29)}$$

(i) Assuming $V' = V_0 - V_x > 0$, and if $V' < \beta$ or $V_x = V_0 - V' > V_0 - \beta$, Eq.(A28) becomes:

$$\frac{\beta + V'}{\beta - V'} = e^{2\alpha\beta t + C} = \frac{e^{2\alpha\beta t + C}}{1}$$

or

$$\frac{\beta + V'}{2\beta} = \frac{e^{2\alpha\beta t + C}}{1 + e^{2\alpha\beta t + C}}$$

and

$$V' = 2\beta \frac{e^{2\alpha\beta t + C}}{1 + e^{2\alpha\beta t + C}} - \beta = \beta \frac{e^{2\alpha\beta t + C} - 1}{e^{2\alpha\beta t + C} + 1}$$

So

$$V_x = V_0 - V' = V_0 - \beta \frac{1 - e^{-(2\alpha\beta t + C)}}{1 + e^{-(2\alpha\beta t + C)}}, \quad \text{Eq.(A30a)}$$

while $V_x > V_0 - \beta$ and $\beta \neq 0$;

(ii) Assuming $V' = V_0 - V_x > 0$, and if $V' > \beta$ or $V_x = V_0 - V' < V_0 - \beta$, Eq.(A28) becomes:

$$-\frac{\beta + V'}{\beta - V'} = \frac{V' + \beta}{V' - \beta} = e^{2\alpha\beta t + C} = \frac{e^{2\alpha\beta t + C}}{1}$$

or

$$\frac{V' + \beta}{2\beta} = \frac{e^{2\alpha\beta t + C}}{e^{2\alpha\beta t + C} - 1}$$

and

$$V' = 2\beta \frac{e^{2\alpha\beta t + C}}{e^{2\alpha\beta t + C} - 1} - \beta = \beta \frac{e^{2\alpha\beta t + C} + 1}{e^{2\alpha\beta t + C} - 1}$$

So

$$V_x = V_0 - V' = V_0 - \beta \frac{1 + e^{-(2\alpha\beta t + C)}}{1 - e^{-(2\alpha\beta t + C)}} \quad \text{Eq.(A30b)}$$

while $V_x < V_0 - \beta$ and $\beta \neq 0$.

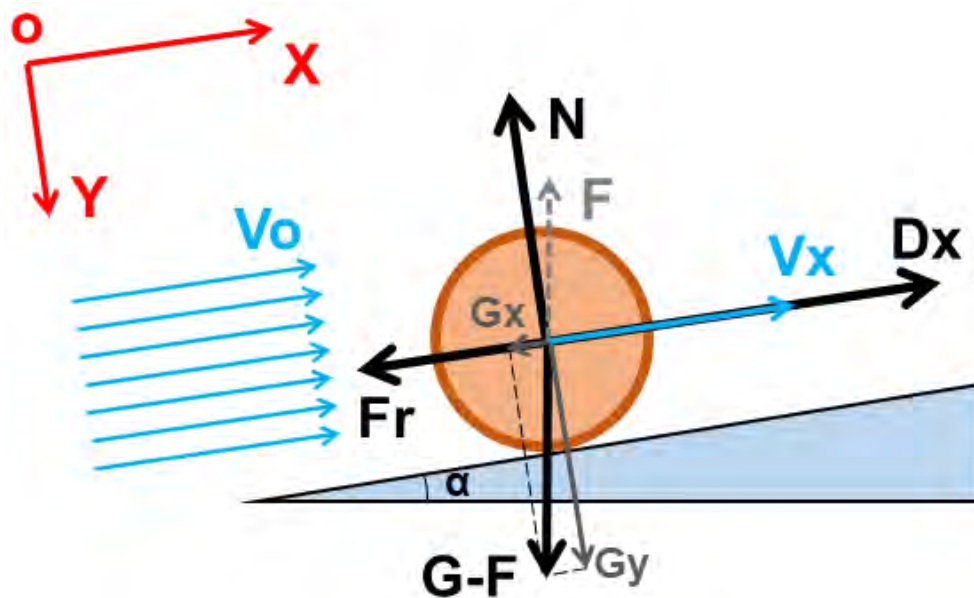
For large t , both Eq.(A30a) & Eq.(A30b) become:

$$V_x \rightarrow V_0 - \beta = V_0 - \sqrt{\frac{4gd\mu}{3C_d} \left(\frac{\rho_n}{\rho_w} - 1 \right)}, \quad \text{Eq.(A31)}$$

noting when $\mu = 0$,

$$V_x \rightarrow V_0. \quad \text{Eq.(A32)}$$

(4) Particle Sliding on a Inclined Surface with Friction and Driven by a Uniform Flow



Newton's 2nd Law:

$$m \frac{dV_x}{dt} = D_x - Fr - G_x = D_x - N\mu - G_x$$

$$= D_x - \mu G_y - G_x = D_x - \mu(G - F) \cos \alpha - (G - F) \sin \alpha$$

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$$= \frac{1}{2} C_d \rho_w S (V_0 - V_x)^2 - (\rho_n - \rho_w) V g (\mu \cos \alpha + \sin \alpha) \quad \text{Eq.(A41)}$$

Defining an “Equivalent Friction Coefficient on Slope” $\mu' = \mu \cos \alpha + \sin \alpha$, Eq.(41) is in the same form as Eq.(21) above:

$$m \frac{dV_x}{dt} = \frac{1}{2} C_d \rho_w S (V_0 - V_x)^2 - (\rho_n - \rho_w) V g \mu' \quad \text{Eq.(A42)}$$

and Eq.(A42) can be solved in the same way as Eq.(A21) above.

When the slope α is small, **“Equivalent Friction Coefficient on Slope”**:

$$\mu' = \mu \cos \alpha + \sin \alpha \approx \mu + \alpha = \mu \left(1 + \frac{\alpha}{\mu} \right). \quad \text{Eq.(A43)}$$

Model Test of Skip Lifting System for Deep-sea Mining

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ABSTRACT

Skip lifting is a new concept of mechanical lifting system for deep-sea mining. It is expected that the skip lifting is capital cost effective and energy efficient compared to hydraulic pump lifting system. Furthermore, the less by-products of seawater and sediment is very attractive in the aspect of environment. This paper presents fundamental results of scaled model test conducted for the purpose of technological feasibility study on skip-lifting system. Main measurement factors are system configuration, angular response and horizontal acceleration of buffer station. It will provide reference data for the pilot test and the commercial realization. The hydrodynamic resistance of skips obtained from single skip test can explore the main composition of water resistance.

KEY WORDS: Skip lifting; model test; dynamic response; offline data logging.

INTRODUCTION

Polymetallic nodules are found on the deep-seabed of oceans worldwide. With the decrease of land minerals resources, value and attraction of the marine mineral resources are increasing. After preliminary exploration the highest density of the nodule are found in Clarion-Clipperton Zone (CCZ) (e.g., Hein, 2016; Keisuke Nishi, 2018). If the human beings' investigation and research of Ocean polymetallic nodules can be described as scientific exploration from the nodules found by Challenger research vessel to 1960s. Then into the 1960s the establishment of OMI, OMA, OMCO, in particular, the successful trial mining of polymetallic nodules in the Pacific Ocean in 1978s marked that human beings have entered the stage of large-scale research on deep-sea mining. (e.g., Xiao, L.J., 2000). Thus far, concepts of deep-sea mining system typically consist of mining vessel, lifting pipeline system (including steel pipe, intermediate tank, hose) and ore collecting unit. (e.g. Li, TT 2018). The geometric scale of the lifting pipeline is very large (e.g. Chen, YX 2014), so it is always the most vulnerable and critical part of the whole mining system. In 2014, Nautilus Minerals came up with a design concept of mechanical hoist to lift nodules.

In cooperation with Nautilus Minerals, Institute of Deep-sea Science and Engineering improved and proposed a skip-lifting system: The skip lifting system consists of a loop of wire rope equipped with two skips – one skip on each side of loop – and a buffer configuring the loop of wire rope and skips like a pendulum weight. Mineral ores collected in the buffer tank are transported by those skips reciprocating up and down by operation of wire rope loop, where skips are loaded at the buffer and offloaded on board of mining vessel, repeatedly.

In 2018, a scaled model test was performed in a test basin of 20m water depth of Institute of Deep-sea Science and Engineering, Sanya, China.

In this paper, fundamental experimental study on the skip-lifting system has been performed through Froude scaled model test. System configuration, hydrodynamic resistances of skips, angular response and horizontal acceleration of buffer station are investigated. These results will be applied for the pilot and full scale skip-lifting system design and furthermore for commercial realization.

MODEL TEST PROGRAM

The Test Model

The model test was performed in the water tank at Engineering Laboratory of Institute of Deep-sea Science and Engineering (IDSSE) of China. The size of the water tank is 10m (width)* 20m (length)* 20m (depth). At the top of test basin, a double girder carriage of 10.8m length moves longitudinally. The test model of the skip-lifting system was mounted on the longitudinal carriage. The water tank, the carriage and the model of skip-lifting system are shown in Fig. 1.



Fig 1 water tank, carriage and top side of skip-lifting model

Mechanical part of test model

The volume of a real skip is considered to be 10m³. Froude scale ratio was selected as 1/10. Considering the basin water depth of 20m, the full scale water depth should be limited to 200m. The parameters of model test (size of skip tank, buffer, top structure and lifting speed) are given in Table 1.

Table 1 model test parameter by scale of 1/10

Parameter	200mwd sea trial and 10m ³ skip volume as the pilot model size					Units	
	Pilot model	Full model	$\lambda=1/50$	$\lambda=1/25$	$\lambda=1/20$		Scale
Skip Diameter	0.914	1.922	0.038	0.077	0.096	0.192	m
Skip Length	4.572	9.612	0.192	0.384	0.481	0.961	m
Skip Volume	2.801	26.030	0.000	0.002	0.003	0.026	m ³
Empty Skip Weight in water	680.400	6323.420	0.051	0.405	0.790	6.323	kg
loaded Skip Weight in water	2268.000	21078.067	0.169	1.349	2.635	21.078	kg
Empty buffer Weight in water	2041.200	18970.260	0.152	1.214	2.371	18.970	kg
loaded buffer Weight in water	3628.800	33724.907	0.270	2.158	4.216	33.725	kg
Slenderness Ratio	5.000	5.000					
Lifting speed			0.566	0.800	0.894	1.300	m/s
Accelerated trip						1.000	m
Accelerated time						1.538	s
Acceleration						0.845	m/s ²
System weight in water						599.650	N
Buoyance of Skip						261.737	N
Mass additional force						36.905	N
Water resistance estimated						4.761	N
Lifting force						490.170	N
Safety factor						9.000	
Max breaking tension						4411.589	N
Breaking strength of steel rope						300.00	Mpa
Sectional area of steel rope						16	mm ²
Diameter of steel rope						4	mm

The aspect ratio of skip tank refers to skip length/skip diameter is 5 and Froude number will be used to decide lifting speed. The sharp of skip tank is a cylinder and two half spheres at two end of skip tank. Each half sphere consists of two quarters sphere, so there is a gap in the middle and four screw holes around for sealing. The roughness of skip tank cannot be considered as smooth surface due to gap and holes on it. The full loaded skip tank is 21kg in water and empty one is 6.3kg in water as shown in table.1. For the wire rope loop, a steel wire rope of 4mm diameter was chosen: The safety factor is estimated to be 9.0.

The conceptual diagram of model test is shown in Fig. 2. Topside and buffer model are both 2m long. Topside structure is fixed on the carriage and a winch operating wire rope loop is mounted on the topside structure. The loop of wire rope is configured by the topside winch and an idling sheave at the surface and two sheaves positioned at both ends of the buffer model underwater. The wire rope passes through two sheaves of the buffer model so that the buffer model is freely hung like a pendulum weight. Two models of skip tanks are inserted in the wire rope loop, where the top and the bottom of each skip tank are connected through tension load-cells to the wire rope. By operation of the winch, the two skips move reciprocally up-and-down in opposite directions with same speed.

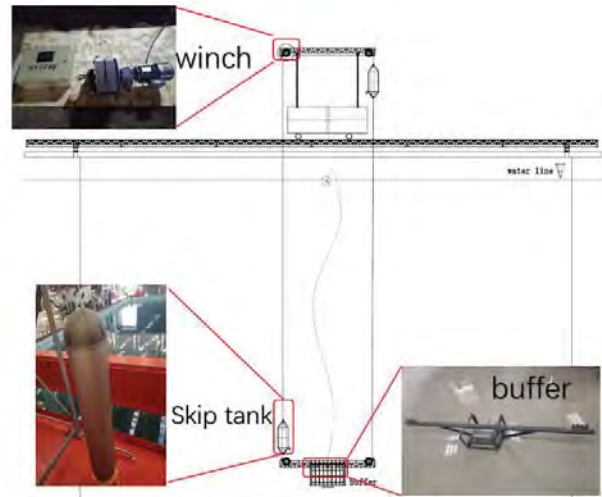


Fig 2 Conceptual diagram of model test

Winch

IDSSE designed a two-way double drum winch, which operates and controls the reciprocating motion of wire rope loop. Two drums of this winch have the same diameter and are fixed on the same axis of rotation. The capacity of each drum can store all the rope with only one layer so the lifting speed and sinking speed are the same during one cycle. Winch can control the speed of wire rope loop, and the maximum speed is 2.7m/s. The driving speed functions consist of acceleration, constant speed and deceleration.

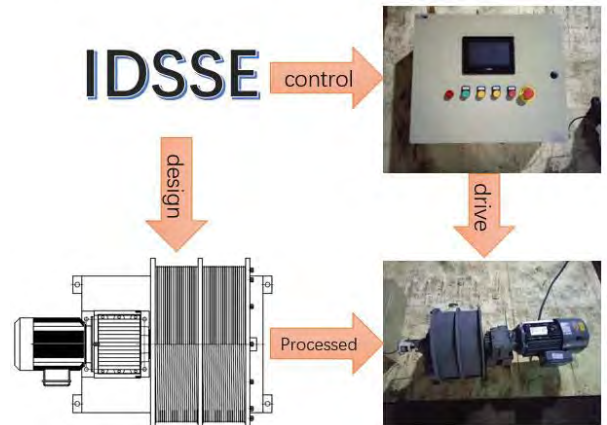


Fig 3 Two-way double drum winch

Offline data logging system

For the measurement and data storage, offline data logging system has been designed and developed. Four tensions and dynamic responses at the skip models and dynamic responses of the buffer model are measured and stored by means of the offline data logging systems. The principle block diagram is shown in Fig. 4. JY901 module is adopted by the attitude sensor, and the attitude measurement accuracy is static 0.05 degree and dynamic 0.1 degree. The system is powered by lithium battery. After the system is powered on, the microcontroller reads the data information of attitude Angle sensor and tension sensor every 10ms and saves it to the SD card. After the experiments have been completed, the measured data are exported from the SD card: Clock time, speed, tension forces, accelerations and angles are measured and stored.

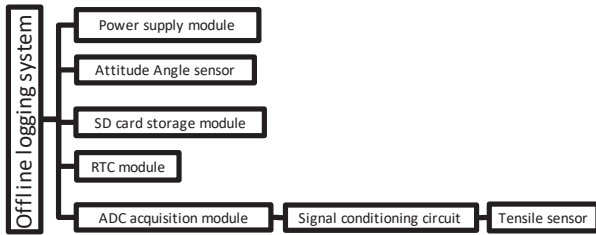


Fig 4 Principle block diagram

Test Conditions

Two kinds of model test were conducted: single skip test and two skips loop test. The single skip test was carried out in full loaded condition without buffer shown in Fig.5. In this test, multiple hoisting and sinking speed conditions were performed. The total hydrodynamic forces on the skip were calculated from the measured results of the tension sensors.

In the two skips loop tests, four different lifting speeds were chosen. By means of the acceleration, the angles of buffer and skip tanks, the configuration change is investigated, and the angle (attitude) change of wire rope loop is obtained with respect to space coordinates system XYZ, where Z-axis is upward positive from underwater to water surface, X-axis is defined along the width of water tank, and Y-axis is defined along the length of water tank (shown in Fig.6).

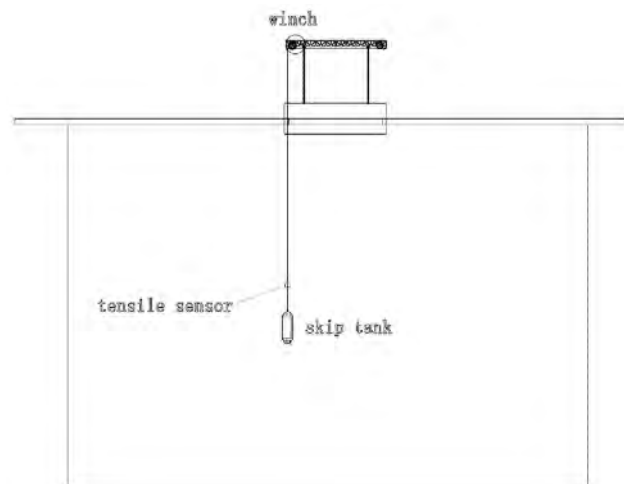


Fig 5 Single skip test



Fig 6 Definition of axis direction

Model Test Results

Total hydrodynamic resistance force

The main purpose of single skip lifting test is to explore the main composition of water resistance through measuring the total hydrodynamic resistance force. The total hydrodynamic resistance force consists of hydrodynamic force caused by shape and additional force caused by vibration and inclination. The hydrodynamic force caused by sharp can be calculated by Eq. (1)

$$F_d = 0.5 * \rho * C_d * v^2 * A \quad (1)$$

Where C_d is 0.2; A is the section area of skip tank. The hydrodynamic is proportional to the square of the velocity. When the velocity is 1.3m/s hydrodynamic force can reach 4.78N. The additional resistance caused by vibration can't be calculated very accurately.

This test is mainly divided into three conditions of lifting speed (0.5m/s, 0.8m/s, 1.0m/s), each speed is divided into five lifting and sinking tests, but in this article only one typical data is plot and analyzed. Skip weight does not change in the whole test procedure.

$$T_{top \text{ sinking}} = T_{down} + W_{skip} - \text{buoyancy} - F_d \quad (2)$$

$$T_{top \text{ lifting}} = T_{down} + W_{skip} - \text{buoyancy} + F_d \quad (3)$$

Eq. (2) is the force equilibrium condition at the skip during sinking. Eq. (3) is the force equilibrium condition at the skip during lifting process.

For $T_{down} = 0$, according to Eq. (2) and (3), the hydrodynamic force on the skip is as follows:

$$F_d = (T_{top \text{ lifting}} - T_{top \text{ sinking}})/2 \quad (4)$$

The test result is shown in the Fig. 7. The weight of skip in still water is about 252.75N. For speed as 0.5m/s, the tension sensor is 275.02N during lifting procedure and 264.64N during sinking procedure, and the total resistance force is 5.19N. For 0.8m/s, the tension sensor is 275.02N during lifting and 264.29N during sinking, and the total resistance force is 5.365N. For 1.0m/s, the tension sensor is 268.55N during lifting and 258.20N during sinking, and the total resistance force is 5.175N. The result is shown in Table.2 that total water resistance is not proportional to the square of the velocity as calculated due to the existing of additional water resistance caused by vibration. When the velocity increase from

0.5m/s to 0.8m/s and 1m/s, the water resistance resultant force does not increase significantly, which indicates that the vibration and inclination will decrease after the velocity reaches a certain critical value.

Table 2 Single skip lifting test result

Skip weight in still water		252.75N	
Moving speed	Sensor reading during Lifting	Sensor reading during Sinking	Total resistance force
0.5m/s	275.02N	264.64N	5.19N
0.8m/s	275.02N	264.29N	5.365N
1.0m/s	268.55N	258.20N	5.175N

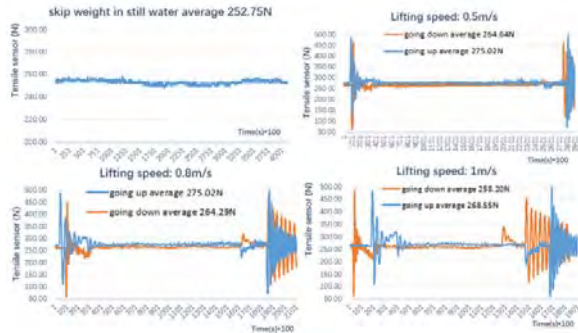


Fig 7 Single-skip lifting test result

Loop configuration through skips moving

In two skips loop tests, four different speeds are used to analyze the loop configuration changes. The speed results are shown in the Fig. 8. The lifting speed recording equipment is made of a custom designed rubber sheave, encoder and offline storage module.

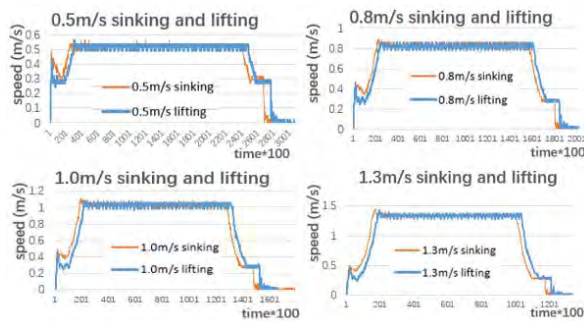


Fig 8 Four lifting speeds

The accelerations of skips in space coordinates system are calculated by the rotation matrix through Matlab and shown in Fig. 10 and Fig. 12. At each moment the displacement of skip along three axes can be calculated from acceleration and time so the skip coordinates of each moment in space is investigated. A position vector of the skip(s) can be defined with respect to the surface structure winch as origin. The angle between this position vector and the space coordinates system is the deviation angle of the skip rope loop in space coordinates system at each moment (as shown in Fig. 11 and Fig. 13). In this paper, the loop configuration change can only be analyzed in case of skip sinking. When skip reaches the buffer position, the angle in figure is just the deviation angle of the whole system occurred through the change of loop configuration.

The deviation angle along X,Y,Z-axis direction are shown in Fig.9. It can describe the configuration of loop system in space during the system working.

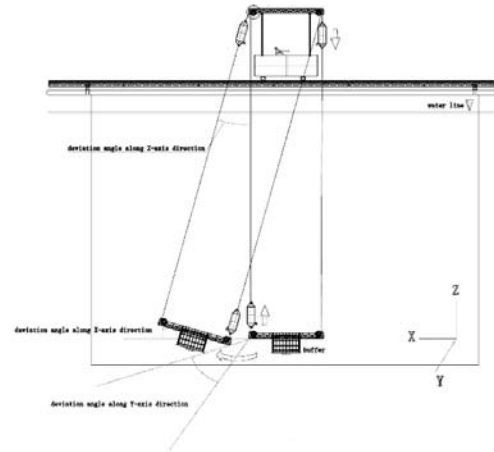


Fig 9 Deviation angle along X,Y,Z direction

As can be seen from Fig. 11 and Fig.13, for the lifting speed of 0.5m/s and 0.8m/s, the loop system has a large deviation angle along z-axis direction, which can be maximum of 28 deg. At the same time, the deviation angle about X and Y direction can be maximum of 25 deg. However, when lifting speed rises to 1.0m/s and 1.3m/s, deviation angles of the loop system about X, Y and Z direction are greatly reduced and the angle w.r.t Z axis is less than 10 deg., and the angle w.r.t X and Y axis is less than 5 degrees. It can be seen the lifting speed of skip-lifting system has a great influence to the change of loop system configuration, and when the speed increases to a certain value, the loop system remains in a relatively stable state. In this model test, this steady-state speed was approximately 1m/s.

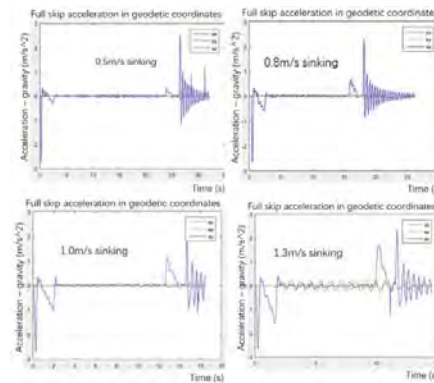


Fig 10 Acceleration of full skip tank in space coordinates

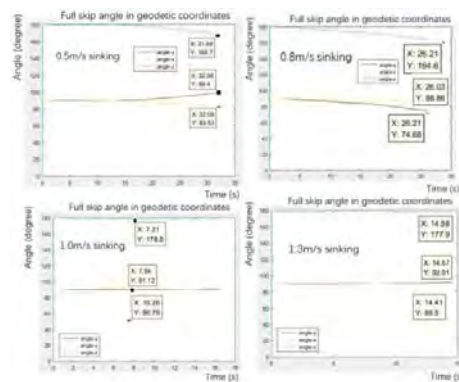


Fig 11 Angle of full skip tank in space coordinates

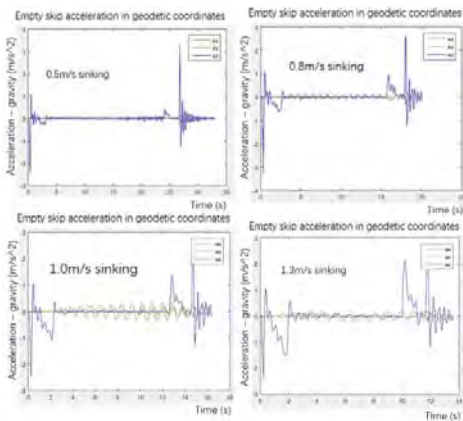


Fig 12 Acceleration of empty skip tank in space coordinates

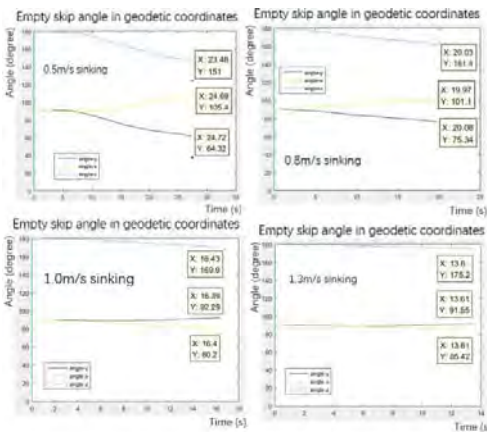


Fig 13 Angle of empty skip tank in space coordinates

Buffer Motion Analysis

Fig 14 shows the acceleration of buffer in space coordinates during both clockwise and counterclockwise directions in four different speeds. It can be seen there is a little fluctuation in X and Z direction during lifting but did not appear any large displacement. Acceleration in Y direction is apparently larger than X and Z directions. The direction of acceleration changes with the change of clockwise and counterclockwise directions, and ascending tendency keeps pointing to the lifting side.

During skips movement the rotation angle of buffer in the local coordinates system can be seen from Fig. 15. There is almost no rotation around x-axis, while the rotation angles around y- and z-axis grow up with increase of lifting speed. The characteristics of rotation direction is similar with the acceleration cases which change with the clockwise and counterclockwise directions of skip lifting, and the rotation direction of angle always points to the lifting side.

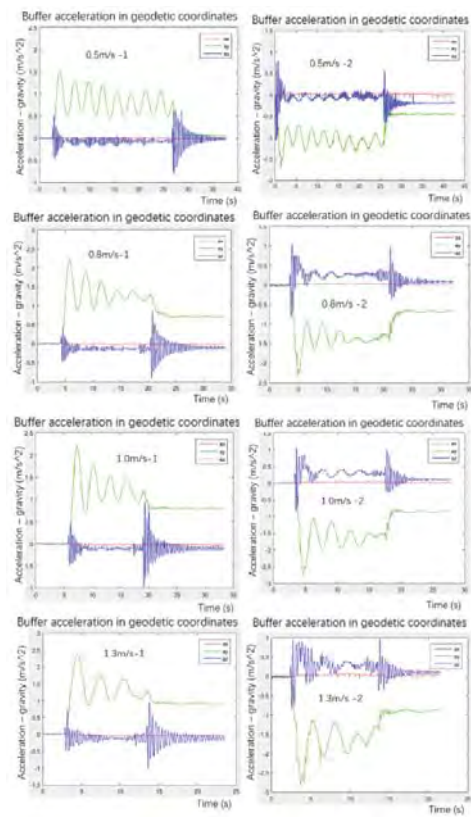


Fig 14 Buffer acceleration in space coordinates

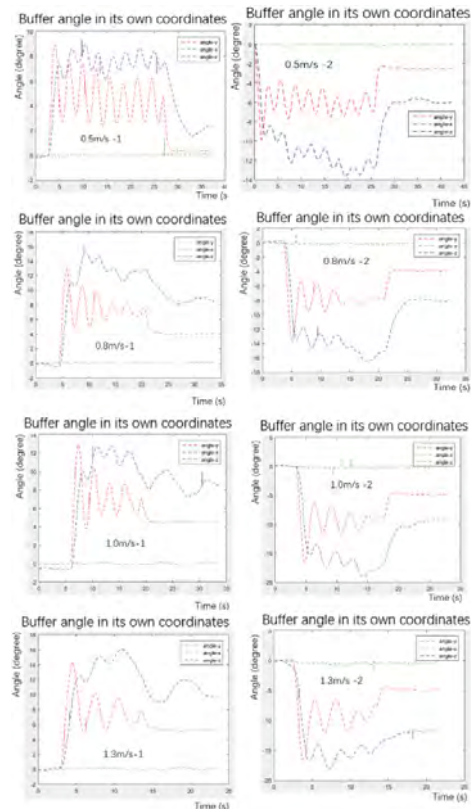


Fig 15 Buffer angle in local coordinates

CONCLUSIONS

This paper presents the analyses results from the skip lifting system model tests: changes of loop system configuration, direction change of buffer, and total hydrodynamic resistance force on skips during skip lifting procedures. The result of Froude scaled model test provide some important aspect on global behaviors of skip lifting system. The conclusions are as following:

- 1) Total water resistance of skip in three different smaller velocities are all around 5.2N. Compare with the theoretical calculation result of 4.78N in 1.3m/s, it is still 0.5N larger. The existing of additional water resistance caused by vibration and inclination can be understood as the reason why the total water resistance is not proportional to the square of the velocity as calculated. While the velocity increasing from 0.5m/s to 0.8m/s and 1m/s, the water resistance resultant force does not increase significantly, which indicates that the vibration and inclination in low lifting speed is much larger than higher speed until the velocity reaches a certain critical value.
- 2) A certain deviation of buffer direction and loop system occurs. The deviation angle reduced with increase of lifting speed. Although, this 3D response characteristics, occurring in spite of the initial 2D configuration, would be a significant phenomenon affecting the feasibility of skip-lifting concept in situ.
- 3) The buffer rotates and vibrates during loop system operation. The magnitude of ascending side appears always higher than descending side due to the rotation about y-axis.

Under the limitation of the facility, we have completed the skip-lifting test. The experimental result are almost similar to the preliminary estimated results during the design process and the further research value of skip lifting test has been verified by both experiment result and

calculation result. But due to the limitation of experimental conditions, a lot more helpful observation methods still didn't been used in test. Such as if add two more circuit boards at both ends of buffer and the torsion trend of buffer in water will be obtained by analyzing the displacement of two circuit boards. Or add an underwater camera to capture the morphological changes of buffer and system, which can show the configuration changes more easily.

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Article

Thermodynamic and Experimental Study on Efficient Extraction of Valuable Metals from Polymetallic Nodules

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Abstract: Polymetallic nodules are promising resources for the extraction of valuable metals such as copper, nickel, and cobalt, as well as manganese alloys. To achieve efficient extraction of useful metals from the emerging resource, high-temperature carbothermic reduction of nodules was investigated by optimizing the reductant addition, slag and alloy systems. Thermochemical software FactSage was used to predict the liquidus temperature of the slag system, which is not sensitive to FeO, CaO and Al₂O₃, but decreases significantly with decreasing MnO/SiO₂ mass ratio. The experiments were designed to reduce the oxides of Cu, Co and Ni completely, and reduce FeO_x partially depending on the amount of graphite addition while leaving the residual slag for further processing into ferromanganese and/or silicomanganese alloys. Co, Cu and Ni concentrations in the alloy decreased with increasing graphite addition. The optimal reduction condition was reached by adding 4 wt% graphite at the MnO/SiO₂ mass ratio of 1.6 in slag. The most effective metal-slag separation was achieved at 1350 °C, which enables the smelting reduction to be carried out in various furnaces.

Keywords: polymetallic nodules; carbothermic reduction; valuable metals; liquidus temperature

1. Introduction

The manganese and iron concretions on the sea bottom formed of concentric layers around a core are known as manganese nodules or polymetallic nodules. Polymetallic nodules contain many valuable elements such as Cu, Ni and Co, besides Mn and Fe. Trace amounts of Mo, V, and rare earth elements (REEs) are also present in the nodules. As the land-based resources for Mn, Cu, Ni and Co are depleting very fast, the exploration and exploitation of manganese nodules are essential to meet the future demands of Cu, Ni, Co and Mn in the world [1]. In recent years, the exploitation of manganese nodules from the deep sea has once again become a political and economic topic [2,3]. One of the biggest and economically most important areas, where polymetallic nodules can be found, is situated between the Clarion and Clipperton Zones in the tropical northern Pacific Ocean. The nodules could serve as an enormous reserve for these metals since they are found in relative abundance. The nodules in the Clarion Clipperton Zone alone constitute an estimated reserve of up to 220 million tons of copper, up to 260 million tons of nickel, up to 50 million tons of cobalt, and up to 5 billion tons of manganese [2,3]. These estimated amounts currently surpass universal land-based reserves in mines for Ni, Cu, Co and Mn. Recently, the increased interest in electrical energy storage and rapid growth in the market for electric vehicles will make the polymetallic nodules promising resources to produce component metals of batteries.

Polymetallic nodules are composed of complex Mn-oxides and Fe-oxyhydroxide minerals with mineral particles smaller than one μm. Ni, Cu, Co and Mo are found in the manganese- or iron-oxide matrix [4]. Therefore, beneficiation with classic techniques (density separation, floatation, etc.) to

generate a metal-bearing concentrate, which could be directly used in existing industries, is not effective [5]. Considerable research has focused on the extraction of valuable metals from ocean nodules. The nodule processing techniques are broadly divided into three categories: (1) hydrometallurgical processing (only); (2) pyrometallurgical treatment followed by hydrometallurgical processing; (3) hydrometallurgical processing followed by pyrometallurgical treatment for recovery of Mn from leaching residue [6–8]. Various hydrometallurgical approaches included reductive ammonia leaching [9–14], reduction and sulphuric acid leaching [15–18], reduction and hydrochloric acid leaching [19,20], and other integrated or synergistic solvent extractions [21–23]. Reductive ammonia and sulphuric acid leaching cannot recover manganese, which makes up nearly half of the nodules' value. Reductive hydrochloric acid leaching can recover manganese, however, the corrosive nature of chloride is the main disadvantage [24]. With time, the environmental regulations are becoming more and more stringent, it is mandatory to properly deal with the disposal of solid/liquid effluents generated during the hydrometallurgical processes. Some researchers reported the pyrometallurgical route to recover the Cu, Ni, Co, as well as Mn metals from polymetallic nodules at temperatures above 1400 °C [25–30]. Recently, the pyrometallurgical process with “zero-waste” has been proposed [28,30], based on the “Inco-process” [7]. Valuable metals such as Cu, Co, Ni are recovered first by smelting reduction at high temperature or sulfurizing into matte. The slag generated contains high manganese can be used in the existing production plants for ferromanganese or silico-manganese alloys. Since the (Cu + Ni + Co) grade of nodules is similar to nickel laterite, the pyrometallurgical treatment route of nickel laterites [31], which is a well-established industrial method, namely, the rotary kiln-electric arc furnace (RKEF) process, can be used to treat nodules to save a new capital investment to build a new process for nodules. However, limited experimental data on the extraction of valuable metals have been reported due to a limited supply of nodules. The operating parameters need to be optimized to prepare industrial scale-up. Of particular significance is that the melting temperatures of slags over 1500 °C were typically quoted significantly higher, which results in high consumption of energy and refractory. Therefore, in this study, the pyrometallurgical process of extraction of useful minerals from deep-sea nodules will be developed and optimized to produce Fe-Cu-Co-Ni master alloys and Mn-rich slag.

2. Materials and Methods

2.1. Nodule Materials

The nodules employed in this study were dredged from the Clarion-Clipperton Zone of the Pacific Ocean. The chemical composition of the nodule sample is shown in Table 1.

Table 1. Chemical composition of the nodules (wt%).

MnO	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	MgO	Na ₂ O	CaO	NiO	CuO	CoO
40.25	13.48	8.28	4.67	3.48	3.01	2.16	1.71	1.65	0.30
K ₂ O	TiO ₂	P ₂ O ₅	BaO	ZnO	SO ₃	PbO	Cr ₂ O ₃	LOI	MnO/SiO ₂
1.24	0.52	0.32	0.22	0.20	0.17	0.03	0.01	17.28	3.0

The microstructure and elemental mapping of a local area of an example nodule were determined by scanning electron microscopy (SEM) with energy dispersive X-ray spectrometry (EDS), which is shown in Figure 1. The nodule consists of concentrically banded zones of micro-layers around a nucleus. The microstructure of the shell is dense, while it is looser in the core of the nodule scanned. The maps of the distribution of each element across the local area show the distribution of Mn and Fe is in striation. Si is incorporated with Al, Na, K and Ca as impurity minerals, likely detrital deep-sea ooze [1]. Valuable metal elements such as Cu, Co and Ni in low concentrations are uniformly distributed in the nodule matrix. Ba is found to be associated with S, which is most likely considered to be precipitated barite (BaSO₄).

primary phase field at different MnO/SiO₂ ratios but decreases in the olivine primary phase field at the MnO/SiO₂ ratio of 1.0. Figure 2b shows the Al₂O₃ concentration has a little effect on the liquidus temperature at the MnO/SiO₂ ratio of 1.0. Figure 2c shows the FeO concentration has a little effect on the liquidus temperature at the MnO/SiO₂ ratio of 1.0. The liquidus temperature increases slightly with increasing Al₂O₃ concentration at the MnO/SiO₂ ratio of 2.0 in the monoxide primary phase field but decreases slightly at the MnO/SiO₂ ratio of 1.0 in the olivine primary phase field. It shows in Figure 2c that the FeO concentration has little effect on the liquidus temperature at different MnO/SiO₂ ratios, which indicates the liquidus temperature of slag will not change significantly when FeO in slag is partially or fully reduced.

It is clear from Figure 2 that the MnO/SiO₂ ratio has a significant impact on the primary phase field and liquidus temperature. SiO₂ can be added as a flux to control the liquidus temperature of the slag. The effect of SiO₂ or MnO/SiO₂ on the liquidus temperature is shown in Figure 3. It can be seen that the autogenic residue without SiO₂ flux has a liquidus temperature of around 1570 °C, which requires an operation temperature of above 1600 °C to keep the slag fully liquid. By adding SiO₂ flux, the primary phase field changes from monoxide to olivine 2(Ca, Mn)O·SiO₂ and rhodonite (Ca, Mn)₂O·SiO₂. A large operating window with the liquidus temperature below 1300 °C can be obtained with 10–50 wt% SiO₂ addition.

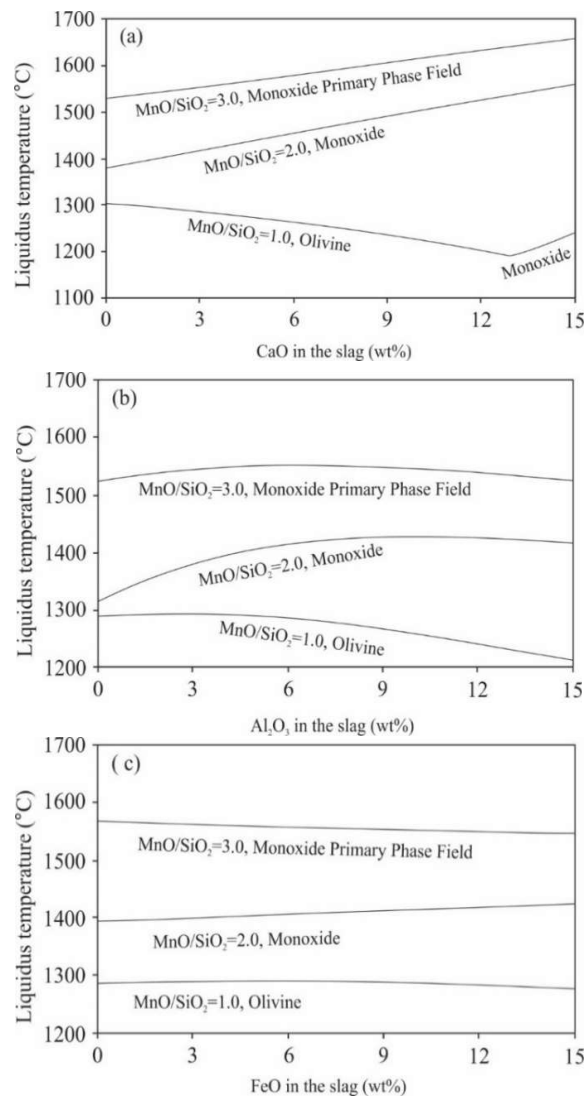


Figure 2. Effects of CaO, Al₂O₃, and “FeO” on liquidus temperatures at different MnO/SiO₂ ratios in equilibrium with iron calculated with FactSage 7.22. (a) CaO in the slag, (b) Al₂O₃ in the slag, (c) FeO in the slag.

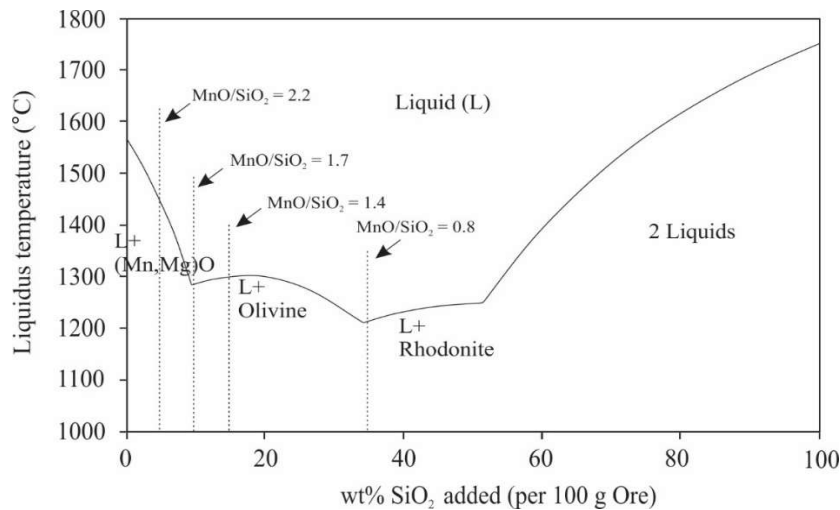


Figure 3. The effect of weight percent of SiO₂ per 100 g nodules added as a flux on the liquidus temperature at a fixed ratio of other components.

Table 2. The composition of the slag used for FactSage calculation (wt%).

CaO	MnO/SiO ₂	"FeO"	"FeO"	Al ₂ O ₃	Al ₂ O ₃	MgO	Na ₂ O	Na ₂ O	K ₂ O	
0-15	0-15	1.0	9.6	9.6	6.2	6.2	4.6	4.0	4.0	1.6
CaO	MnO/SiO ₂	"FeO"	"FeO"	Al ₂ O ₃	Al ₂ O ₃	MgO	Na ₂ O	Na ₂ O	K ₂ O	
0-15	2.0	2.0	9.6	9.6	6.2	6.2	4.6	4.0	1.6	1.6
CaO <th>MnO/SiO₂</th> <th>"FeO"</th> <th>"FeO"</th> <th>Al₂O₃</th> <th>Al₂O₃</th> <th>MgO</th> <th>Na₂O</th> <th>Na₂O</th> <th>K₂O</th>	MnO/SiO ₂	"FeO"	"FeO"	Al ₂ O ₃	Al ₂ O ₃	MgO	Na ₂ O	Na ₂ O	K ₂ O	
0-15	3.0	3.0	9.6	9.6	6.2	6.2	4.6	4.0	1.6	1.6
Al ₂ O ₃ <th>MnO/SiO₂</th> <th>"FeO"</th> <th>"FeO"</th> <th>Al₂O₃</th> <th>Al₂O₃</th> <th>MgO</th> <th>Na₂O</th> <th>Na₂O</th> <th>K₂O</th>	MnO/SiO ₂	"FeO"	"FeO"	Al ₂ O ₃	Al ₂ O ₃	MgO	Na ₂ O	Na ₂ O	K ₂ O	
0-15	0-15	2.0	9.6	9.6	2.9	2.9	4.6	4.0	4.0	1.6
Al ₂ O ₃ <th>MnO/SiO₂</th> <th>"FeO"</th> <th>"FeO"</th> <th>Al₂O₃</th> <th>Al₂O₃</th> <th>MgO</th> <th>Na₂O</th> <th>Na₂O</th> <th>K₂O</th>	MnO/SiO ₂	"FeO"	"FeO"	Al ₂ O ₃	Al ₂ O ₃	MgO	Na ₂ O	Na ₂ O	K ₂ O	
0-15	0-15	3.0	9.6	9.6	2.9	2.9	4.6	4.0	1.6	1.6
"FeO" <th>MnO/SiO₂</th> <th>"FeO"</th> <th>"FeO"</th> <th>Al₂O₃</th> <th>Al₂O₃</th> <th>MgO</th> <th>Na₂O</th> <th>Na₂O</th> <th>K₂O</th>	MnO/SiO ₂	"FeO"	"FeO"	Al ₂ O ₃	Al ₂ O ₃	MgO	Na ₂ O	Na ₂ O	K ₂ O	
0-15	0-15	2.0	9.6	9.6	2.9	2.9	4.6	4.0	1.6	1.6

2.2.2. Effect of Carbon Addition on the Reduction Degree

The effect of carbon addition on the extension of the reduction was examined by FactSage 7.2 with the SiO₂ addition of 10 wt% of ore weight at 1350 °C. The recovery rate and alloy composition as a function of carbon addition are shown in Figure 4. It can be seen from Figure 4 that the NiO and CuO are first reduced and Ni and Cu concentrations in the alloy reached a maximum. With increasing carbon addition, FeO and CoO are reduced and their concentrations in the alloy gradually increase.

At 1.2 wt% carbon addition, all NiO, CuO and CoO are reduced and the alloy composition is 50Ni-12Cu-6Co-32Fe. Further addition of carbon will continuously reduce FeO_x and increase Fe in the alloy. Accordingly, the concentrations of Ni, Co and Cu will decrease as the total alloy increases. At carbon 2.5 wt%, all FeO_x is reduced and Fe in the alloy reaches maximum. MnO starts to be reduced and carbon starts to dissolve into the alloy. Further addition of carbon will increase Mn and carbon addition. FeO_x and CoO are reduced and their concentrations in the alloy gradually increase. At 1.2 wt% carbon addition, all NiO, CuO and CoO are reduced and the alloy composition is 50Ni-12Cu-6Co-32Fe. Further addition of carbon will continuously reduce FeO_x and increase Fe in the alloy. Accordingly, the concentrations of Ni, Co and Cu will decrease as the total alloy increases. At carbon 2.5 wt%, all

FeO_x is reduced and Fe in the alloy reaches maximum. MnO starts to be reduced and carbon starts to dissolve into the alloy. Further addition of carbon will increase Mn and carbon concentrations in the alloy, and decrease the concentrations of other components in the alloy. Over 6.5 wt% carbon addition, the alloy composition will be constant, which is considered as the critical amount of graphite. Thus, adding graphite greater than 6.5 wt% would not change the composition of alloy significantly.

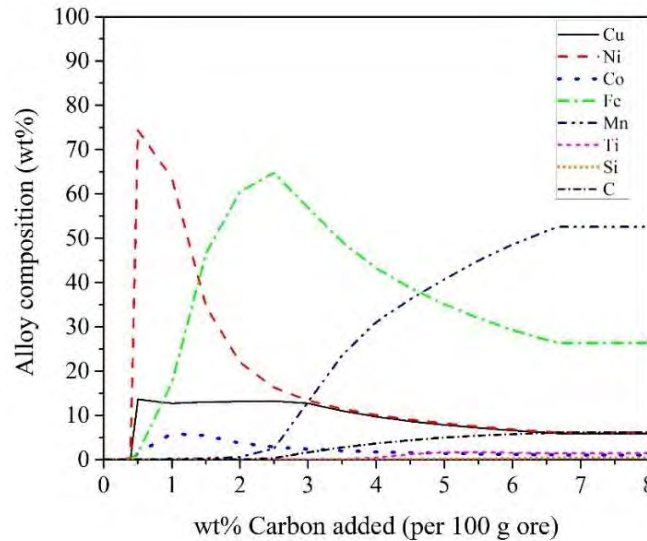


Figure 4. Reduction degree and alloy composition as a function of carbon addition for 100 g ore and 10 g SiO₂ at 1350 °C.

2.3. Experimental Procedure

2.3.1. Experimental Procedure

A vertical tube furnace with lanthanum chromate heating elements was used for the experiments. For each experimental run, 100 g of iron ore and 10 g of lanthanum chromate powder were crushed and well mixed with flux and reductant in aagate mortar and pressed into a pellet. Pure graphite powder (99.99%) was used as the reductant. The flux (SiO₂) and reductant (graphite) were added in a certain proportion. The addition of SiO₂ was adjusted based on the MnO/SiO₂ ratio and the liquidus temperature as shown in Figure 3. The experimental conditions are shown in Table 3. The pelletized sample was then placed in an alumina crucible (ID: 18 mm, H: 25 mm). The sample was heated and pre-reduced under an Ar atmosphere at 1000 °C for 60 min. Then, each pre-reduced sample was heated immediately to the smelting temperature and held there for 60 min. A Pt-30% Rh-16% Pt thermocouple placed in an alumina sheath was located adjacent to the sample to monitor the temperature. The temperature was controlled to an accuracy of ±2 K. The samples were directly quenched into the water after the smelting reduction. After drying, they were mounted in resin and polished for metallographic analysis. The microstructures were examined by scanning electron microscopy coupled with X-ray energy-dispersive spectroscopy analysis (SEM-EDS). Compositions of the liquid and solid phases were measured by electron probe X-ray microanalysis (EPMA). The EPMA operation was conducted at an accelerating voltage of 15 kV and a probe current of 15 nA. The standards used for analysis were spinel (MgAl₂O₄) for Al and Mg, wollastonite (CaSiO₃) for Ca and Si, chalcopyrite (FeCuS₂) for Cu, standards used for analysis were spinel (MgAl₂O₄) for Al and Mg, wollastonite (CaSiO₃) for Ca and rutile (TiO₂) for Ti, chromite (FeCrO₄) for Cr, albite (NaAlSi₃O₈) for Na, orthoclase (KAlSi₃O₈) for K, Si, chalcopyrite (FeCuS₂) for Cu, rutile (TiO₂) for Ti, chromite (FeCrO₄) for Cr, albite (NaAlSi₃O₈) for olivine (Ni₂SiO₄) for Ni, spessartine (Mn₃Al₂Si₃O₁₂) for Mn, hematite (Fe₂O₃) for Fe, and pure Co for Co. The ZAF correction procedure, which is a series of multiplicative factors that account for the effects of atomic number (Z—stopping power, back-scattering factor and X-ray production power), absorption (A) and fluorescence (F), built-in the electron-probe software was applied automatically to the matrix correction. The average accuracy of the EPMA measurements is within ±1 wt%. The alloy droplets were collected to be measured by Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES).

Table 3. Experimental conditions for nodule reduction.

Exp. No.	Nodules (G)	Flux	Reductant	Crucible	Pre-Reduction		Reduction Smelting	
		SiO ₂	Graphite		Temp. (°C)	Time (Min)	Temp. (°C)	Time (Min)
ND1	10	9%	0.8%	Al ₂ O ₃	1000	60	1420	60
ND2	10	9%	1.2%	Al ₂ O ₃	1000	60	1420	60
ND3	10	9%	12%	Al ₂ O ₃	1000	60	1420	60
ND4	10	17.5%	4%	Al ₂ O ₃	1000	60	1350	60
ND5	10	17.5%	8%	Al ₂ O ₃	1000	60	1350	60
ND6	10	35%	4%	Al ₂ O ₃	1000	60	1300	60
ND7	10	35%	8%	Al ₂ O ₃	1000	60	1300	60
ND8	10	15%	2%	Al ₂ O ₃	1000	60	1350	60
ND9	10	15%	4%	Al ₂ O ₃	1000	60	1350	60
ND10	10	15%	6%	Al ₂ O ₃	1000	60	1350	60
ND11	10	15%	8%	Al ₂ O ₃	1000	60	1350	60
ND12	10	10%	4%	Al ₂ O ₃	1000	60	1350	60
ND13	10	5%	4%	Al ₂ O ₃	1000	60	1350	60

Note: Exp., experimnet; Temp., temperature.

3. Results and Discussion

3.1. Pre-Reduction

Pre-reduction was conducted to calcinate nodules and enable nickel, copper, cobalt and iron oxides to be partly reduced. The microstructures of samples ND2 and ND9 after pre-reduction at 1000 °C for 60 min are shown in Figure 5. In Figure 5a, the sample ND2 contains pyroxene ((Si, Ti, Mn)O₂·(Al, Fe)₂O₃·(Mn, Fe, Mg, Ca, Ni)O), rhodonite ((Mn, Ca, Mg)O·SiO₂), spinel ((Al, Fe)₂O₃·(Mn, Fe, Mg, Ca, Ni)O), olivine 2(Mn, Mg, Ca, Ni, Fe)O·SiO₂, and glass phases. At 1000 °C, the mineral SiO₂-Al₂O₃ incorporated with low melting point oxides K₂O and Na₂O may diffuse and react with MnO-FeO phases. Some reactions occurred in the local area near the pore, where olivine and liquid together with rhodonite were formed. Metals were not observed in the samples after pre-reduction due to the insufficient reductant addition. In Figure 5b, alloy droplets were observed by the reduction with more reductant addition. Olivine and liquid phases were formed in the sample ND9. The alloy and liquid compositions are 38.4Ni-36.1Fe-19.7Cu-3.4Co-2.3Mn and 49.7SiO₂-13.4MnO-11.8Al₂O₃-12.9Na₂O-5.5K₂O-2.5FeO-2.8CaO-0.7MgO-0.6TiO₂, respectively.

3.2. Reduction Smelting

3.2.1. Effect of Reductant Addition on the Alloys and Slags

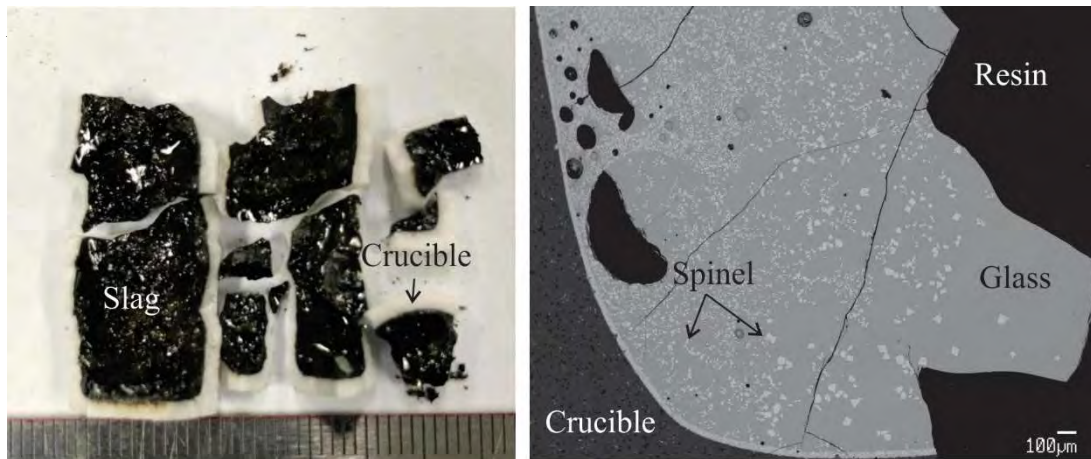
The smelting process was conducted at high temperatures to further reduce nickel, copper, cobalt, and iron oxides to form the required alloys and slags. Figure 6 shows the pictures and microstructures of samples ND8, ND9, and ND10 after smelting at 1350 °C with a carbon addition of 2, 4, and 6 wt%, respectively. It can be seen from Figure 6a that in sample ND8, the slag contains spinel crystals and the alloy is not observed. In samples ND9 and ND10, the slag is fully liquid and alloy sphere (around 5 mm in diameter) settled at the bottom of the crucible can be easily separated from the slag, and small alloy droplets are also present in the slag. A small amount of graphite was left after smelting reduction in sample ND10, which indicates the addition of graphite was in excess. Comparing Figure 6a–c, when the addition of the reductant was insufficient, the liquidus temperature of slag was much higher due to the presence of Fe³⁺. Consider the results that no alloy was observed with 2 wt% graphite addition and excess graphite was observed with 6 wt% graphite addition. Therefore, an optimal addition of graphite is around 4 wt% per residues in terms of alloy morphology and full-liquid slag. The effect of the addition of graphite on the reduction extent of copper, nickel, cobalt, iron and manganese oxides will be discussed in the following section.

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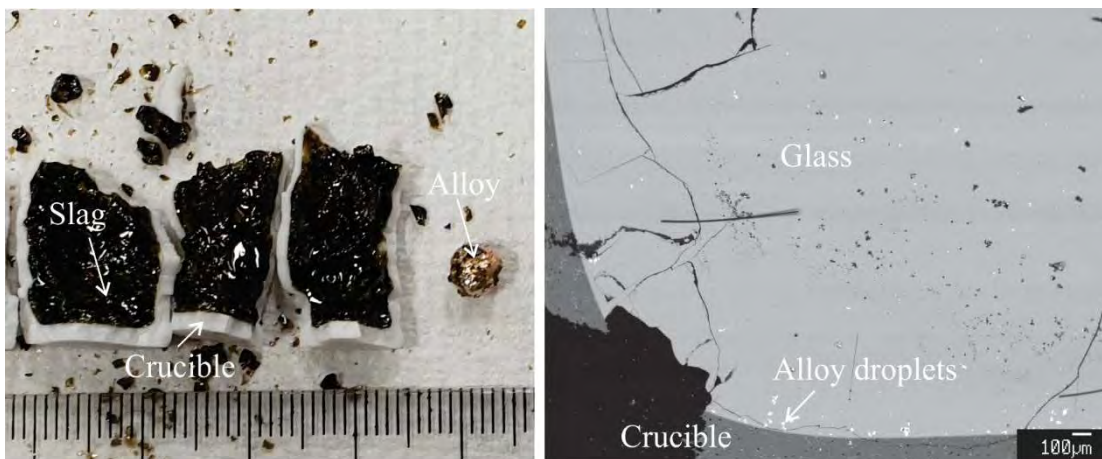
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3.2.

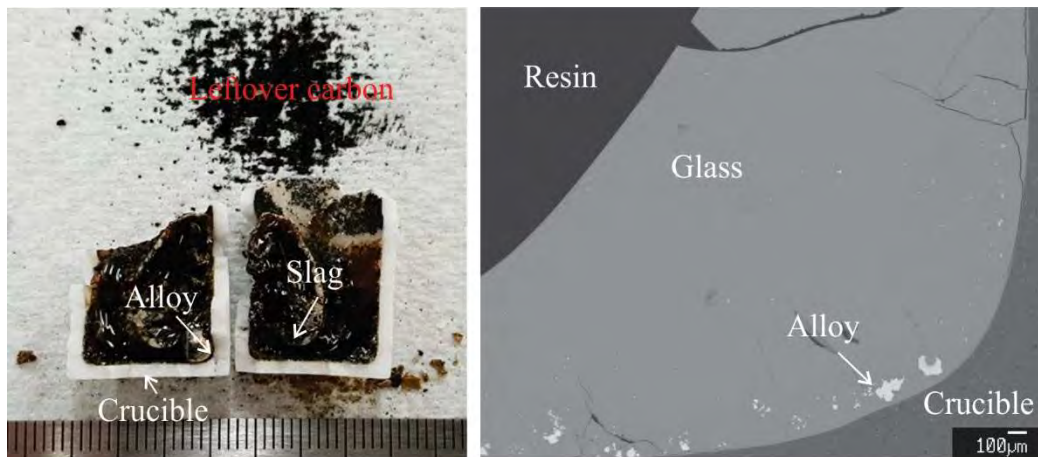


(a) Sample ND8 (2 wt% graphite addition)



(b) Sample ND9 (4 wt% graphite addition)

Figure 6. Cont.



(c) Sample ND10 (6 wt% graphite addition)

Figure 6. Pictures and microstructures of quenched samples after smelting at 1350 °C: (a) Sample ND8 (2 wt% graphite addition); (b) sample ND9 (4 wt% graphite addition); (c) sample ND10 (6 wt% graphite addition).

3.2.2. Effect of Flux Addition

SiO₂ as a flux was added to decrease the liquidus temperature of slag, which enables the slag to be a fully-liquid at the smelting temperature. FactSage calculations shown in Figure 3 demonstrated that the liquidus temperature of the slag decreases rapidly with the addition of up to 50 wt% SiO₂. Different amounts of SiO₂ were added to verify the predictions at a given temperature of 1350 °C. The dependence of SiO₂ addition on the formation of slags with the same amount of graphite additive is shown in Figure 7. It is evident from Figure 7a–c that the slags were fully liquid at the experimental temperature with SiO₂ addition over 10 wt%. However, as shown in Figure 7d, with the SiO₂ addition down to 5 wt%, the liquidus temperature of the slag was above the experimental temperature, resulting in the presence of some primary monoxide phase precipitated in the slag, and the alloy heels are distributed in the remainder of the monoxide solids. In addition to the liquidus temperature, the viscosity of slag can influence the settlement of alloys and tappings of slag. The viscosity of slag in the fully liquid state at 1350 °C with the addition of different amounts of SiO₂ was calculated by FactSage 7.2. Figure 8 shows the viscosity of slag increases with increasing SiO₂. The addition of SiO₂ needs to be minimized to keep the slag in a fully liquid state with a relatively low viscosity. Overall, SiO₂ addition can be optimized by several factors including the liquidus temperature of slag for operational temperature, the viscosity of slag for separation of alloy and slag tapping, and MnO grade of the residue slag for further production of ferromanganese alloys or ferromanganese or silicomanganese alloys.

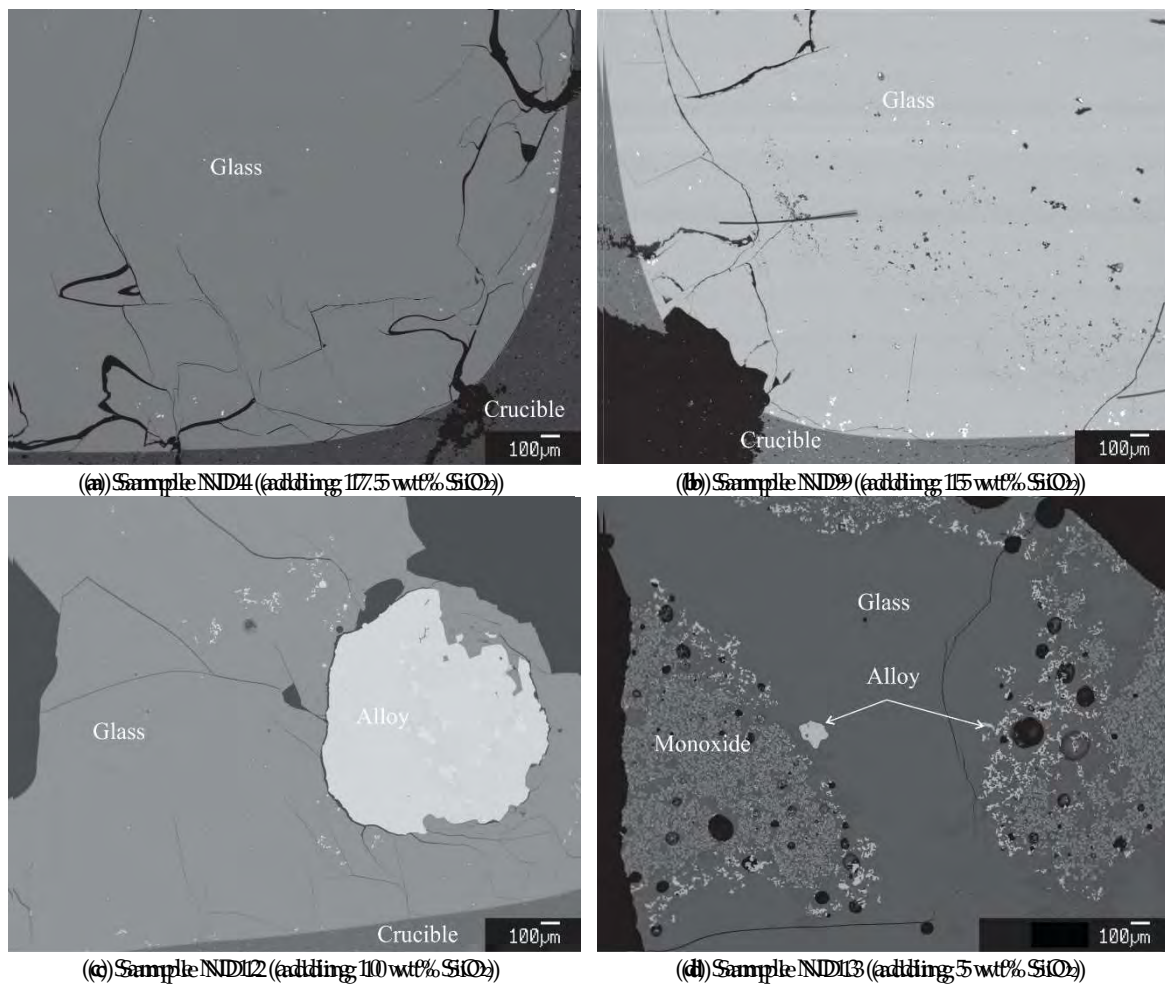


Figure 7. Microstructures of slags of the quenched samples with different SiO₂ addition.

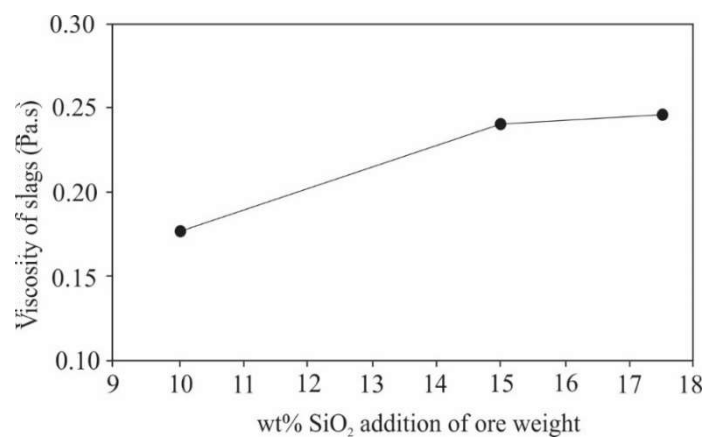


Figure 8. The viscosity of slags as a function of SiO₂ addition (wt%) of ore weight.

3.3. Effect of Graphite Addition on the Alloy Grade

The liquidus temperature of slags has been predicted by FactSage, and verified by the experiments with a variation of SiO₂ flux and carbon addition in the above sections. The liquidus temperature of slags decreases with the SiO₂ addition and reduction of Fe³⁺ to Fe²⁺ in the slag by carbon. The reduction degree of FeO in the slag and reduced Fe in the alloy as a function of carbon are shown in Figure 9, where experimental results of samples ND8 to ND11 with 15 wt% SiO₂ addition at 1350 °C are compared with FactSage calculation. The compositions of alloys and phases present in the quenched samples are listed in Table 4. Figure 9 shows FeO concentration in the slag

compared with FactSage calculation. The compositions of alloys and phases present in the quenched samples are along with Table 4. Figure 9 shows FeO concentration in the alloy increases along with iron addition. A slight FeO concentration in the alloy between experimental results and FactSage calculation for the FeO. The difference between experimental calculation and FactSage calculation is only FeO. FactSage calculation enriches FeO in the slag is expedited by which approximately 6% carbon is needed fully to reduce the FeO in the slag. One of the reasons is that a small fraction of MnO was in the slag. During the reaction, a small fraction of MnO was reduced during the theoretical reduction, which results in the metal oxides that have potential to be reduced (e.g., MnO) rather than to be reduced (e.g., MnO) that require additional carbon to reduce them.

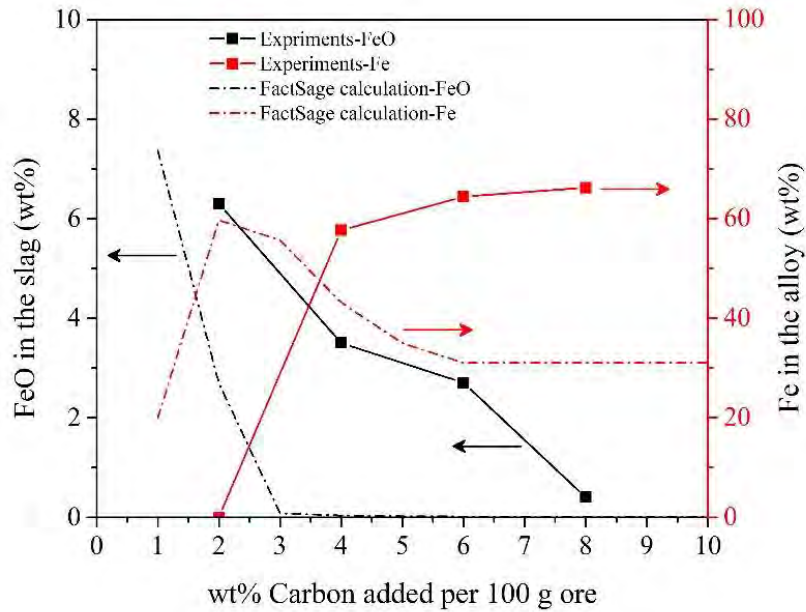


Figure 9. A comparison between experimental results and FactSage calculation on the FeO and Fe concentration in the slag and alloy with the addition of carbon.

Full reduction of CuO, NiO, and CoO are desired to allow for high recovery rates, while the iron oxide can be partly/sufficiently reduced depending on the amount of reductant. Recovery of Cu, Ni, and Co is taken as a whole, and the alloy grade is defined as the weight percentage of the sum of Cu, Ni, and Co. The effect of graphite addition on the alloy grade is shown in Figure 10, where the data is plotted from Table 4. The alloy grade decreases with increasing graphite addition. The sequential ease of reduction of metal oxides is (Cu, Ni, Co) > Fe > (Mn, Si). The (Cu + Ni + Co) concentration gradually decreases in the alloy along with the reduction of Fe and Mn oxides. Figure 10 can be divided into three areas, where “Area I” represents the insufficient addition of reductant and no alloys are reduced; “Area II” means excess addition of reductant, beyond that, MnO (or even SiO₂) in the slag will be significantly reduced into the alloys; and “Area III” represents the insufficient addition of reductant, beyond that, MnO (or even SiO₂) in the slag will be significantly reduced into the alloys. SiO₂ and MnO are not required to be reduced at the smelting reduction stage to produce high-grade Fe-Ni-Cu-Co alloy. “Area II” in Figure 10 is thus the working area to optimize the addition of reductant to control the alloy grade and recovery of valuable metals. Within “Area II”, iron oxide is gradually reduced into the alloy along with graphite addition. Iron oxide is almost fully reduced with 8 wt% graphite addition.

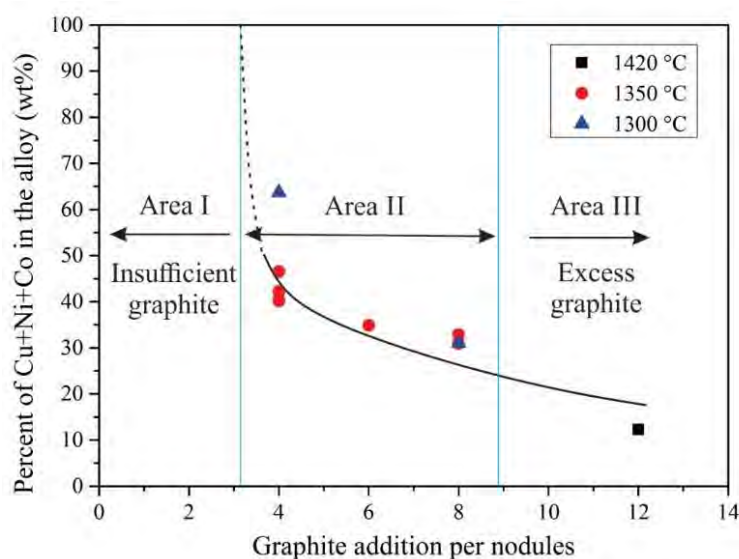


Figure 10. Relationship between alloy grade (Cu + Ni + Co) and graphite addition.

Figure 10. Relationship between alloy grade (Cu + Ni + Co) and graphite addition.

Table 4. The compositions of the phases present in the quenched samples (wt%).

Sample No.	Slag	MnO	SiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	Cu ₂ O	NiO	CoO
Sample No.	Slag	MnO	SiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	Cu ₂ O	NiO	CoO
ND1	Glass	36.4	29.8	8.2	19.7	3.8	0.1	0.0	0.0	0.8	0.7	4.1	0.4
ND2	Glass	36.0	29.8	8.2	19.7	3.8	0.1	0.0	0.0	0.8	0.7	4.1	0.4
ND3	Glass	36.0	29.8	8.2	19.7	3.8	0.1	0.0	0.0	0.8	0.7	4.1	0.4
ND4	Spinel	62.2	0.5	8.2	19.7	3.3	0.0	0.0	0.0	0.8	0.7	4.1	0.4
ND5	Glass	36.0	29.8	8.2	19.7	3.8	0.1	0.0	0.0	0.8	0.7	4.1	0.4
ND6	Glass	36.1	31.7	10.5	6.8	3.1	2.4	3.7	1.1	0.7	0.1	0.0	0.0
ND7	Glass	38.0	44.7	4.8	0.7	3.6	2.2	4.1	1.2	0.5	0.0	0.0	0.0
ND8	Glass	44.0	34.3	6.8	1.2	4.3	2.6	4.8	1.3	0.7	0.0	0.1	0.0
ND9	Glass	40.3	32.2	5.0	6.3	3.3	2.0	3.7	1.1	0.5	1.1	1.5	0.0
ND10	Glass	47.1	0.4	9.8	31.2	2.8	0.0	0.0	0.0	1.5	0.2	6.7	0.4
ND11	Spinel	38.0	44.7	4.8	0.7	3.6	2.2	4.1	1.2	0.5	0.0	0.0	0.0
ND12	Glass	42.0	31.4	1.6	3.5	3.9	2.5	3.1	1.7	0.6	0.4	0.5	0.3
ND13	Glass	47.9	32.8	7.6	2.7	4.2	2.5	5.5	1.1	0.6	0.0	0.0	0.0
ND14	Spinel	47.1	0.4	9.8	31.2	2.8	0.0	0.0	0.0	1.5	0.2	6.7	0.4
ND15	Glass	44.0	31.4	11.0	2.5	4.9	2.4	5.0	1.5	0.6	0.1	0.0	0.0
ND16	Glass	42.9	32.9	7.5	3.4	4.2	2.5	6.5	1.1	0.6	0.0	0.0	0.0
ND17	Glass	47.1	0.4	9.8	31.2	2.8	0.0	0.0	0.0	1.5	0.2	6.7	0.4
ND18	Monoxide	48.5	33.0	8.8	0.8	5.2	0.5	0.8	0.1	0.6	0.1	0.0	0.0
Sample No.	Alloy	Mn	Si	Al	Fe	Mg	Ca	Na	K	Ti	Cu	Ni	Co
ND19	Glass	44.5	28.1	11.2	2.1	4.2	2.5	5.5	1.0	0.6	0.0	0.0	0.0
ND20	Glass	47.1	22.9	10.5	3.4	4.2	2.8	6.7	1.1	0.7	0.0	0.0	0.0
ND21	Alloy	60.7	1.0	0.0	25.9	0.0	0.0	0.0	0.0	0.1	5.6	5.9	0.8
ND22	Monoxide	86.3	0.0	0.0	5.8	5.9	0.1	0.1	0.0	0.1	20.1	23.1	3.1
Sample No.	Alloy	Mn	Si	Al	Fe	Mg	Ca	Na	K	Ti	Cu	Ni	Co
ND23	Alloy	1.1	0.0	0.0	67.9	0.0	0.0	0.0	0.0	0.0	12.8	15.5	2.0
ND24	Alloy	0.1	0.0	0.0	36.1	0.0	0.0	0.0	0.0	0.0	24.8	34.5	4.4
ND25	Alloy	60.7	10.0	0.0	65.9	0.0	0.0	0.0	0.0	0.1	10.6	17.9	2.8
ND26	Alloy	0.2	0.0	0.0	53.2	0.0	0.0	0.0	0.0	0.0	18.2	20.1	3.2
ND27	Alloy	0.4	0.0	0.0	64.4	0.0	0.0	0.0	0.0	0.0	14.4	17.7	2.8
ND28	Alloy	1.1	0.0	0.0	66.2	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND29	Alloy	0.9	0.0	0.0	66.2	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND30	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND31	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND32	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND33	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND34	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND35	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND36	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND37	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND38	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND39	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND40	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND41	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND42	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND43	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND44	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND45	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND46	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND47	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND48	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND49	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND50	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND51	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND52	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND53	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND54	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND55	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND56	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND57	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND58	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND59	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND60	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND61	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND62	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND63	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND64	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND65	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND66	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND67	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND68	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND69	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND70	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND71	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND72	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND73	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND74	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND75	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND76	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND77	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND78	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND79	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND80	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND81	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND82	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND83	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND84	Alloy	0.5	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	13.8	16.5	2.5
ND85	Alloy	0.5	0.0	0.0	58.5								

- (1) The as-received nodules mainly contain Mn and Fe oxides in striation. Si is incorporated with Al, Na, K and Ca as impurity minerals. Valuable metal elements such as Cu, Co and Ni in low concentrations are uniformly distributed in the nodule matrix. Ba is found to be associated with S, most likely as barite.
- (2) FactSage software was used to simulate/predict the liquidus temperature of the slag system, which is not sensitive to FeO, CaO and Al₂O₃, but decreases most significantly with decreasing MnO/SiO₂ mass ratio. The SiO₂ flux to decrease the liquidus temperature of slag was experimentally verified.
- (3) The alloy grade was found to decrease with increasing graphite addition. The optimal reduction was achieved by adding a 4 wt% graphite at the MnO/SiO₂ mass ratio of 1.6 in slag. The most effective metal-slag separation was achieved at 1350 °C. This relatively low-temperature smelting process for the utilization of polymetallic nodules is promising for industrial applications.

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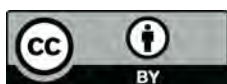
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Alternative Resources for Producing Nickel Matte - Laterite Ores and Polymetallic Nodules

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ABSTRACT

Polymetallic nodules and nickel laterite ores are composed of various valuable metals and have similar nickel concentration, which makes them ideal alternatives for industries seeking to meet the increasing demand for nickel resources. The extraction process of polymetallic nodules can utilize the well-established nickel laterite treatment process without the need for developing new processes and thus, save capital costs. Herein, to efficiently extract nickel from these resources, high-temperature carbothermic reduction and sulfurization were investigated by optimizing the slag and matte systems. FactSage, a thermodynamic software was used to predict the slag system's liquidus temperature and the formation of nickel matte. It was found that nickel matte formation was not dependent on CaSO₄ addition whereas the nickel concentration in matte decreased with an increasing amount of the sulfiding agent FeS. Furthermore, the addition of a reductant significantly affected the concentration of nickel in the matte. A nickel concentration of ≥ 30 wt% and iron concentration of ≤ 40 wt% in matte were achieved by adding 0.5 wt% and 3 wt% carbon to nickel laterite ores and polymetallic nodules, respectively. Furthermore, replacing the sulfiding agent FeS with CaSO₄ during the smelting of polymetallic nodules decreased the iron concentration in matte ≤ 15 wt% and increased the nickel concentration ≥ 50 wt%. Thus, this study confirmed the possibility of matte formation with high nickel concentration and low iron content by utilizing alternative nickel resources at 1350–1450°C.

KEYWORDS

Marine mineral resources; thermal reduction/sulfurization; slag optimization; pyrometallurgy; thermodynamic modeling

1. Introduction

Mineral resources are invaluable for the development of society. Nickel is essential for the development of iron, steel, and battery industries. In particular, nickel-containing alloys are vital materials in aerospace, electronics, and marine applications (Mäkinen and Taskinen 2008). Recently published data shows that out of 130 million tons of global land-based nickel reserves, about 60% exist in laterite and 40% in sulfide deposits (McRae 2020). Because of the relatively high-energy consumption and complexity in processing nickel-laterite compared to nickel sulfide ores, nickel has been mainly produced from nickel-copper sulfide ores instead of nickel-cobalt laterite since the late 20th century (Mudd 2010; Schmidt, Buchert and Schebek 2016). With the ongoing diminution of nickel sulfide ores and increasing industrial demand for nickel, a sharp decrease in the contribution from sulfide nickel resources to the nickel industry has been observed (Geng et al. 2019; Zhang et al. 2020). Consequently, there has been a steady increase in the consumption of laterite ores, this trend will likely continue to increase in the foreseeable future (Ghorbani, Franzidis and Petersen 2016; Mudd 2010; Schmidt, Buchert and Schebek 2016). Nickel extraction methods from alternative resources have gained research attention because the extraction of nickel from nickel sulfide ores involves issues, such as high mining costs and environmental pollutants (Zhang et al. 2020). Polymetallic nodules

on the ocean floor have been shown to contain high nickel content (Kuhn et al. 2017). A conservative estimation shows that the nodules in the Clarion-Clipperton Zone (CCZ) contains 1.8 times more Ni than the entire global land-based reserves (Hein et al. 2013). Similar to nickel laterite ores, polymetallic nodules have a complicated composition, which leads to similar challenges in the development of metallurgical process routes, such as requirement of high energy consumption, high operating temperatures and complicated extraction methods. Inspired by the International Nickel Company and the direct Outokumpu nickel smelting processes, this study aimed to develop a processing route to produce nickel matte from both nickel laterite and polymetallic nodules via pyrometallurgical process, which could then be further processed through hydrometallurgical practices to produce high-grade nickel products (Geng et al. 2019; Kerfoot et al. 2000).

Nickel laterites are typically formed by the prolonged weathering of ultramafic rocks, most commonly ophiolitic peridotite, in tropical and/or subtropical regions (Dong et al. 2018). Laterite deposits are found worldwide, but the majority are located in Indonesia, Papua New Guinea, Australia, Cuba, New Caledonia and the Philippines (Moskalyk and Alfantazi 2002a). Generally, nickel laterite comprises two types of ores – saprolitic and limonitic – with key metal hosting minerals of silicate/hydrosilicate and oxide/hydroxide types (Chen et al. 2004). In general, most of the

saprolitic ores are processed through pyrometallurgical routes to produce nickel class II products (contain less than 99% nickel) including ferronickel (through the rotary kiln electric furnace process, RKEF) and; nickel pig iron (through the blast furnace/electric arc furnace) (Dong et al. 2018; Moskalyk and Alfantazi 2002b; Schmidt, Buchert and Schebek 2016). Most limonitic ores are processed either through hydrometallurgical routes such as high-pressure acid leaching to produce class I nickel products (contain greater than 99% nickel) or the Caron process (hydro- and pyrometallurgical processes) to produce an oxide sinter (Whittington and Muir 2000). Limited by the high temperature and pressure requirements during the processing of limonitic ores, the majority of class I nickel products are processed from sulfide ores because they can be concentrated through flotation before well-established pyrometallurgical processes. However, with the depletion of sulfide ores, a development of new technologies for extracting class I nickel via pyrometallurgical processes is needed.

Polymetallic nodules were found first in the Pacific Ocean at a depth between 4000 and 6000 m during the scientific expeditions of the HMS Challenger between 1872 and 1876 (Das and Anand 2017; Hein and Koschinsky 2014; Monhemius 1980). The nodules have drawn significant attention since 1970s as they contain high amounts of valuable metals that are essential for the green-technology and high-technology industries (Hein and Koschinsky 2014). The CCZ in the East Pacific Ocean is of particular interest for mining because it hosts enormous quantities of nodules (minimum 21 Gt with an areal density up to 10–15 kg/m²). The nodules have a high metal grade and local abundance, making their use economical for metal production (ISA 2010). The CCZ nodules contain high contents of various metals, such as manganese (typically 26–30 wt%), nickel (1.2–1.4 wt%), copper (0.9–1.3 wt%), and cobalt (0.15–0.25 wt%) (ISA 2010; Sen 1999). They are therefore triggering a high interest for deep-ocean mining operations. National agencies and private companies have carried out numerous research activities over the past four decades (Van Nijen, Van Passel and Squires 2018). Although no commercial mining has been reported yet, it was estimated that polymetallic-nodule mining is likely to begin in earnest in the mid to late 2020s (Hein, Koschinsky and Kuhn 2020).

Previous research found that conventional mineral separation techniques cannot be used to process polymetallic nodules because non-ferrous metals are not present as isolated minerals (Das and Anand 2017; Faris et al. 2017). Therefore, a complete destruction of the matrix in the nodules is needed to extract valuable metals (Zhao et al. 2019). Extracting valuable metals from alloys obtained by pyrometallurgy routes requires high acid consumptions in the following hydrometallurgical processes (Sridhar, Jones and Warner 1976). Hence, extraction of nickel from polymetallic nodules as nickel mattes through a direct smelting process is promising by avoiding high operating costs associated with high acid consumption in the following wet process. Extraction of nickel from nickel matte through acid leaching is a commercialized approach. Other metals including Cu and Co need to be extracted by methods, such as electrowinning or hydrogen reduction. The optimized smelting conditions required to achieve high recovery of nickel and high-grade matte were investigated. Slag and matte formation through the addition of different sulfiding agents and

fluxes were studied to determine the optimized conditions. In particular, the effects of adding calcium sulfide and/or ferrous sulfide as sulfiding agents on the matte formation were examined. Systematic and comprehensive thermodynamic assessments and modeling were also carried out to evaluate the effect of key parameters including slag reduction degree, smelting temperature, amount of reductant, and sulfiding agents on matte formation. The present study purposed and reserved a sustainable process to extract valuable metals from raw materials with complicated mineralogy. Research proposed a two-stage pyrometallurgical process to extract valuable metals from nickel resources but our research explores the option of a one-stage process at lower temperatures and could potentially be accompanied by lower energy consumptions and operating time (Sommerfeld et al. 2018; Sridhar, Jones and Warner 1976; Stefanova, Iliev and Stefanov 2013). Combined pyro-hydrometallurgy processes utilize low-grade nickel resources to produce high-grade nickel products with low energy consumption and environmental impact as no mineral processing stages are needed, thereby meeting several goals of sustainable development. The diminution of sulfide ores and the increasing demand for nickel resources could be solved by utilizing laterite ores and polymetallic nodules.

2. Materials and methods

2.1. Thermodynamic consideration and modeling approach

FactSage 7.3, a thermochemical software and its optimized compound and solution databases, were used to calculate thermodynamic assessments and models (Bale et al. 2016). The FactSage databases used were FactPS (for pure substance), FToxid (for oxides), and FTmisc (for miscellaneous). Thermodynamically, it is possible to reduce oxides of nickel, cobalt, copper and iron into metals and leave the manganese oxide in slag, see Ellingham diagram in Figure 1. Equilib mode of FactSage uses Gibbs free energy minimization calculations to simulate the state of chemical equilibrium. The behavior of the liquidus temperature during flux (SiO₂ or CaO) addition was studied to optimize the operating temperature during nickel matte production. The reactions between graphite reductants and raw materials (laterite ores and polymetallic nodules) were evaluated. The effects of adding different sulfiding agents (FeS or CaSO₄) to the nickel matte production were also investigated. Note that for these simulations, the crystal water and moisture in the raw materials were assumed to have evaporated and decomposed. The calculations were also carried out assuming a closed system and with ideal gas behavior. The input information for FactSage calculation were summarized in Table 1 below.

2.2. Thermodynamic analysis of laterite ores

The nickel laterite ore received from Dongying Fanyuan Nonferrous Metals Co., Ltd. has the chemical composition analyzed by X-ray fluorescence (XRF) and listed in Table 2. However, nickel laterite mineralogy can be complicated and vary between samples (Watling et al. 2011). It was assumed that nickel and iron

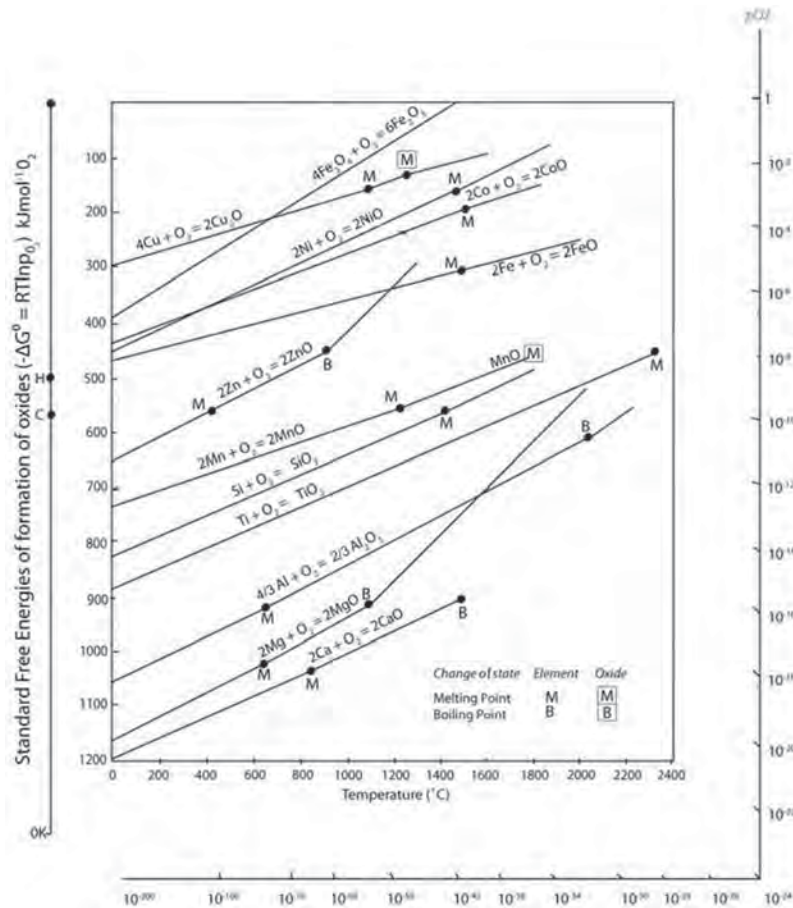


Figure 1. Ellingham diagram for different related oxides (Ellingham 1944).

Table 1. The used composition for FactSage calculation (g).

Figure 2a	CaO	FeS	FeO	MgO	SiO ₂	Al ₂ O ₃	Cr ₂ O ₃		
	0–15	5–20	20.0	14.7	44.2	4.0	0.6		
Figure 2b	Al ₂ O ₃	FeS	FeO	MgO	SiO ₂	Al ₂ O ₃	Cr ₂ O ₃		
	0–15	5–20	20.0	14.7	44.2	4.0	0.6		
Figure 3	C	FeS	NiO	Fe ₂ O ₃	MgO	SiO ₂	Al ₂ O ₃	Cr ₂ O ₃	CaO
	1–5	1–15	2.2	20.0	14.7	44.2	4.0	0.6	8.7
Figure 4	C	MnO	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	MgO	Na ₂ O	CaO	
	1–10	40.25	23.48	8.28	4.67	3.48	3.01	2.16	
	NiO	CuO	K ₂ O	TiO ₂	P ₂ O ₅	BaO	ZnO	CoO	
	1.71	1.65	1.24	0.52	0.22	0.2	0.17	0.3	
Figure 5a	C	FeS	MnO	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	MgO	Na ₂ O	
	1–10	1–7	40.25	23.48	8.28	4.67	3.48	3.01	
CaO	NiO	CuO	K ₂ O	TiO ₂	P ₂ O ₅	BaO	ZnO	CoO	
	2.16	1.71	1.65	1.24	0.52	0.22	0.2	0.17	
Figure 5b	C	CaSO ₄	MnO	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	MgO	Na ₂ O	
	1–10	1–7	40.25	23.48	8.28	4.67	3.48	3.01	
CaO	NiO	CuO	K ₂ O	TiO ₂	P ₂ O ₅	BaO	ZnO	CoO	
	2.16	1.71	1.65	1.24	0.52	0.22	0.2	0.17	
Figure 11	FeS	NiO	Fe ₂ O ₃	MgO	SiO ₂	Al ₂ O ₃	Cr ₂ O ₃	CaO	
	2–15	2.2	20.0	14.7	44.2	4.0	0.6	8.7	
Figure 12	C	FeS	NiO	Fe ₂ O ₃	MgO	SiO ₂	Al ₂ O ₃	Cr ₂ O ₃	
	0–3	5	2.2	20.0	14.7	44.2	4.0	0.6	

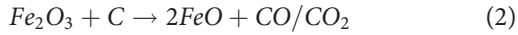
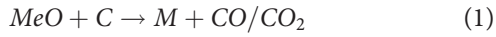
Table 2. Chemical composition of the nickel laterite ores (wt%).

Ore	NiO	Fe ₂ O ₃	MgO	SiO ₂	Al ₂ O ₃	Cr ₂ O ₃	MnO	CaO	LOI*
Type-I	2.2	20.0	14.7	44.2	4.0	0.6	0.3	0.7	13.3

LOI*: Loss on ignition.

oxide exist in the form of NiO and Fe₂O₃, respectively. Thermodynamically, the reduction of nickel oxide at high temperatures must occur before the reduction of iron oxide. This is

due to the difference in the standard Gibbs free energies of formation between nickel and iron oxides, which is shown in Figure 1. Therefore, NiO can be selectively reduced over Fe₂O₃ or FeO with an addition of carbon, which are simplified in reactions (1) and (2). By adding the sulfiding agents, the reduced Ni forms nickel matte along with the partially reduced iron from iron oxides and lowers the matte/alloy liquidus and influences the nickel matte composition.



where Me = Fe, Ni, Co, Cu.

A previous study estimated that the liquidus temperature of laterite ores is approximately 1450°C (Ma, Cui and Zhao 2016), which leads to a relatively high operating temperature and associated energy consumption. To ensure that the slag reaches a completely molten state, oxides (e.g., CaO and Al₂O₃) are commonly added as fluxes. FactSage 7.3 was used to predict the liquidus temperatures of the system SiO₂-MgO-FeO-Al₂O₃-Cr₂O₃-CaO under an iron saturation condition based on the normalization of major components shown in Table 2. It was assumed that any nickel oxide is completely reduced and any iron oxide is present in the form of FeO under reduction conditions. Elemental oxides ≤0.5 wt% were excluded to simplify the calculations for practical purpose. The effects of adding CaO and Al₂O₃ as a flux on the liquidus temperature of the slag are shown in Figure 2. The concentration of FeO in the slag changes dynamically under the reduction conditions. Hence, the behavior of the liquidus temperature at different FeO and flux concentration is important to understand. It can be seen from Figure 2a that the liquidus temperature decreased

with increasing CaO concentration within the pyroxene primary phase field. The liquidus temperature increased as the FeO concentration in the slag decreases. The liquidus temperature decreased only till the addition of ≥10 wt% CaO in the olivine primary phase field. Similarly, Figure 2b shows that the liquidus temperature decreased with increasing Al₂O₃ concentration in the pyroxene primary phase field. However, when entering the cordierite primary phase field, the liquidus temperature increased as the Al₂O₃ concentration increases. The results showed that addition of both CaO and Al₂O₃ (up to 10 wt%) have significant effects on the liquidus temperature. As the flux exceeds 10 wt%, Figure 2 showed limited ability to further reduce the liquidus temperature, whereas Al₂O₃ dramatically increased the liquidus temperature.

The effect of carbon addition and sulfiding agents (FeS) on nickel matte production with 8 wt% CaO flux at 1450°C was modeled in FactSage 7.3. By adding 8 wt% CaO into the slag, the liquidus temperature can be controlled approximately below 1360°C, which gives an ~100°C margin to ensure the slag is completely melted. Figure 3 shows the mass and nickel concentration in matte as a function of the amount of added carbon for various FeS amounts. The sulfiding agent (FeS) limited the amount of nickel matte formed during the reaction as shown in Figure 3a. With constant addition of carbon, a large amount of

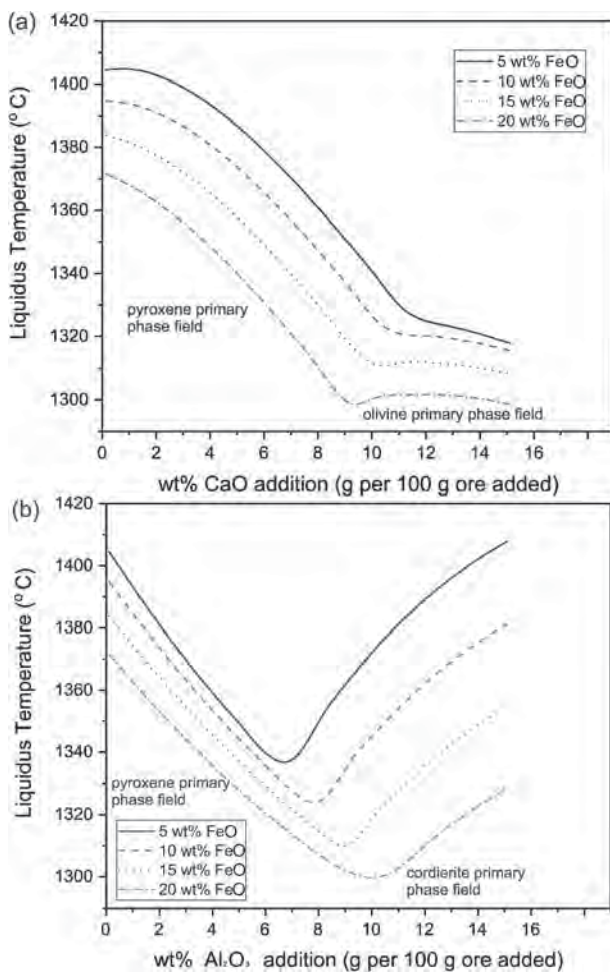


Figure 2. Effects of CaO and Al₂O₃ on liquidus temperature of laterite ores at different FeO concentration in equilibrium with iron calculated with FactSage 7.3: (a) CaO in the slag, (b) Al₂O₃ in the slag.

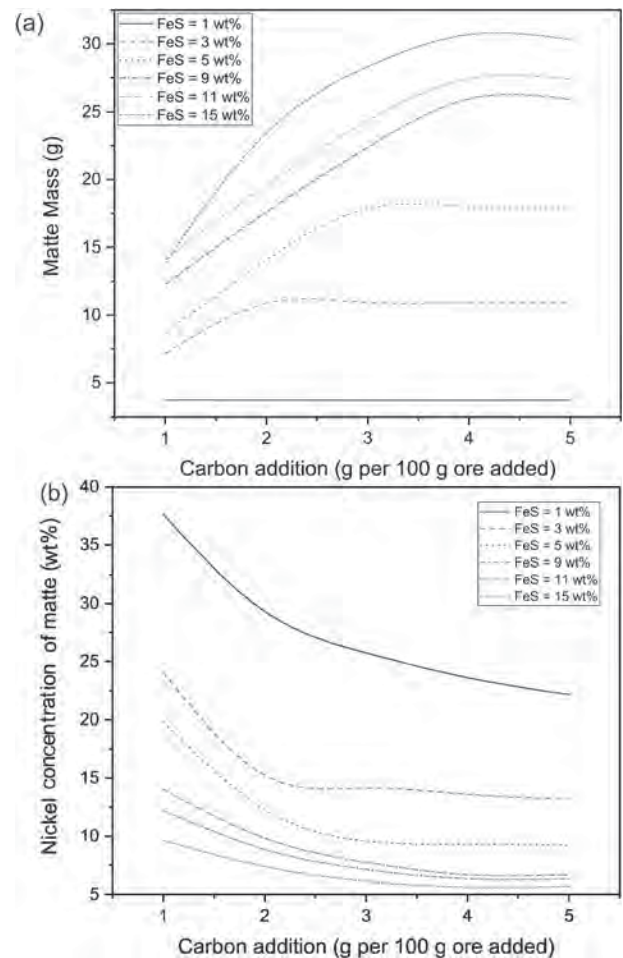


Figure 3. Effects of additives and carbon on nickel matte production calculated with FactSage 7.3 (assuming 8 wt% CaO flux added): (a) mass of matte as a function of the amount of added carbon, (b) nickel concentration of matte as a function of the amount of added carbon.

nickel matte was produced because of the increasing in the amount of iron (from FeS) that entered the matte system. Figure 3b shows that increasing the amount of FeS resulted in a lower nickel concentration when the same amount of carbon was added. With increasing amount of carbon and FeS additives, the formation of matte gradually increased simultaneously lowering nickel concentration in the matte. The content of nickel in the matte decreases dramatically when 1–2 wt% carbon was added. The nickel oxide in the ore was completely reduced, and iron oxide started to reduce when ≥ 1 wt% carbon was added. Therefore, addition of 1 wt% carbon is considered as the critical amount, above which the nickel concentration in the matte is significantly lowered.

2.3. Thermodynamic analysis of polymetallic nodules

The nodules used in this study were dredged from the CCZ of the Pacific Ocean by Tonga Offshore Mining Limited. Table 3 shows the chemical composition of the nodules analyzed by XRF. The nodules contain 1.71 wt% nickel oxides, which is slightly lower than the nickel concentration of the tested laterite ore sample. Thermodynamically, the reduction of NiO and Fe₂O₃ into a Ni-Fe-S matte system would also reduce copper and cobalt oxides because of the differences in Gibbs free energy shown in Figure 1. The selective reduction of NiO, CuO, CoO over Fe₂O₃ or FeO can be simplified in reaction (1) and (2) with an addition of carbon. Iron oxides can either be completely or partially reduced in the reaction to control the composition of matte and adjust the slag composition. Our previous study reported that the liquidus temperature of the MnO-SiO₂-FeO-Al₂O₃-MgO-Na₂O-CaO-K₂O system without any flux addition is $\geq 1570^\circ\text{C}$, and the MnO/SiO₂ ratio has a significant impact on the liquidus temperature (Su et al. 2020). The effects of SiO₂ on the slag liquidus temperature are in agreement with findings from other researchers (Sommerfeld et al. 2018). Modeling shows that the addition of 10–50 wt% SiO₂ reduced the liquidus temperature to $\leq 1300^\circ\text{C}$, which was proven experimentally. The addition of 10 wt% SiO₂ allowed the slag to reach a completely molten state at 1350°C (Su et al. 2020). Comparing the nodule compositions in the literature, nodules obtained from various license areas are similar especially the concentration of slag forming oxides. The MnO, SiO₂, Al₂O₃, Fe₂O₃ and MgO concentrations varying from 36.67% to 40.25%, 12.2 to 13.48%, 4.24 to 4.67%, 7.25 to 8.28%, and 3.37 to 3.48%, respectively (Abramovski et al. 2017; Kohga et al. 1995; Sommerfeld et al. 2018). Thus, it is expected that the proposed process could be capable of treating nodules from other locations in the CCZ without major changes in operation.

Based on the nodule composition listed in Table 3, FactSage 7.3 was also used to predict the effect of carbon addition on the extent of oxide reduction and the effect of the addition of sulfiding agents on the formation of matte. The alloy and slag composition as a function of carbon addition are shown in Figure 4.

Table 3. Chemical composition of polymetallic nodules (wt%).

MnO	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	MgO	Na ₂ O	CaO	NiO	CuO	CoO
40.25	13.48	8.28	4.67	3.48	3.01	2.16	1.71	1.65	0.30
K ₂ O	TiO ₂	P ₂ O ₅	BaO	ZnO	S	PbO	Cr ₂ O ₃	LOI*	MnO/SiO ₂
1.24	0.52	0.32	0.22	0.20	0.09	0.03	0.01	17.28	3.0

LOI* = Loss on ignition.

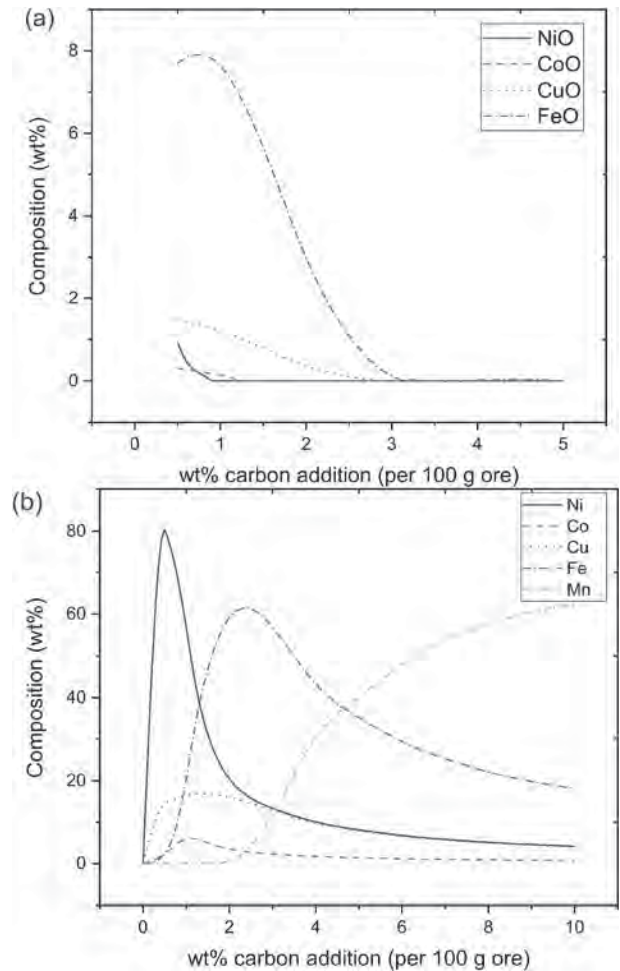


Figure 4. Slag and liquid metal composition as a function of the carbon addition (100 g ore and 10 g SiO₂ at 1350°C): (a) slag composition; (b) alloy composition.

Furthermore, FactSage 7.3 was used to examine the degree of reduction by adding carbon along with 10 wt% SiO₂. As shown in Figure 4a, NiO and CuO were first reduced, followed by CoO and FeO. Figure 4b shows that the concentration of Cu and Ni in the alloy reach their maximum and then decreases with increasing amount of added carbon. With decreasing Ni concentration, Co and Fe were progressively reduced and their concentrations in the alloy phase gradually increased. When 0.9 wt% carbon was added, NiO was completely reduced and the alloy composition was 64Ni-16Cu-14Fe-6Co. The iron oxide composition decreased as the amount of carbon was increased, which resulted in the decrease of the nickel concentration in the alloy phase. When 3 wt% carbon was added, all iron oxide was reduced and the Fe concentration in the alloy phase reached a maximum. Meanwhile, MnO started to reduce when ≥ 2 wt% carbon was added. The presence of Mn in the alloy phase should be avoided to minimize impurities in the nickel alloy. Therefore, the addition of 2 wt% carbon is considered as the optimum amount.

Figure 5a,b show the FactSage results for nickel concentration in the alloy as a function of the amount added carbon for various amounts of FeS or CaSO₄, which were added as sulfiding agents. As shown in Figure 5a, the nickel concentration dropped significantly while adding carbon to the process. When ≥ 3 wt% carbon was added, nickel reached its lowest concentration at 7 wt% FeS. The addition of CaSO₄ caused an effect similar to FeS. However,

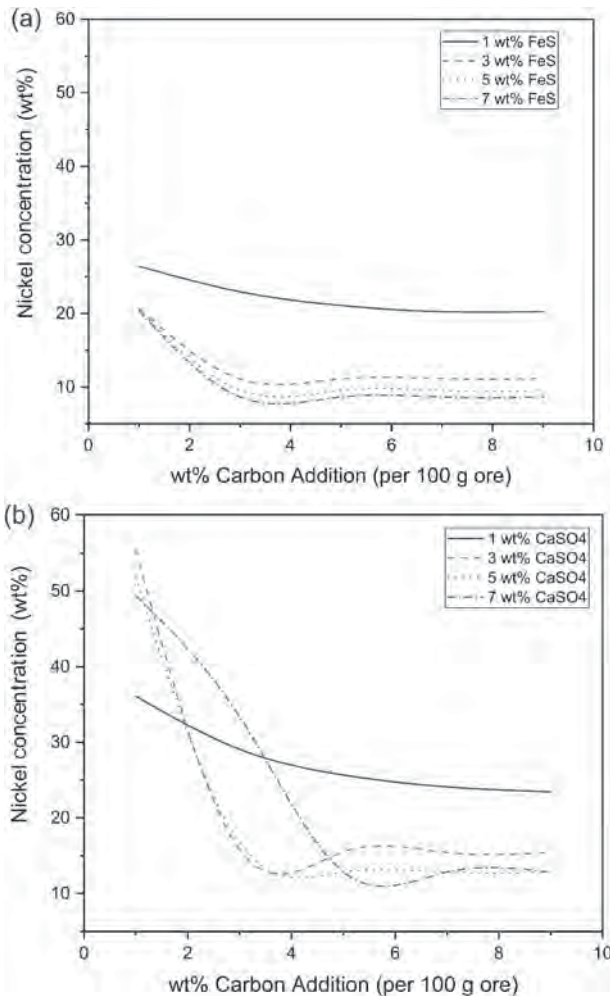


Figure 5. Grade of nickel in the matte as a function of the amount added carbon with the addition of sulfiding agents: (a) addition of FeS; (b) addition of CaSO₄.

the minimum nickel concentration obtained after adding CaSO₄ is higher than that after adding FeS, which was 12.8 wt% and 8.7 wt%, respectively. This phenomenon is expected because part of Fe associated with FeS entered the matte phase, and CaO associated with CaSO₄ enters the slag phase.

2.4. Experimental approach

The experimental method used in this study involved high-temperature equilibration, quenching, and electron probe X-ray microanalysis (EPMA). A vertical furnace with lanthanum chromate heating elements (supplied by Pyrox Thermique Matériaux, France) was used to conduct the experiments. A Pt-30% Rh/Pt-6% B-type thermocouple was periodically calibrated against a standard thermocouple (supplied by the National Measurement Institute of Australia) and placed in an alumina sheath next to the crucible to measure and monitor the hot zone temperature. A temperature accuracy of $\pm 2^\circ\text{C}$ was achieved. A schematic view of the furnace setup is shown in Figure 6. For each experiment, 10 g of material was crushed into powder, mixed well with fluxes and reductants in an agate mortar then pressed into briquettes. The experimental conditions are listed in Table 4. The abbreviation NL represents nickel laterite and NM represents polymetallic nodules. Pure graphite (carbon) powder (99.99 wt%) was used as

the reductant. Fluxes SiO₂ (99.9 wt%) and CaO (99 wt%, prepared by decomposition of CaCO₃ at 900°C for 16 h); sulfiding agents FeS (99 wt%) and CaSO₄ (99 wt%) were added as per ore weight. SiO₂ was supplied by Thermo Fisher Scientific Inc. and all other chemicals were supplied by Sigma Aldrich Pty Ltd. The pelletized sample was then placed in an alumina crucible (ID: 18 mm, H: 25 mm). The sample was heated and pre-reduced under an Ar atmosphere at 1000 or 1100°C for 60 min. After the pre-reduction, samples were heated immediately to the smelting temperature and held for 60 min. Samples were directly quenched in water after smelting reduction. Then, the samples were dried and mounted in a resin and polished for metallographic analysis. The microstructures and compositions of the reduced sample were analyzed by scanning electron microscopy coupled with X-ray energy-dispersive spectroscopy analysis (SEM-EDS) and JEOL JXA-8200 electron probe X-ray micro-analyzer (EPMA) with wavelength-dispersive detectors. EPMA was conducted at an accelerating voltage of 15 kV and a probe current of 15 nA. The standards used for the analysis were spinel (MgAl₂O₄) for Al and Mg, wollastonite (CaSiO₃) for Ca and Si, chalcopyrite (FeCuS₂) for Cu and S, rutile (TiO₂) for Ti, chromite (FeCrO₄) for Cr, albite (NaAlSi₃O₈) for Na, orthoclase (KAlSi₃O₈) for K, olivine (Ni₂SiO₄) for Ni, spessartine (Mn₃Al₂Si₃O₁₂) for Mn, hematite (Fe₂O₃) for Fe, and pure Co for Co. The ZAF correction procedure supplied with the electron-probe software was applied. Overall the EPMA measurements have an average accuracy within ± 1 wt%.

3. Results and discussion

3.1. Pre-reduction

Nodules and laterites were calcinated at the pre-reduction step, which enabled the partial reduction of nickel, cobalt, copper, and iron oxides. Two additional pre-reduction experiments (NL4 and NM1) were conducted to obtain their microstructures information. The microstructures of samples NL4 and NM1 after pre-reduction at 1100°C and 1000°C, respectively, for 60 min are shown in Figure 7. In Figure 7a, the sample contained pyroxene ((Ca, Fe, Mg)O-Si₂O₄), olivine (2(Fe, Mg)O-SiO₂) and spinel ((Al, Fe, Cr)₂O₃-(Fe, Mg)O). Alloy droplets, including ferronickel alloy with a composition of 79.4Ni-19.8Fe-0.8Si wt% and nickel matte with a composition of 70.2Ni-18.2S-10.9Fe wt%, were observed. The mineral phases of the sample remained similar to the original laterite ore during pre-reduction, while nickel and iron oxides were partly reduced and the formation of nickel matte was observed. Similarly, the mineral phases of polymetallic nodule sample NM1 remained constant, except for nickel, cobalt, copper, and iron oxides, which were partly reduced during pre-reduction. The sample comprised spinel (Fe₂O₃-(Fe, Mn, Mg)O) and olivine (2(Mn, Fe, Ca, Mg)O-SiO₂), as shown in Figure 7b. Copper matte with a composition of 59.7Cu-24.5S-8.6Fe-7.2Mn wt% and nickel matte with a composition of 49.4Ni-27.7Fe-12.6Cu-7.1Co-3.0Mn-0.2S wt% were observed in sample microstructures.

3.2. Effect of reductant addition on the matte and slag formation

High-temperature smelting processes were conducted to further reduce nickel and iron oxides to form the desired nickel

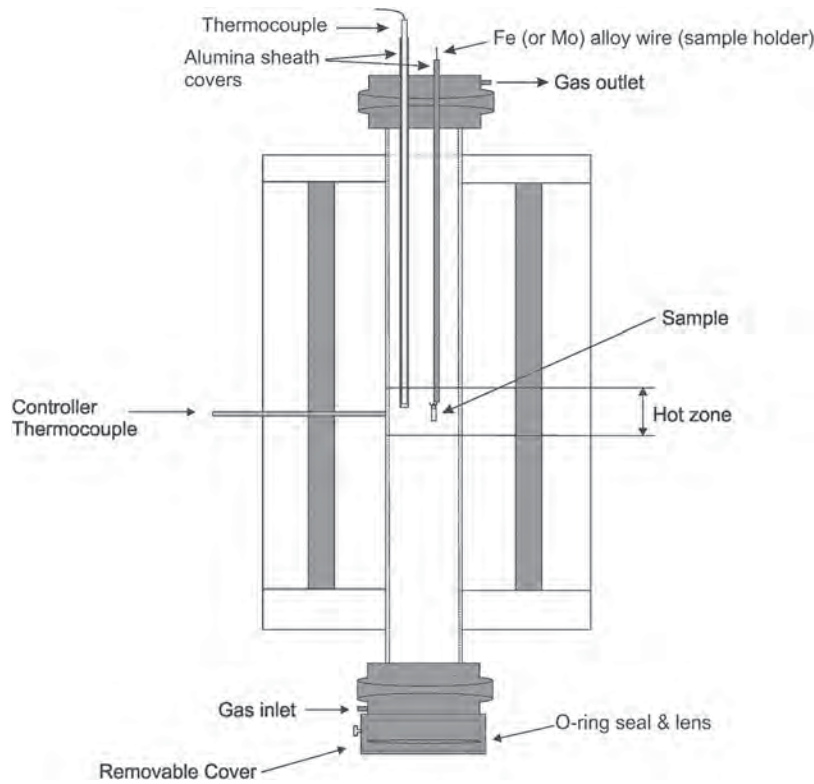


Figure 6. The schematic view of the vertical tube furnace used in the present study.

Table 4. Experimental conditions for nickel matte production.

Exp. No.	Ore (g)	Flux (%)				Reductant		Pre-Reduction		Reduction Smelting	
		CaO	FeS	SiO ₂	CaSO ₄	Graphite (g)	Crucible	Temp (°C)	Time (Min)	Temp (°C)	Time (Min)
NL1	10	8	5	n/a	n/a	0.5	Al ₂ O ₃	1100	60	1450	60
NL2	10	8	5	n/a	n/a	1.0	Al ₂ O ₃	1100	60	1450	60
NL3	10	8	5	n/a	n/a	1.5	Al ₂ O ₃	1100	60	1450	60
NL4	10	8	5	n/a	n/a	n/a	Al ₂ O ₃	1100	60	1450	60
NL5	10	8	10	n/a	n/a	n/a	Al ₂ O ₃	1100	60	1450	60
NM1	10	n/a	n/a	17.5	5	2.0	Al ₂ O ₃	1000	60	1350	60
NM2	10	n/a	n/a	10	5	4.0	Al ₂ O ₃	1000	60	1350	60
NM3	10	n/a	5	10	n/a	3.0	Al ₂ O ₃	1000	60	1350	60

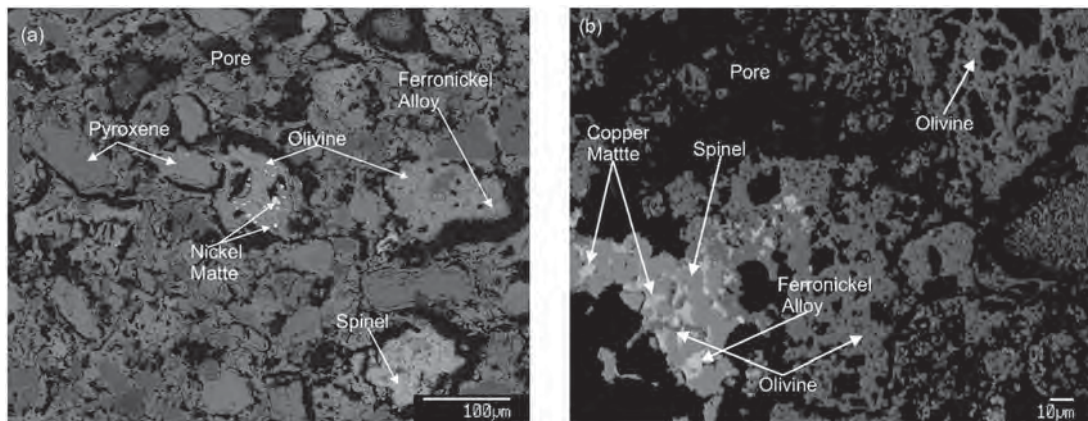
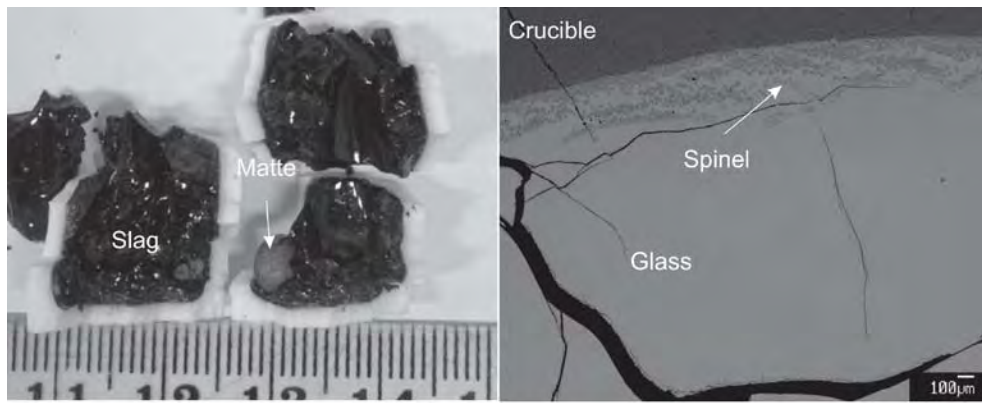


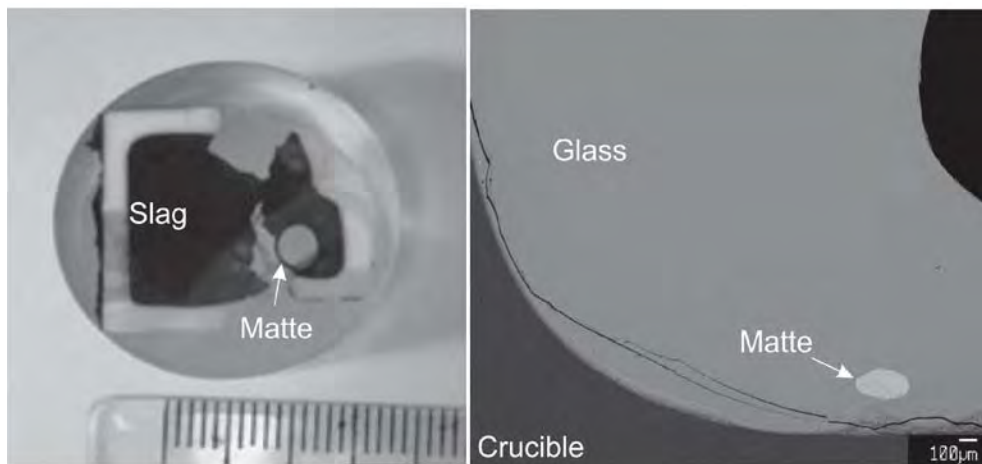
Figure 7. Microstructures of the samples after 60 min pre-reduction: (a) NL4 (laterite ores) at 1100°C and (b) NM1 (polymetallic nodules) at 1000°C.

mattes and slags with the addition of sulfiding agents. Images and microstructures of NL1, NL2, and NL3 after smelting reduction at 1450°C and with 0.5, 1, and 1.5 wt% carbon are shown in Figure 8. The experimental results showed that the

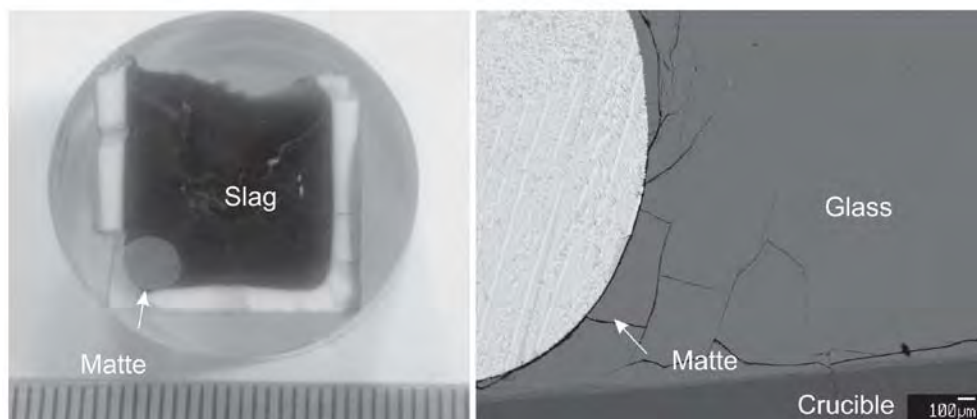
slag was completely liquidized and the matte sphere settled at the bottom of the crucible. Thus, the matte could be easily separated from the slag. Visual inspection suggested that the diameter of the matte sphere increased with increasing amount



(a) Sample NL1 (0.5 wt% carbon addition)



(b) Sample NL2 (1 wt% carbon addition)



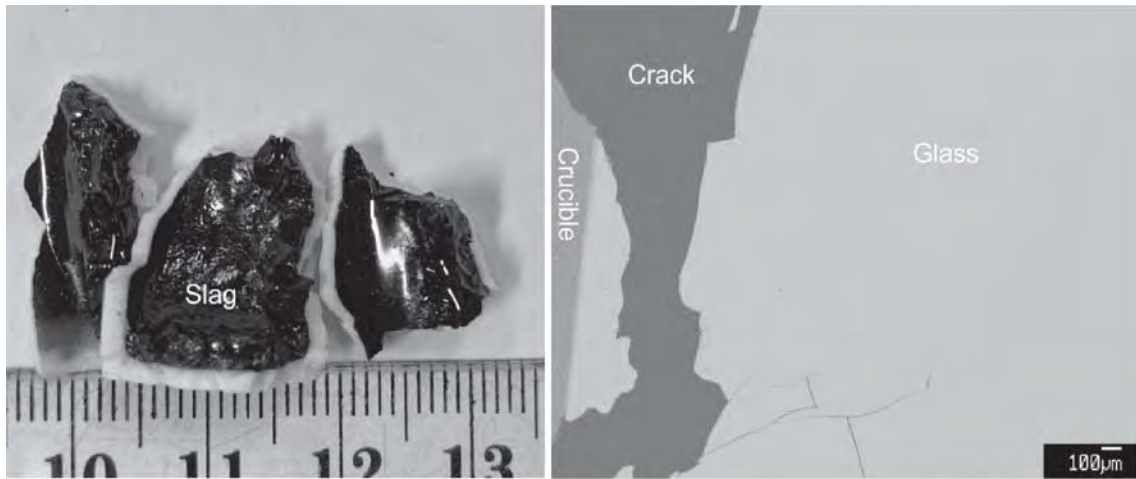
(c) Sample NL3 (1.5 wt% carbon addition)

Figure 8. Images and microstructures of quenched samples after smelting at 1450°C (laterite ores). (a) sample NL1 (0.5 wt% carbon addition); (b) sample NL2 (1 wt% carbon addition); (c) sample NL3 (1.5 wt% carbon addition).

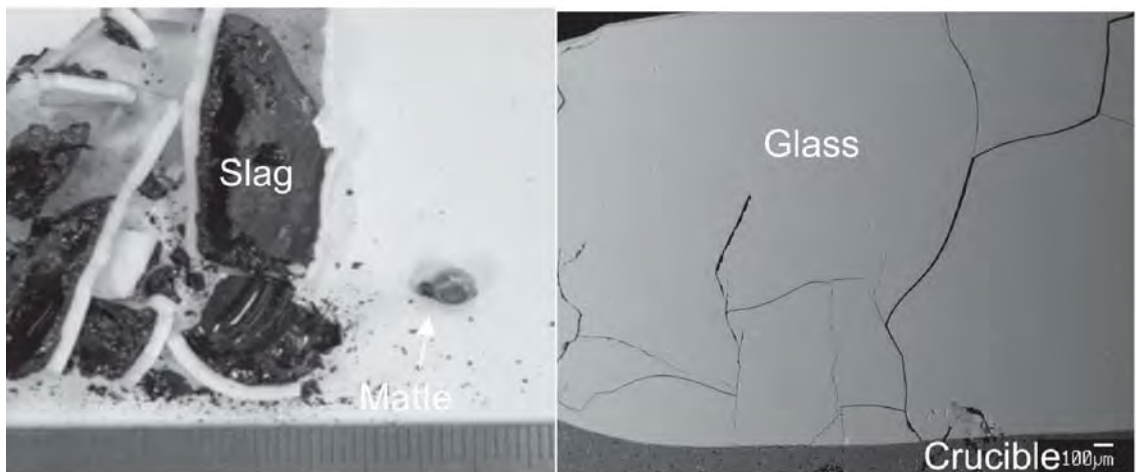
of carbon. Figure 8a showed that spinel crystals can be observed in the slag of NL1, which contained 0.3 wt% NiO. In NL2, small matte droplets were present in the slag. Comparing the reduction of oxides shown in Figure 8a–c, the addition of the reductant reduced the metal oxides to alloy/matte, and the formation of the matte droplets could be observed with increasing amount of the reductant. The matte droplets were initially distributed in the slag, see Figure 7, and aggregated to a large matte particle when more oxides were

reduced. Hence, the addition of the reductant promoted the aggregation of the reduced matte in the slag, which eventually reduced the loss of the desired metals during smelting reduction.

Similarly, smelting reduction of polymetallic nodules with 2 and 4 wt% carbon was carried out at 1350°C. The microstructure images of NM1 and NM2 are shown in Figure 9. It can be seen from Figure 9a that the matte was not observed in NM1. In NM2, the slag was completely liquidized and an matte sphere



(a) Sample NM1 (2 wt% carbon addition)



(b) Sample NM2 (4 wt% carbon addition)

Figure 9. Images and microstructures of quenched samples after smelting at 1350°C (polymetallic nodules). (a) Sample NM1 (2 wt% carbon addition); (b) sample NM3 (4 wt% carbon addition).

(approximately 4 mm in diameter) settled at the bottom of the crucible. Comparing the reduction of oxides shown in Figure 9a and b, addition of 2 wt% carbon was insufficient, as no matte was observed and around 1.3 wt% nickel oxides were found in the slag. Whereas, in NM2, nickel oxides were completely reduced because of the addition of 4 wt% carbon. The effects of carbon addition on the extent of metal oxide reduction and matte composition are further discussed in the following section.

3.3. Effect of flux and sulfiding agents addition

In the smelting reduction process, flux was added to decrease the liquidus temperature of the slag. The addition of a flux ensured that the slag maintained a complete liquid status at the smelting temperature, which is needed for future alloy and matte separation by tapping. The FactSage calculation shown in Figure 2a indicates that the liquidus temperature of nickel laterite ores decreases rapidly with

the addition of up to 15 wt% CaO during smelting. Figure 8a–c show evidence of the slag reaching the complete liquid status at the experimental temperature with the addition of 8 wt% CaO. Likewise, Figure 9a and b show that with the addition of SiO₂ to fully liquid slag was achieved during the reduction of polymetallic nodules. Initially, 17.5 wt% SiO₂ was added (NM1) during the experiment. The concentration of SiO₂ flux was reduced to 10 wt% for samples NM2 and NM3 to minimize the flux addition while still maintaining completely liquid state of the slag. The results after SiO₂ flux addition during the smelting reduction of polymetallic nodules were in agreement with the results of our previous studies wherein the slag was liquid for the investigated SiO₂ addition of 10–17.5 wt% at the experimental temperature of 1350°C (Su et al. 2020). Furthermore, the effects of SiO₂ to the liquidus temperature was proved experimentally by Sommerfeld and Friedmann (Friedmann, Pophanken and Friedrich 2017).

The effects of the addition of a sulfiding agent on the formation of nickel matte were studied. The matte formation with the presence of carbon and sulfiding agents are represented by reaction (3) below.



Figure 10a,b shows the microstructures of NL4 and NL5, which were smelted at 1450°C with the FeS additive. It should be noted that the reaction did not involve the addition of graphite. Therefore, FeS acted as the reductant to reduce NiO because of the high activity of Fe²⁺. Figure 11 compares the matte compositions as a function of FeS addition; the values of matte composition were obtained from the FactSage calculations and the experimental results. The compositions of the matte and phases present in the quenched samples are listed in Table 5. The results of the FactSage calculation and experiments were anomalous to some extent. In particular, the experimental results showed that the nickel concentration was 20 wt% higher than that predicted by FactSage when 5 wt% FeS was added. The nickel concentration in the matte decreased significantly from 59.9 to 24.8 wt% when the amount of FeS was increased from 5 to 10 wt%. This trend is observed because Fe in FeS was directly introduced to the matte phase. Overall, comparing with literature, the matte obtained in the study have

higher or similar nickel and sulfur concentrations as well as lower iron concentration (Harris, Peacey and Pickles 2013).

The formation of matte by smelting polymetallic nodules with two types of sulfiding agents was examined. The microstructures of the quenched samples obtained after smelting at 1350°C with the addition of CaSO₄ and FeS are shown in Figure 10c and d, respectively. The sulfur concentration in the matte was 3 wt% after adding 5 wt% sulfiding agents (compositions of the matte are listed in Table 5), as approximately 20% added sulfur were lost via vaporization during the process.

Comparing the slag compositions of NM2 and NM3, addition of CaSO₄ results in a higher CaO concentration in the slag phase. Based on our study, increasing CaO increased the slag liquidus temperature (for polymetallic nodules) and ultimately the energy consumption of the process (Su et al. 2020). Therefore, FeS is preferable to CaSO₄ because the FeO concentration in the slag shows minor impacts on the slag liquidus temperature.

3.4. Effect of graphite addition on matte composition

The addition of graphite reductant plays a significant role in controlling the matte composition. The composition of the matte as a function of graphite addition is shown in Figure 12, wherein the experimental matte compositions of NL1–NL4 with 8 wt% CaO addition at 1450°C are compared with the FactSage

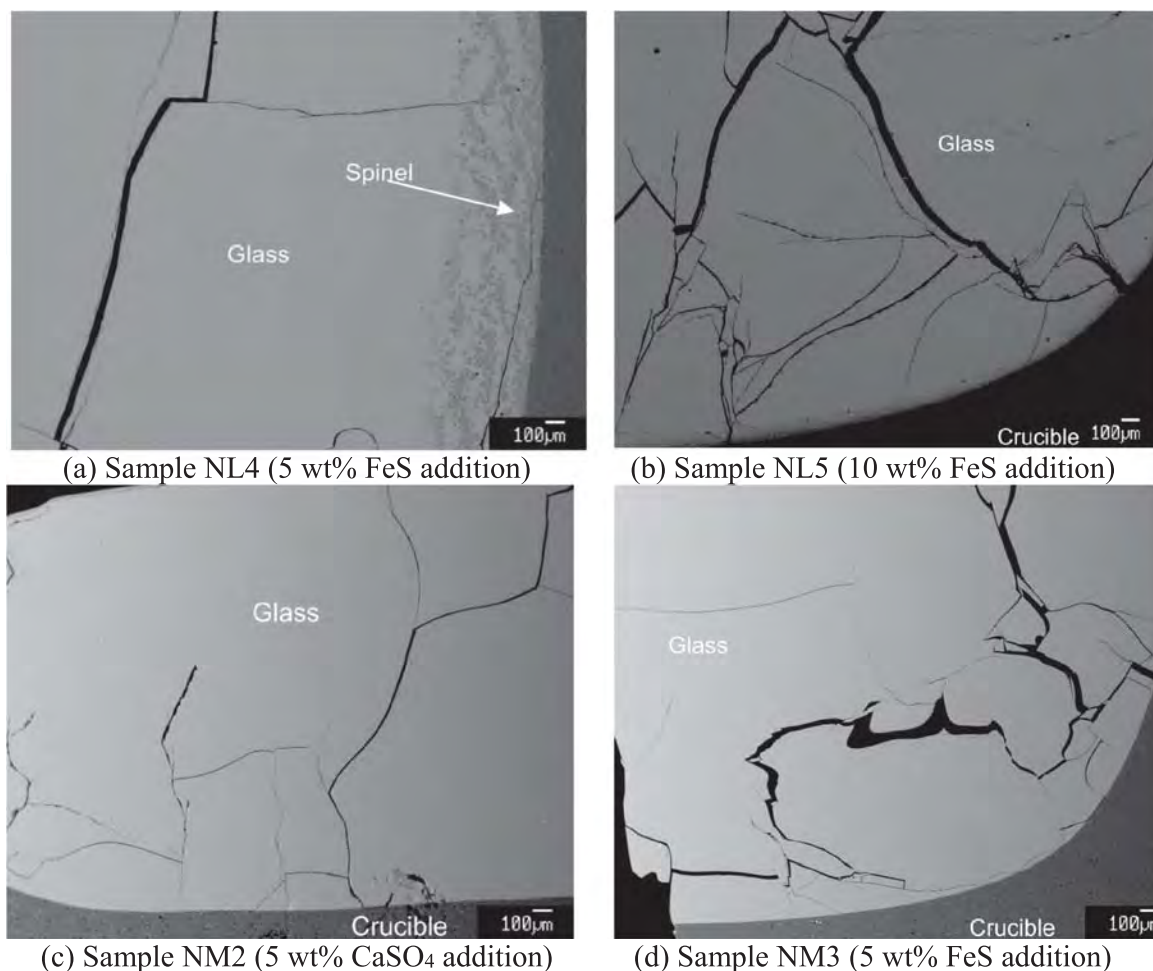


Figure 10. Slag microstructures of quenched samples for different sulfiding agents. (a) Sample NL4 (5 wt% FeS addition); (b) sample NL5 (10 wt% FeS addition); (c) sample NM2 (5 wt% CaSO₄ addition); (d) sample NM3 (5 wt% FeS addition).

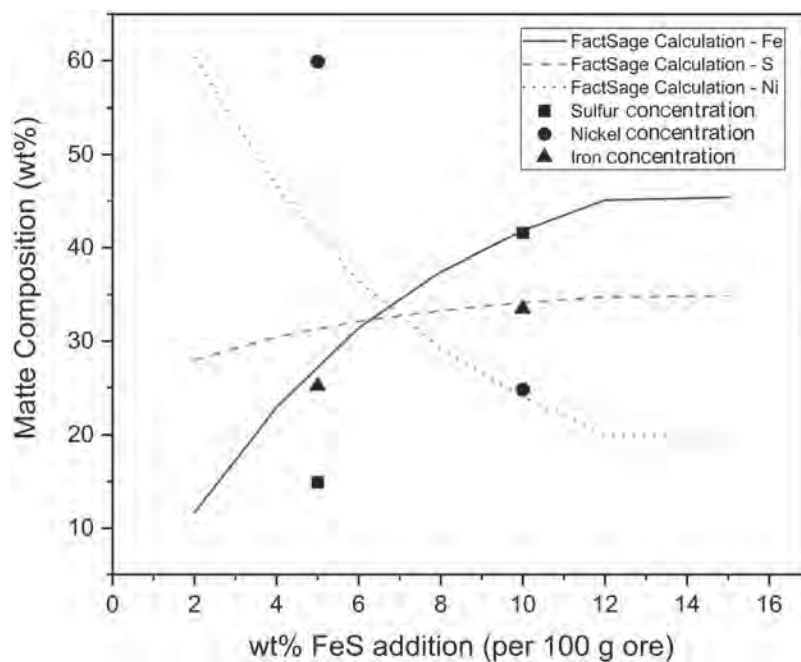


Figure 11. A comparison between experimental results and FactSage calculations of the matte composition as a function of FeS addition (laterite ores).

Table 5. Compositions of the phases present in the quenched samples (wt%).

No.	Slag	NiO	FeO	Al ₂ O ₃	CuO	CoO	SiO ₂	S	MgO	CaO	MnO	Cr ₂ O ₃	TiO ₂	Na ₂ O	K ₂ O
NL1	Glass	0.1	20.3	4.1	n.d.	n.d.	49.8	0.2	16.0	8.5	0.3	0.7	n.d.	n.d.	n.d.
	Spinel	0.3	12.1	69.4	n.d.	n.d.	0.1	n.d.	18.0	n.d.	0.1	n.d.	n.d.	n.d.	n.d.
NL2	Glass	n.d.	20.5	5.1	n.d.	n.d.	47.9	0.2	17.2	8.1	0.3	0.8	n.d.	n.d.	n.d.
NL3	Glass	0.2	19.0	4.5	n.d.	n.d.	49.9	0.2	16.6	8.4	0.3	0.8	n.d.	n.d.	n.d.
NL4	Glass	0.5	21.8	4.3	n.d.	n.d.	48.0	0.2	16.0	8.2	0.3	0.6	n.d.	n.d.	n.d.
	Spinel	1.3	14.3	66.1	n.d.	n.d.	n.d.	n.d.	18.1	n.d.	0.1	n.d.	n.d.	n.d.	n.d.
NL5	Glass	n.d.	20.9	19.1	n.d.	n.d.	41.7	0.3	12.6	8.1	0.1	0.2	n.d.	n.d.	n.d.
NM1	Glass	1.2	5.7	7.0	1.3	0.2	33.8	n.d.	3.7	4.3	35.8	n.d.	0.5	5.4	1.0
NM2	Glass	n.d.	6.9	10.9	0.3	0.2	25.1	0.7	3.7	4.4	39.3	n.d.	0.6	6.7	1.0
NM3	Glass	n.d.	11.1	9.8	0.1	0.1	24.9	0.7	3.7	2.2	39.3	n.d.	0.5	6.5	1.0
No.	Matte	Ni	Fe	Cu	Co	S	Mn								
NL1	Matte	35.0	35.9	n.d.	n.d.	29.0	n.d.								
NL2	Matte	18.8	61.4	n.d.	n.d.	19.8	n.d.								
NL3	Matte	11.9	69.0	n.d.	n.d.	19.0	n.d.								
NL4	Matte	59.9	14.9	n.d.	n.d.	25.2	n.d.								
NL5	Matte	24.8	41.6	n.d.	n.d.	33.5	n.d.								
NM2	Matte	43.6	15.9	31.4	5.5	3.1	0.4								
NM3	Matte	34.9	30.6	25.5	6.0	2.8	0.3								

calculated compositions. The compositions of the matte and slag phases present in the quenched samples are listed in Table 5. The nickel concentration of matte gradually decreased when iron oxide was reduced into the matte by the addition of a graphite reductant. Nickel oxide in the slag was completely reduced when ~1.5 wt% graphite was added. Thus, the nickel and sulfur concentrations in the matte were varied between 60–10 wt% and 25–20 wt%, respectively, by controlling the amount of graphite additive. A distinct difference was observed in the FactSage calculation and the experimental results, especially when ≤1 wt% carbon was added. A greater amount of carbon was needed initially in the experiments to produce matte as predicted by the FactSage calculation. One of the reasons for the discrepancies is the presence of multivalent metallic oxides (e.g., MeOx) in the raw materials, which would require the addition of a higher amount of the reductant during the experiments when compared to bivalent forms (e.g., MeO) used in the FactSage

calculations. Moreover, a portion of carbon may react with crystallized water under anaerobic condition (Libby and Blake 1981; Smith, Pierce and Joel 1954), which results in discrepancies due to the consumption of carbon. Another reason could be the iron sulfide decomposes to pyrite and pyrrhotite under inlet condition (Chen et al. 2019; Zhang et al. 2019). Pyrite and pyrrhotite further reacts with hematite to form wustite, which bring down the iron concentration in the matte hence, increases the concentration of nickel in the matte. With the increasing of carbon addition, the impacts were minimized and the experimental results trend to agree with the modeling accurately. The distribution coefficients of valuable metals (wt% Me in slag/wt% Me in matte) were calculated. It is worth noticing that the distribution coefficients for metals that were not detected in slag phase are represented by zero. Furthermore, distribution coefficients for slag phase that contained spinel were not calculated as the spinel phases were not uniformly distributed. The Ni

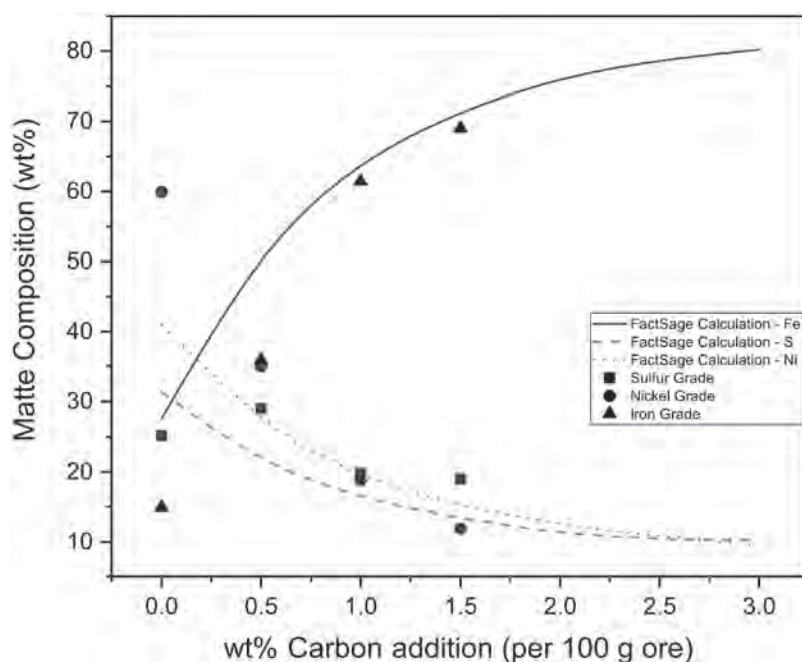


Figure 12. A comparison between experimental and FactSage calculated matte composition as a function of carbon addition (laterite ores).

distribution coefficient for NL2, NL3, NL4 and NL5 were 0, 0.017, 0.0083 and 0, respectively.

Due to the presence of copper and cobalt oxides in the polymetallic nodules, copper and cobalt were found in the matte along with nickel and iron after smelting reduction. The compositions of the matte, slag and phases are listed in Table 5. Results for sample NM1 show that 2 wt% carbon addition was insufficient to reduce nickel as 1.3 wt% NiO was detected in the slag phase. By increasing the amount of the graphite addition to 3 wt%, the complete reduction of nickel oxide was observed in NM3. It should be noticed that copper oxides were almost completely reduced with 3 wt% of the graphite and 5 wt% FeS additives, which was not observed in NM2 with 4 wt% graphite and 5 wt% CaSO₄ additives. Moreover, the cobalt reduction was higher compared to the trial with CaSO₄. Aiming for a higher cobalt extraction might decrease the concentration of nickel in the product due to undesirable iron being extracted simultaneously. This is because in a complex systems, the reduction of metal oxides would not follow the Ellingham diagram strictly. Comparing the NM2 and NM3 slag compositions, it is evident that FeS promotes the reduction of nickel, cobalt and copper oxides as a higher extent of reduction was achieved with fewer amount of graphite additives. The presence of FeS acted as the reductant to reduce NiO due to the high activity of Fe²⁺. However, Fe associated with the addition of FeS dilutes the concentration of nickel in the matte. The nickel concentration of 43.6 wt% and 34.9 wt% were detected in NM2 and NM3, respectively. Therefore, in a future study, the smelting conditions should be optimized by further evaluating the effects of sulfiding agents and graphite addition on the matte composition and the degree of the slag reduction. The calculated Ni distribution coefficients were zero for both NM2 and NM3. The distribution coefficients for Cu and Co were 0.0096 and 0.036 for NM2; 0.0032 and 0.017 for NM3, respectively. The distribution coefficients decreased due to the presence of FeS prompts the

recovery of Cu and Co in the slag phase. Comparing the data from literature, concentration of nickel, cobalt and copper in the obtained matte are higher than other alloys extracted from polymetallic nodules. For example, nickel, copper and cobalt concentrations in matte were reported between 12.81–22.3 wt%, 8.4–16.7 wt% and 0.7–5.4 wt%, respectively (Friedmann, Pophanken and Friedrich 2017; Kohga et al. 1995; Sridhar, Jones and Warner 1976; Stefanova, Iliev and Stefanov 2013). Low iron concentration in the matte is the major factor that impacts the concentration of other valuable metals. Most metals have an iron concentration between 54.3 and 70.7 wt%, whereas the iron concentration is between 15.9 and 30.6 wt% in the present study (Friedmann, Pophanken and Friedrich 2017; Kohga et al. 1995; Sridhar, Jones and Warner 1976; Stefanova, Iliev and Stefanov 2013). Due to the limiting value of iron in the matte, it is considered as an impurity that need to be minimized. Another advantage of the proposed process is that valuable metals are extracted as matte rather than metal as the intermediate product (Sridhar, Jones and Warner 1976). Selectively extract metals from matte via leaching requires fewer acid consumptions than extracting from matte (Jeong et al. 2016). Hence, it reduces the costs and pollution in the downstream process.

4. Conclusion

A novel process that extracts nickel and associated metals from laterite ores and polymetallic nodules for the production of nickel matte was developed through the optimization of both slag and matte systems. The key findings are summarized as follows:

- (1) A Single-step extraction of nickel matte from alternative low-grade, complex mineral resources (i.e. laterite ores and polymetallic nodules) was achieved by optimizing

the slag and matte system at 1350–1450°C. Matte with high nickel concentration and low iron concentration was obtained and well separated from the slag phase.

- (2) The FactSage software was used to simulate and predict the formation of the nickel matte and the extent of slag reduction. The nickel concentration of the matte was not affected by CaSO₄ addition but decreased with increasing amount of FeS. This was likely caused by Fe associated with FeS entering the matte system. However, the presence of FeS also promotes the reduction degree of laterite ores, which was verified experimentally.
- (3) The addition of graphite played an essential role in controlling the nickel and iron concentration in the matte system. A nickel concentration ≥30 wt% and iron concentration in mattes ≤40 wt% were achieved by limiting the graphite addition to 0.5 wt% and 3 wt% for nickel laterite ores and polymetallic nodules, respectively. Moreover, replacing the sulfiding agent FeS with CaSO₄ during the smelting of polymetallic nodules could further reduce the iron concentration in mattes below ~15 wt% and improve the nickel concentration to ≥40 wt%. Based on these results, there exists potential to smelt both polymetallic nodules and nickel laterite ores in industrial scale reduction at 1350–1450°C.

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The authors would like to thank Jie Yu for assisting with the high-temperature experiments. The authors acknowledge the facilities, scientific and technical assistance, of the Australian Microscopy and Microanalysis Research Facility at the Centre for Microscopy and Microanalysis, The University of Queensland. Tonga Offshore Mining Limited provided polymetallic nodules and Dongying Fangyuan Nonferrous Metals Co., Ltd provided laterite ores for the present study.

Disclosure statement

The authors declare no conflict of interest.

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10 Maps and cross-sections

The maps and cross-sections in this chapter are a major part of this thesis. They are placed here as in the printed version of this thesis they are folded and stored in a solander box presented as a second volume.

10.1 CCZ wide regional scale 1:4,000,000 scale map

per Chapter 2 including bathymetric cross-sections:

- M1. CCZ geomorphology map.

10.2 Series of seven 1:250,000 scale maps

per Chapter 3

- M2. Sheet 1 (NORI A)
- M3. Sheet 2 (NORI B and TOML B)
- M4. Sheet 3 (TOML C)
- M5. Sheet 4 (TOML D and E)
- M6. Sheet 5 (Marawa 19. 20)
- M7. Sheet 6 (NORI C)
- M8. Sheet 7 (TOML F and NORI D)

10.3 Series of two side-scan maps & nine sections and swath maps at 1:25,000 scale

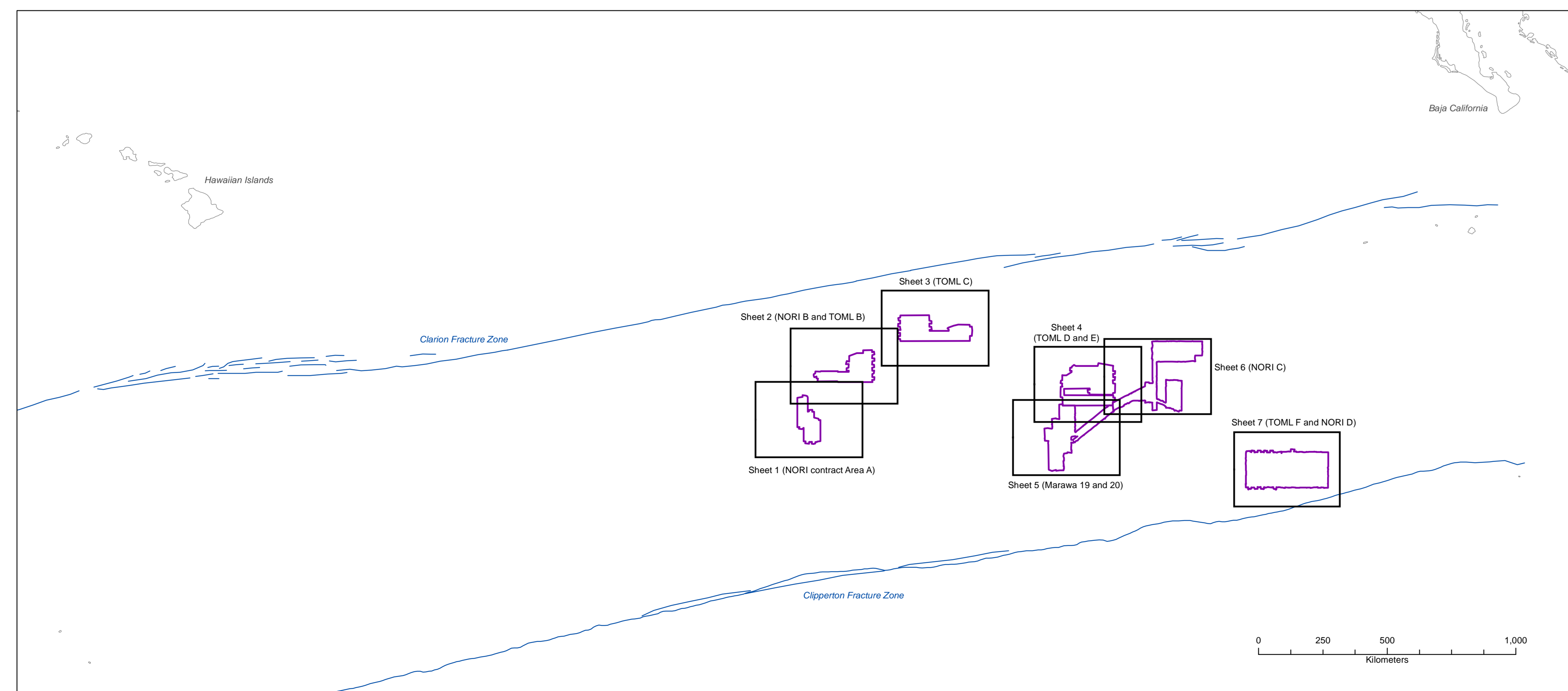
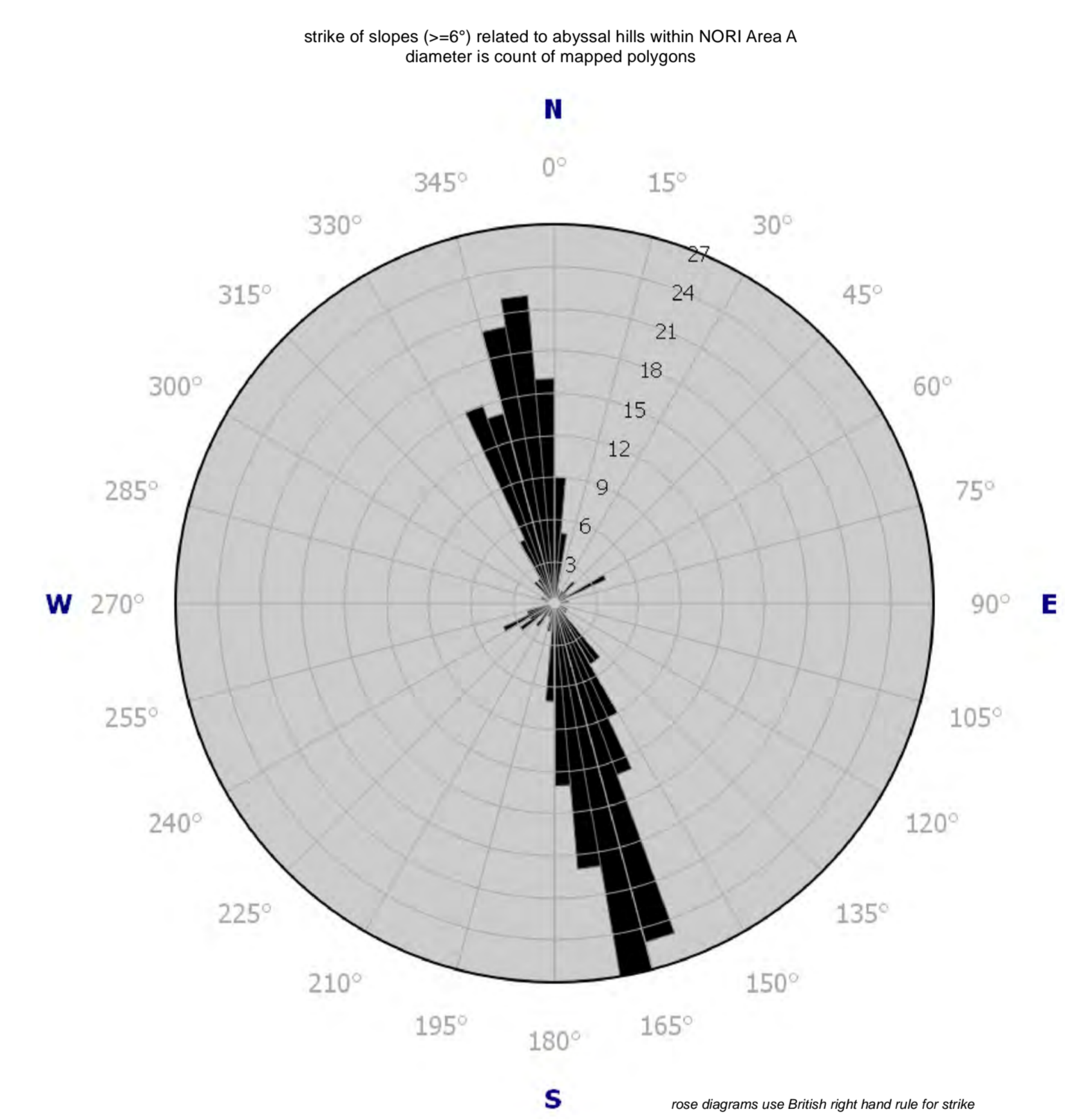
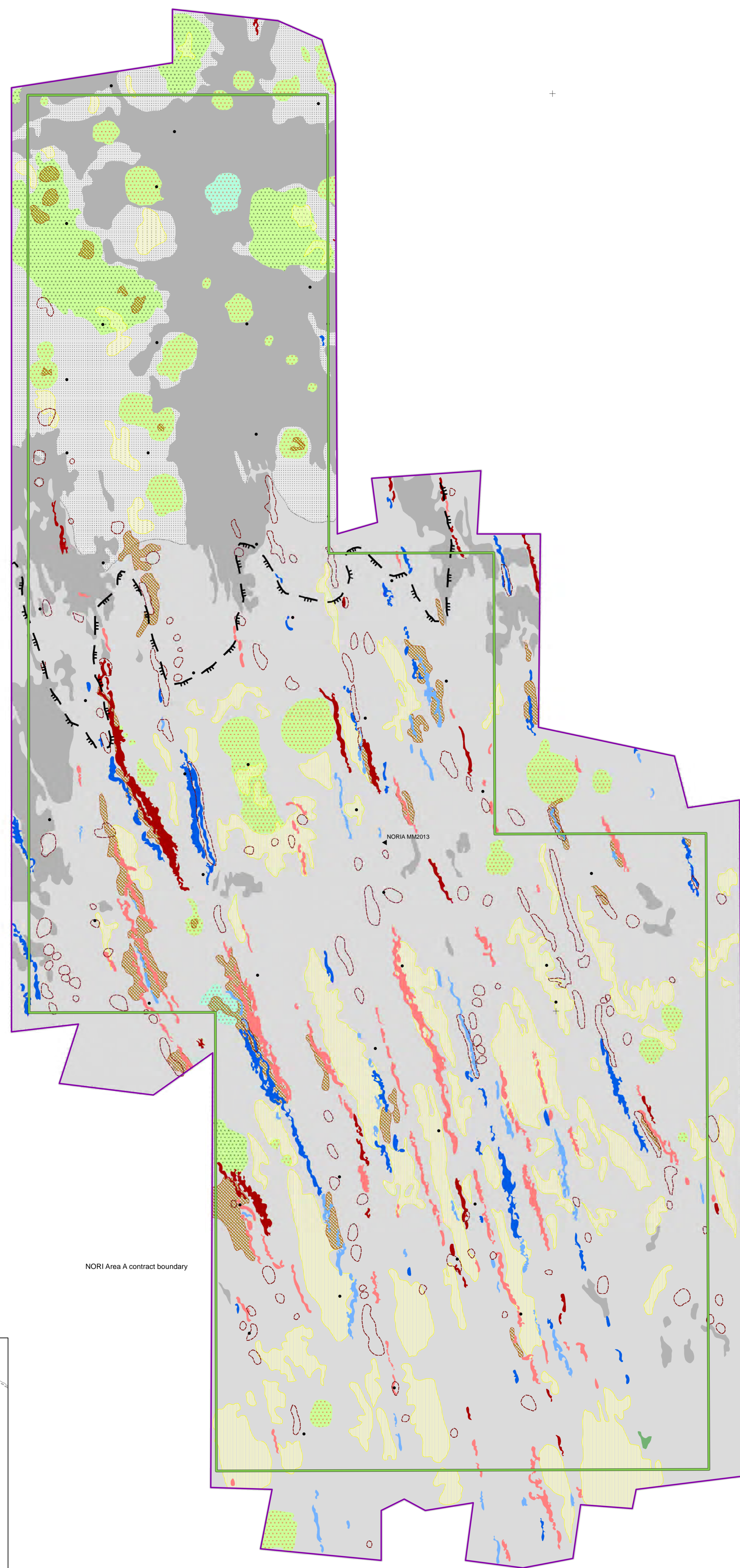
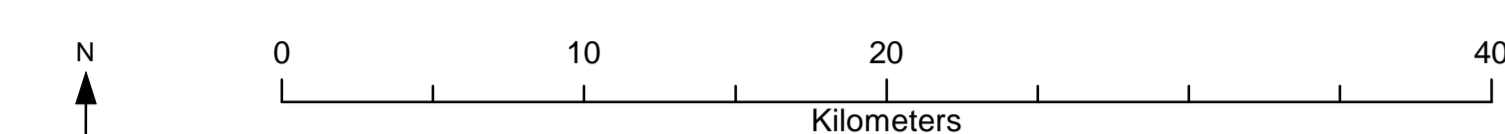
per Chapter 3

- M9. SBP section and SSS swath for CCZ15-M01, TOML B1₂
- M10. SBP section and SSS swath for CCZ15-M02, TOML B1₂
- M11. SBP section and SSS swath for CCZ15-M03, TOML B1₂
- M12. SBP section and SSS swath for CCZ15-M04, TOML B1₂
- M13. SBP section and SSS swath for CCZ15-M05, TOML C1₂
- M14. SBP section and SSS swath for CCZ15-M06, TOML D2₂
- M15. SBP section and SSS swath for CCZ15-M07/7B, TOML D2₂
- M16. SBP section and SSS swath for CCZ15-M08, TOML D2₂
- M17. SBP section and SSS swath for CCZ15-M09, TOML D1₂
- M18. SSS Map for TOML B1 and C1₂
- M19. SSS Map for TOML D1 and D2₂

Surface Geology of part of the Clarion Clipperton Zone, tropical North Pacific Ocean - Sheet 1

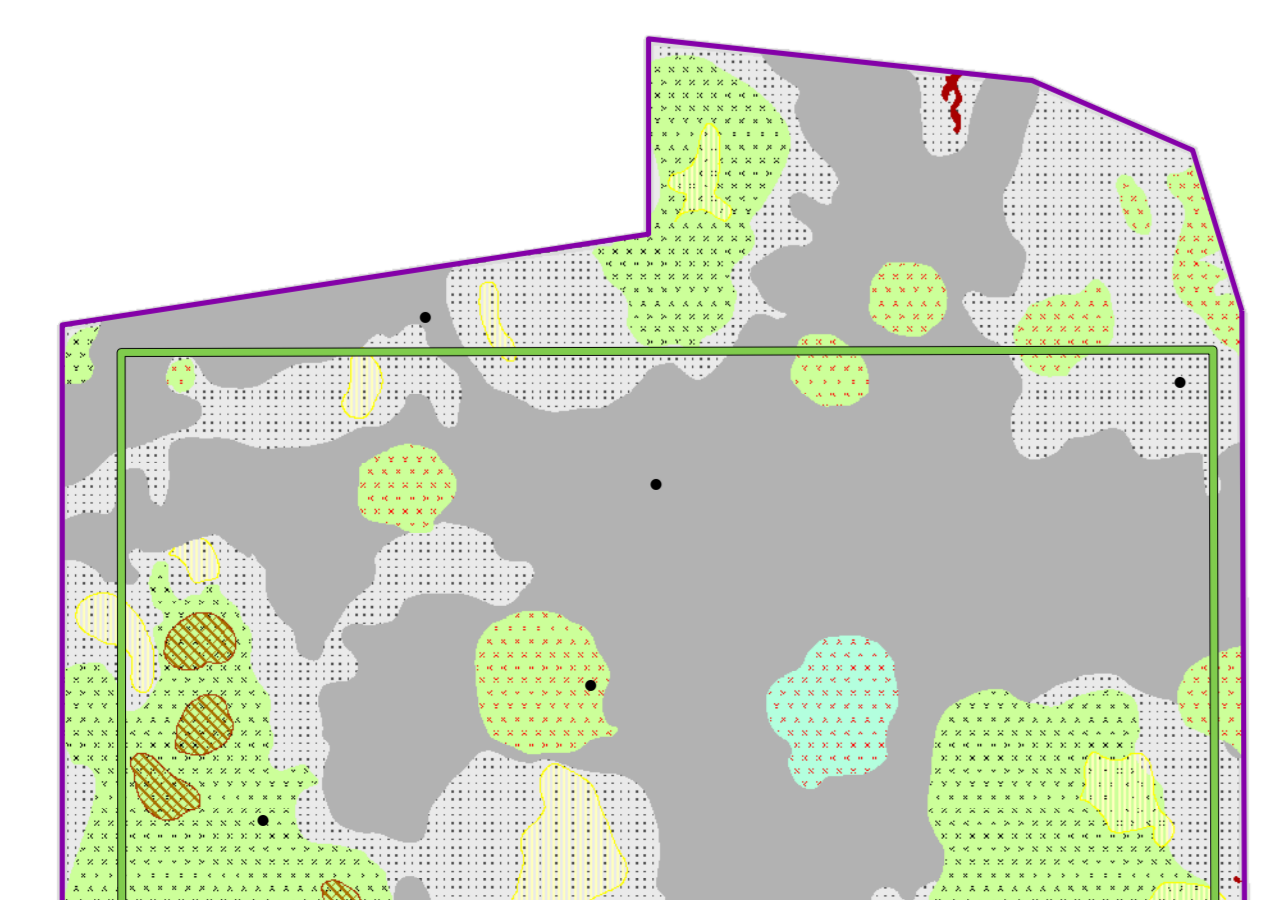
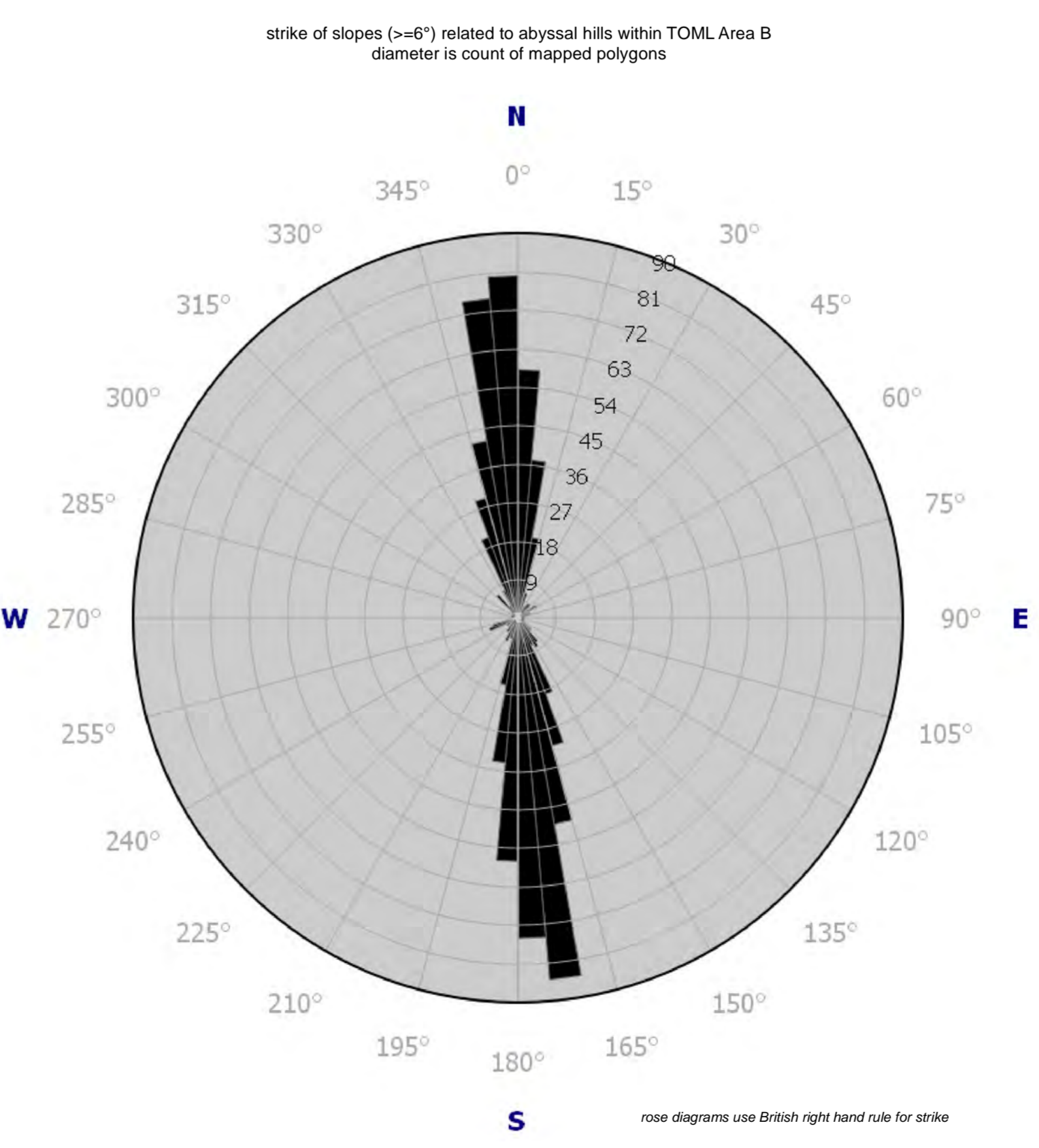
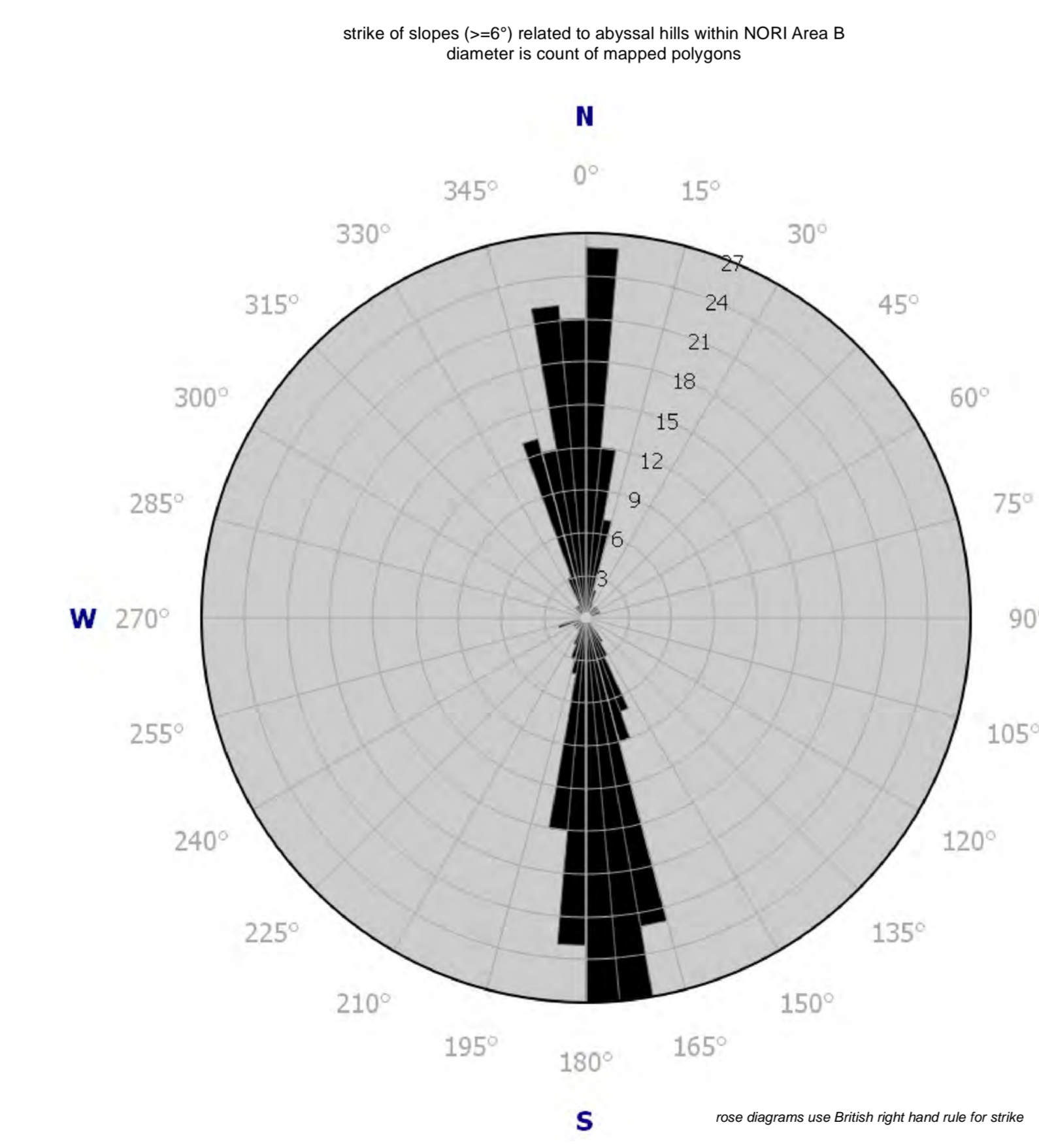
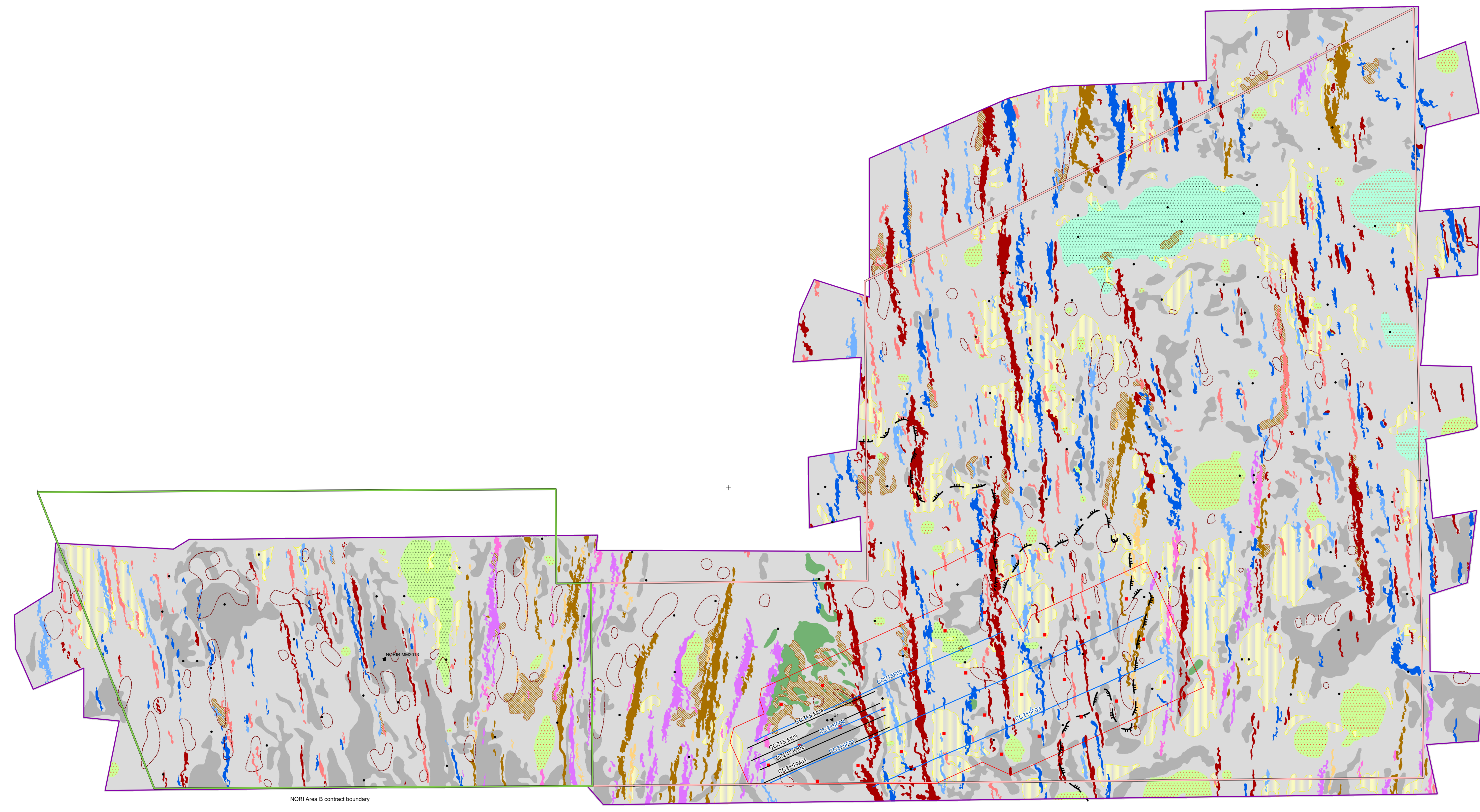
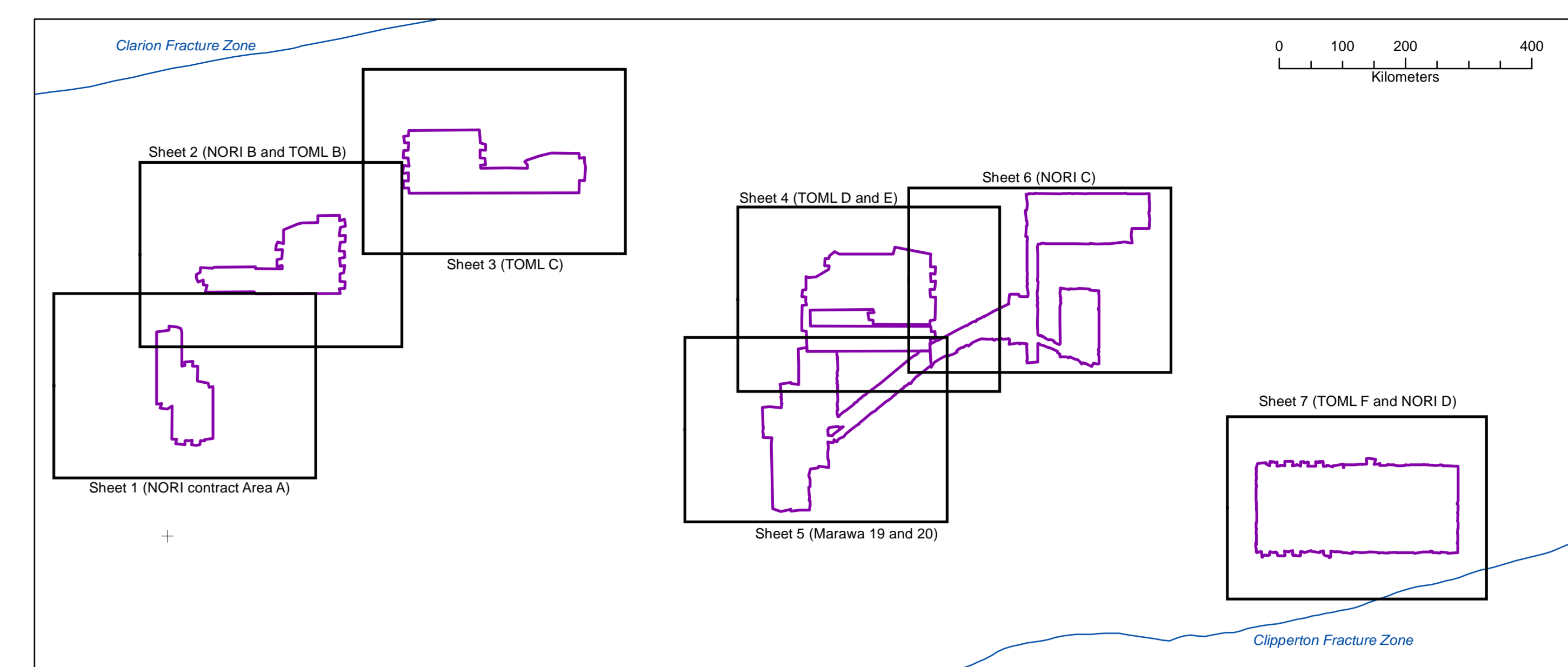
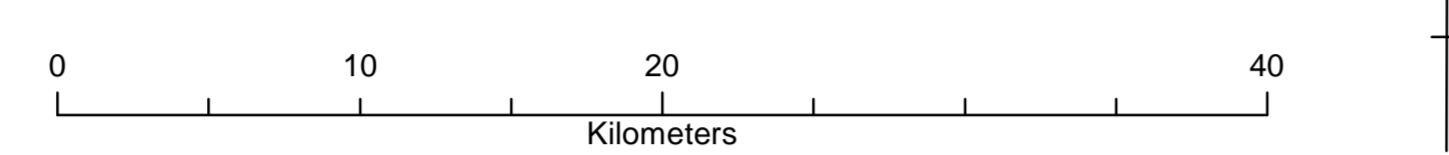
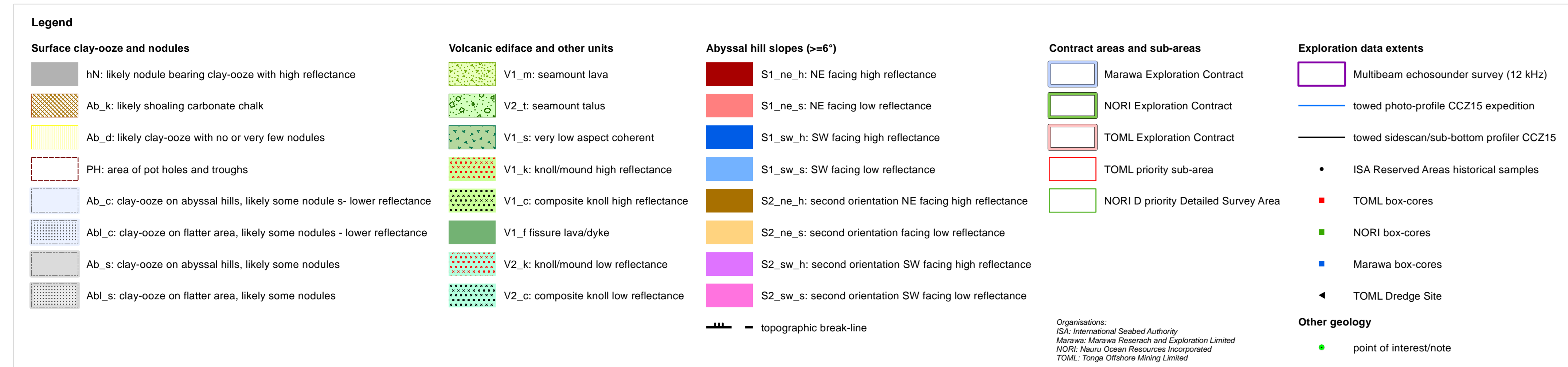
1:250,000 scale
map is projected to UTM 8N WGS84

Surface clay-coze and nodules		Volcanic edifice and other units		Abyssal hill slopes (±4°)		Contract areas and sub-areas		Exploration data extents	
HN: likely nodule bearing clay-coze with high reflectance	V1_m: seamount lava	S1_ne_h: NE facing high reflectance	Mawaa Exploration Contract	Multibeam echosounder survey (12 kHz)					
AD_k: likely shoaling carbonate chalk	V2_l: seamount talus	S1_ne_s: NE facing low reflectance	NORI Exploration Contract	towed photo profile CCZ15 expedition					
AD_d: likely clay-coze with no or very few nodules	V1_s: very low aspect coherent	S1_sw_h: SW facing high reflectance	TOML Exploration Contract	towed sidescan/sub-bottom profiler CCZ15					
PH: area of pot holes and troughs	V1_k: knoll/mound high reflectance	S1_sw_s: SW facing low reflectance	TOML priority sub-area	ISA Reserved Areas historical samples					
AD_c: clay-coze on abyssal hills, likely some nodule s- lower reflectance	V1_c: composite knoll high reflectance	S2_ne_h: second orientation NE facing high reflectance	NORI D priority Detailed Survey Area	TOML box-cores					
AD_l: clay-coze on flatter area, likely some nodules - lower reflectance	V1_f: fissure lavadike	S2_ne_s: second orientation facing low reflectance		NORI box-cores					
AD_s: clay-coze on abyssal hills, likely some nodules	V2_k: knoll/mound low reflectance	S2_sw_h: second orientation SW facing high reflectance		Mawaa box-cores					
AD_ls: clay-coze on flatter area, likely some nodules	V2_c: composite knoll low reflectance	S2_sw_s: second orientation SW facing low reflectance		TOML Drift Site					
				Other geology					
				point of interest					



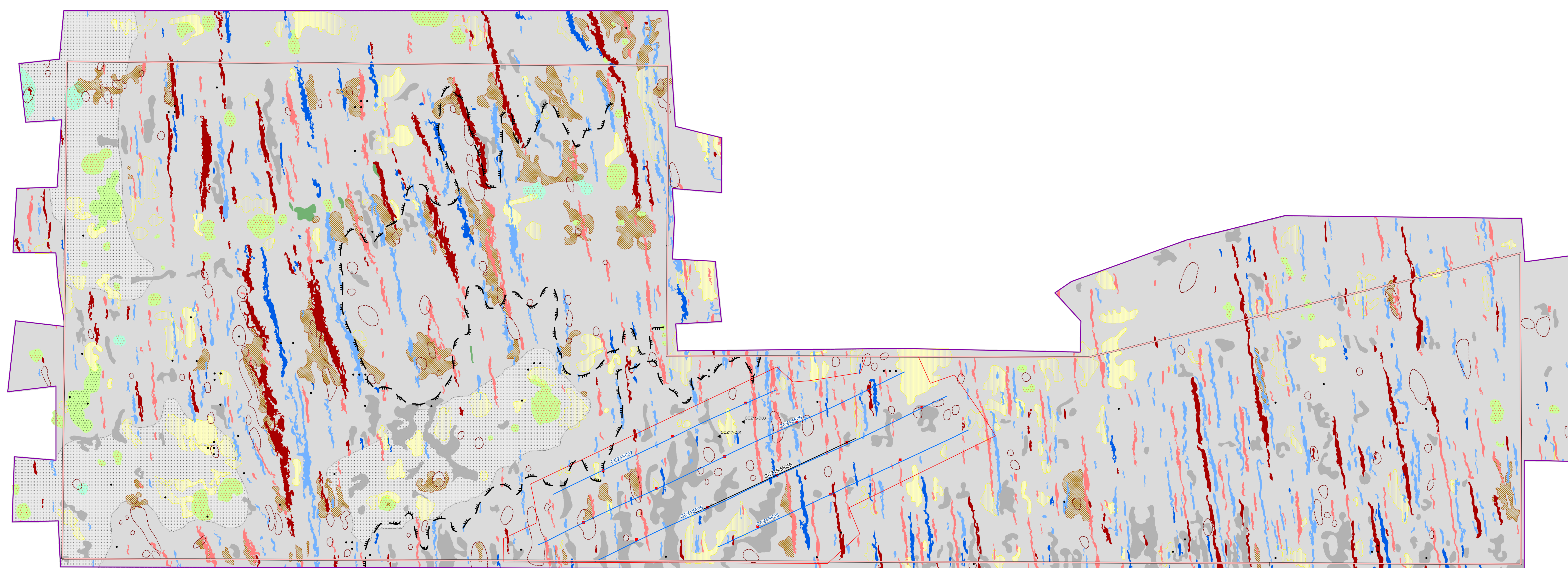
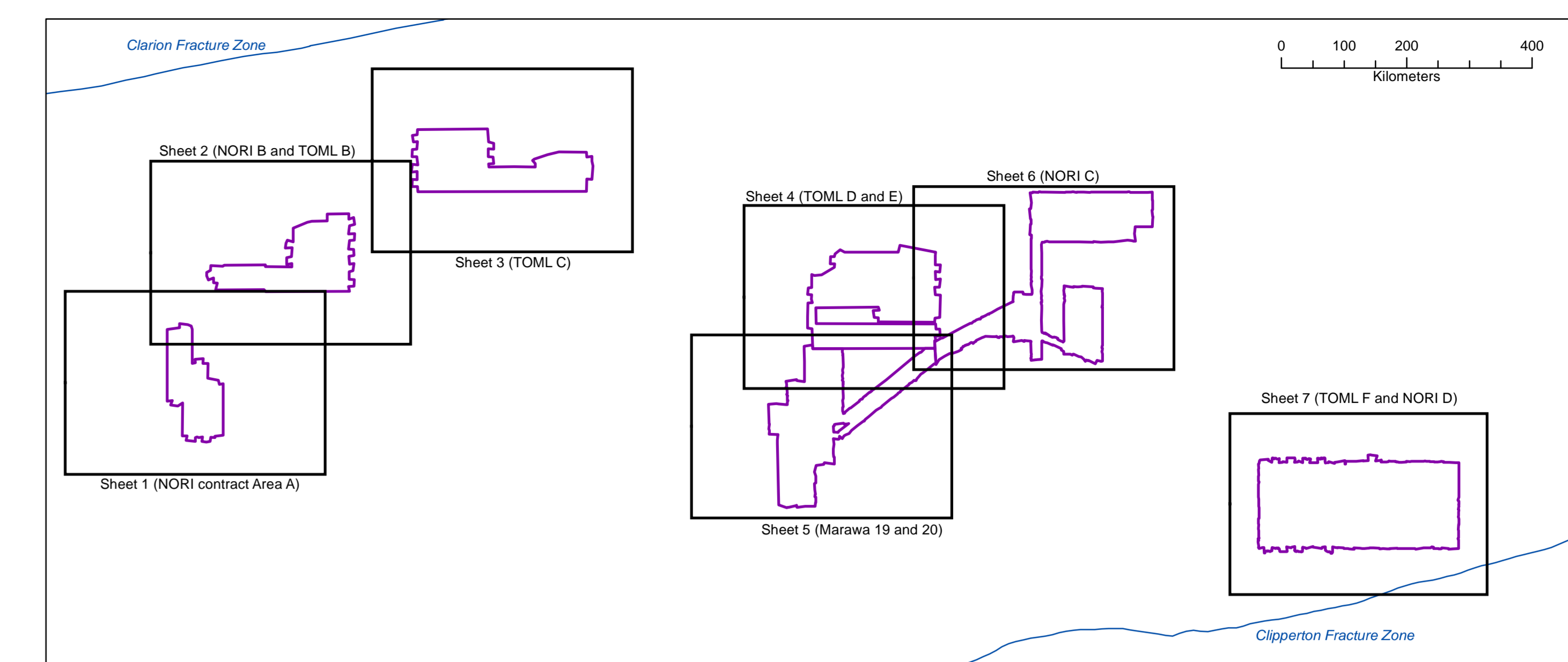
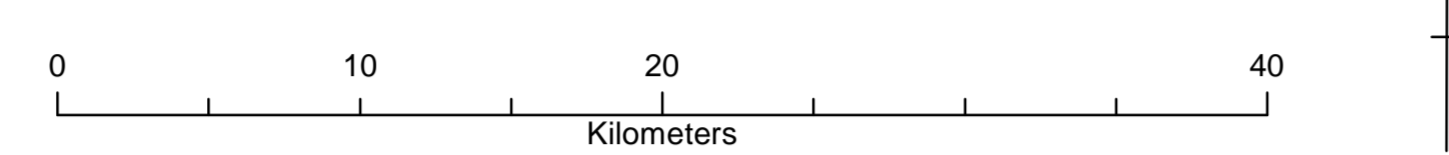
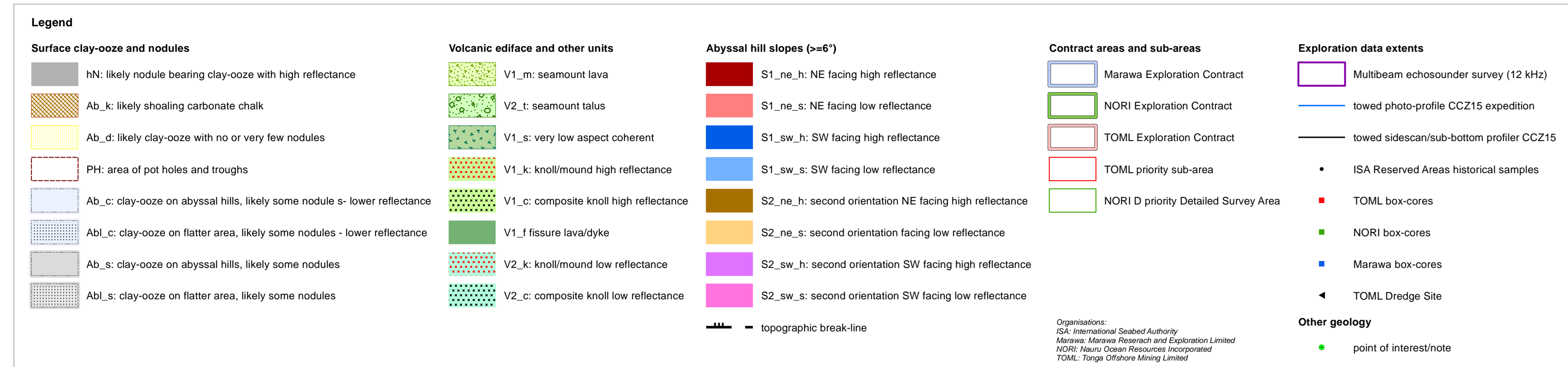
Surface Geology of part of the Clarion Clipperton Zone, tropical North Pacific Ocean - Sheet 2

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map is projected to UTM 8N WGS84

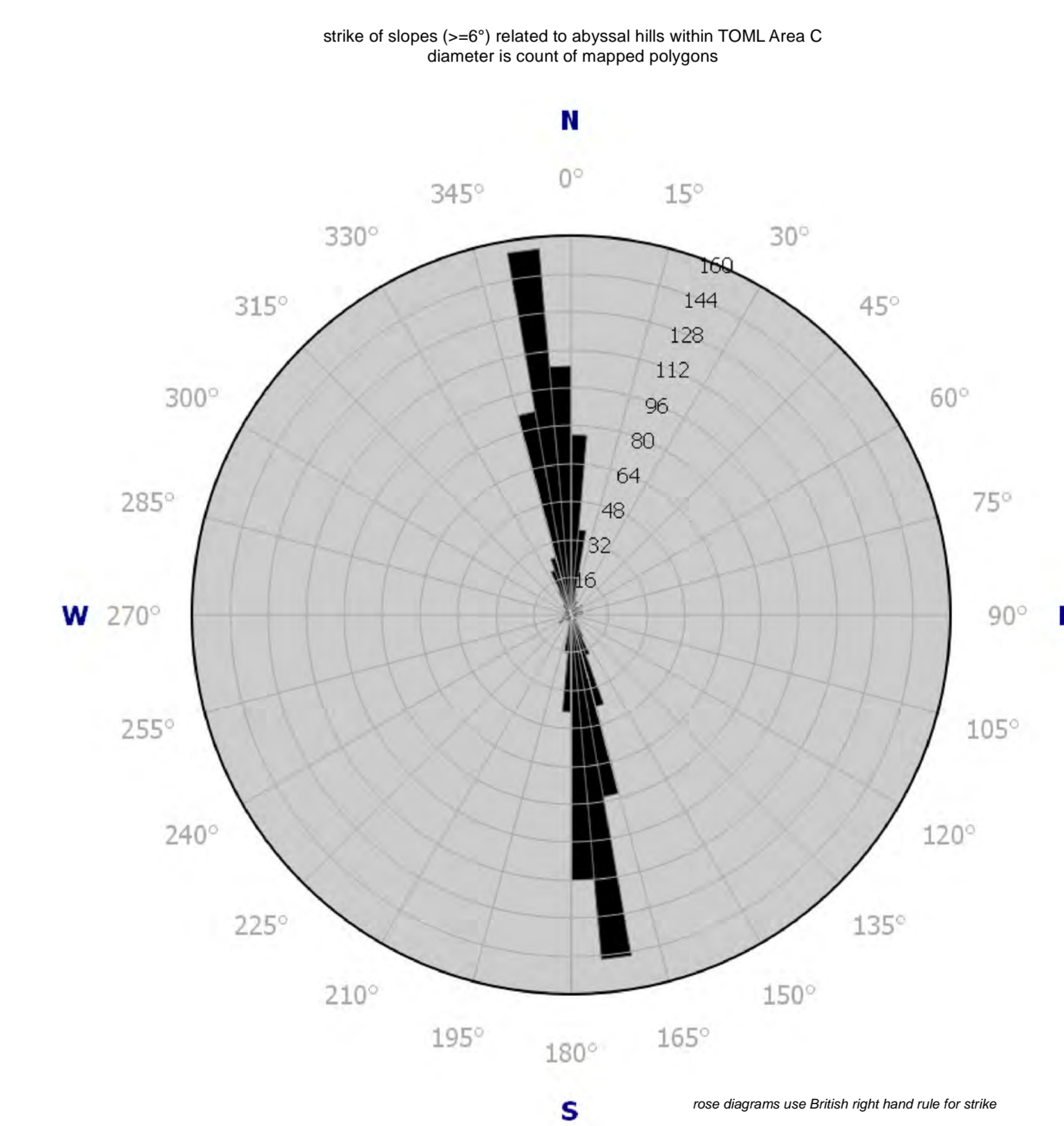


Surface Geology of part of the Clarion Clipperton Zone, tropical North Pacific Ocean - Sheet 3

1:250,000 scale
map is projected to UTM 9N WGS84

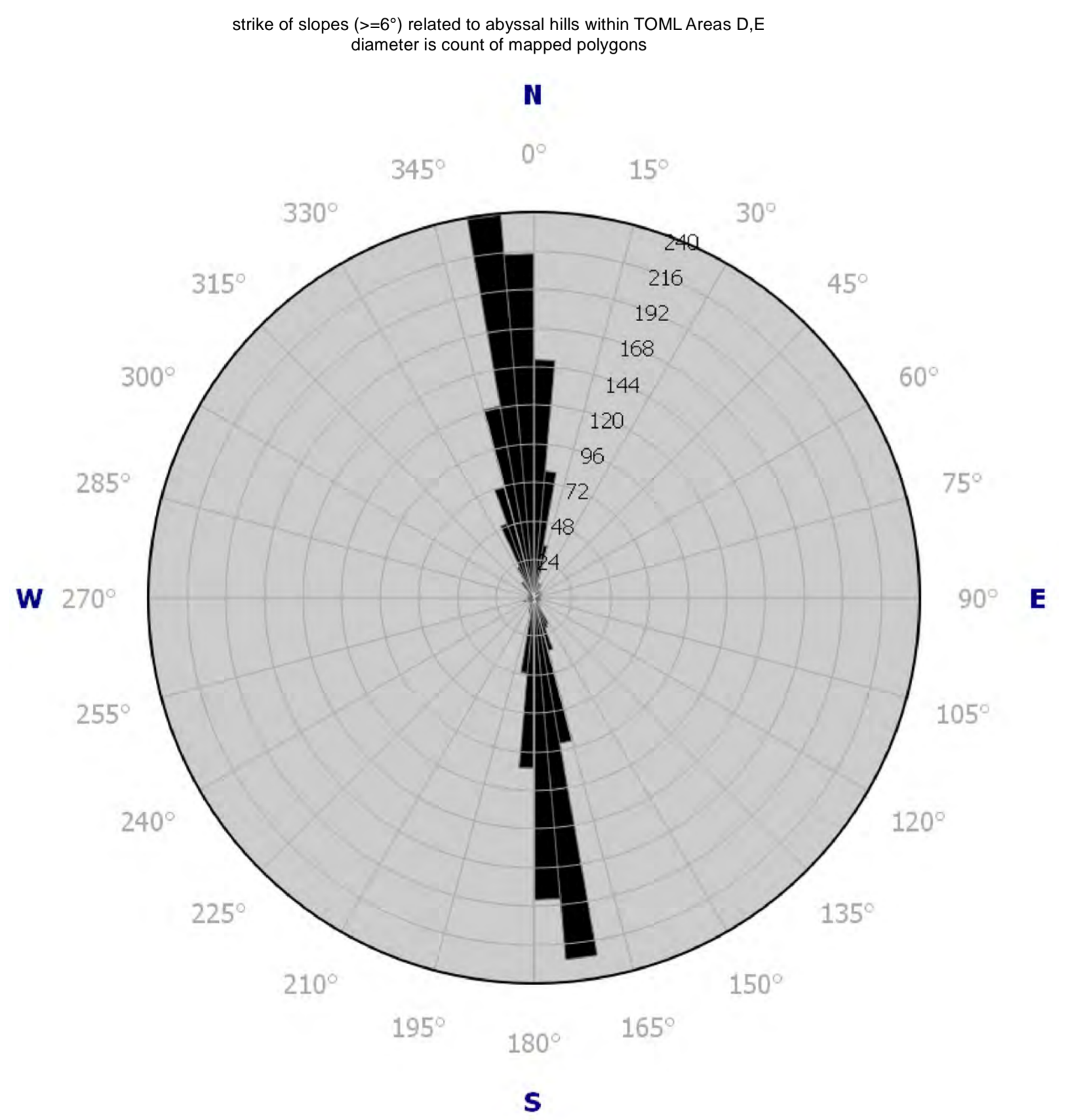
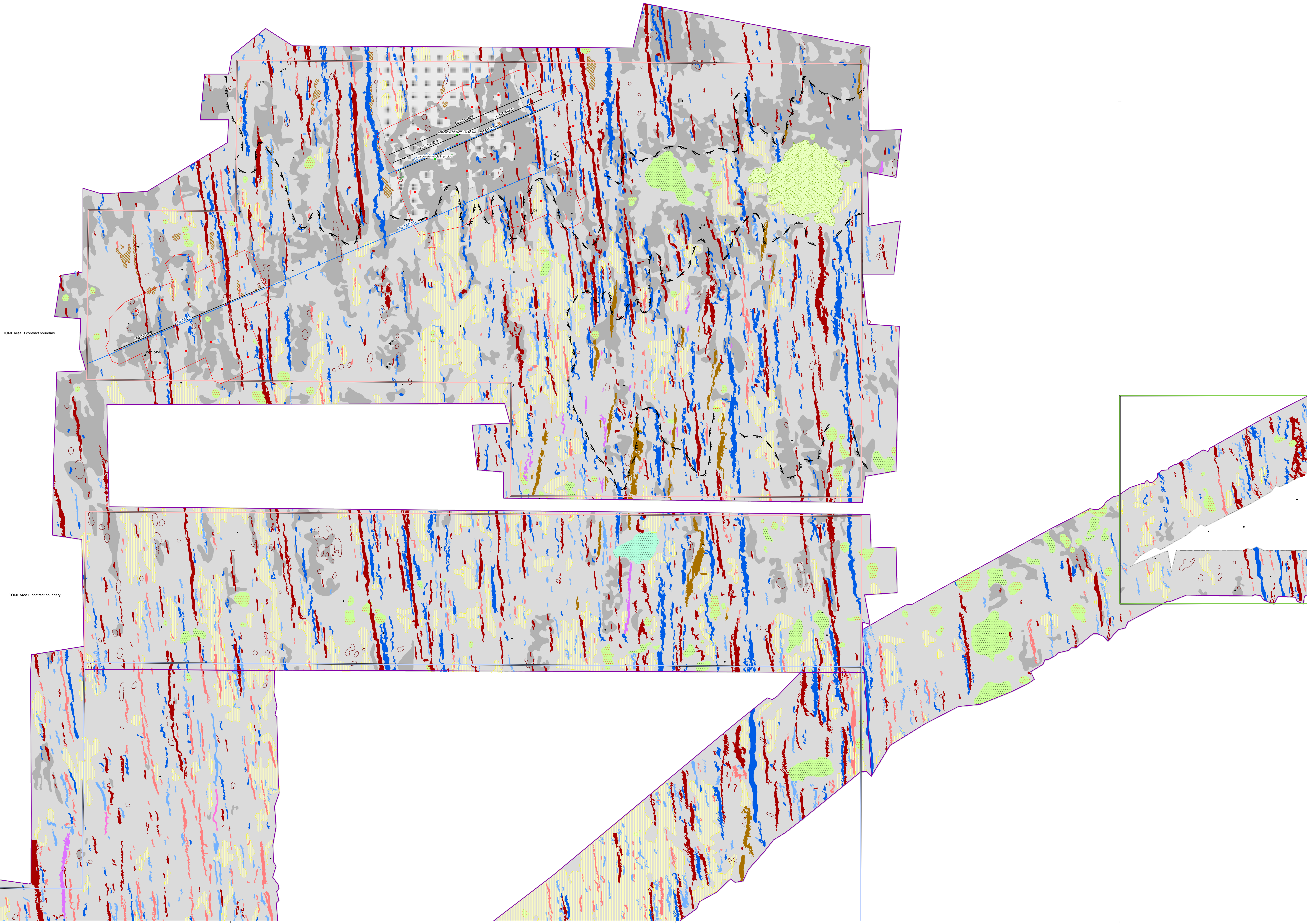
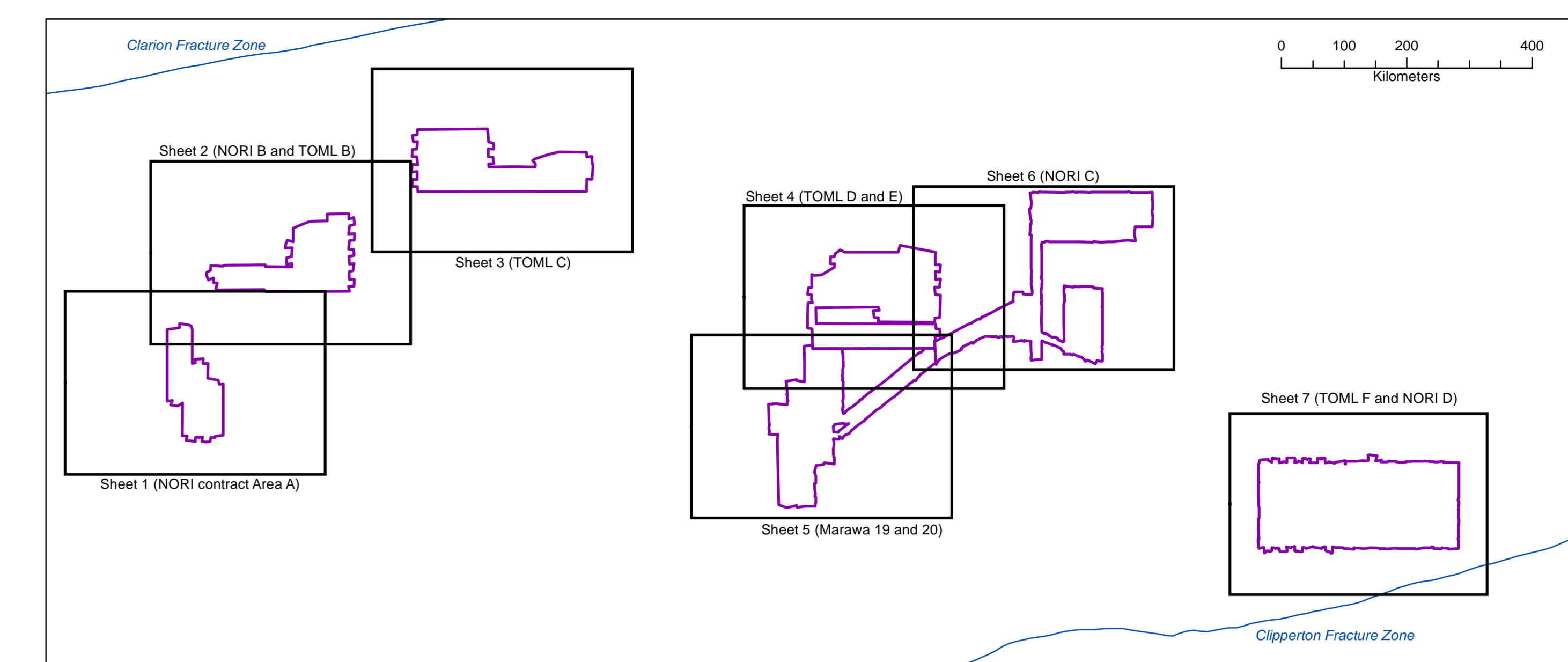
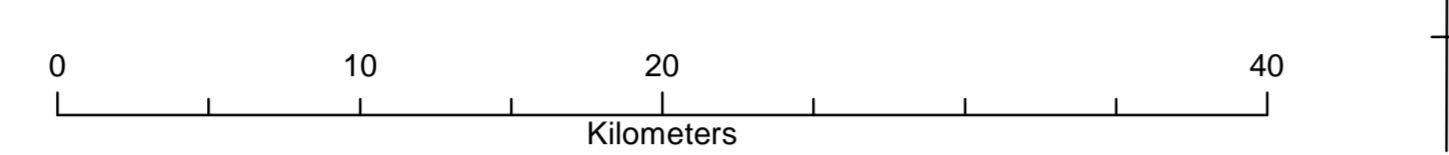
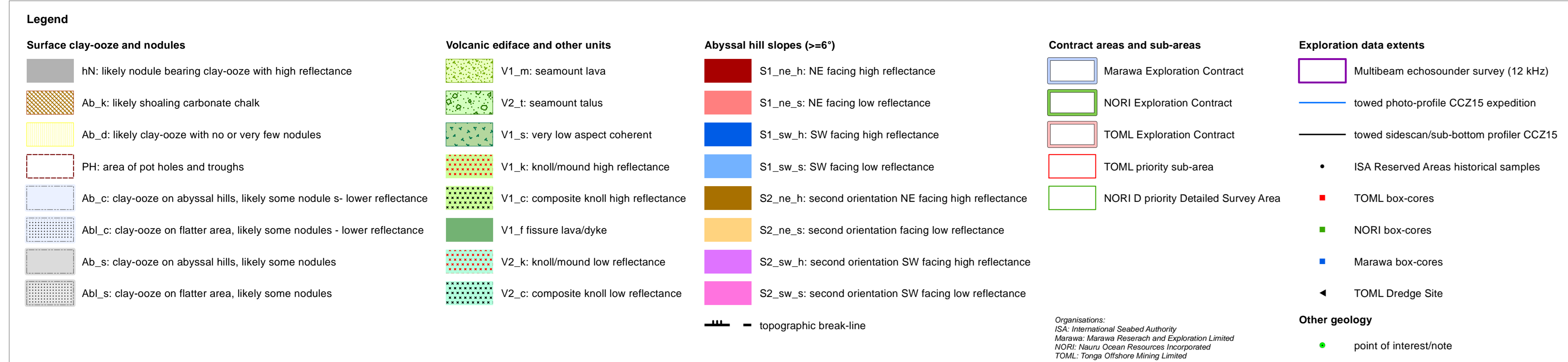


TOML Area C contract boundary



Surface Geology of part of the Clarion Clipperton Zone, tropical North Pacific Ocean - Sheet 4

1:250,000 scale
map is projected to UTM 10N WGS84



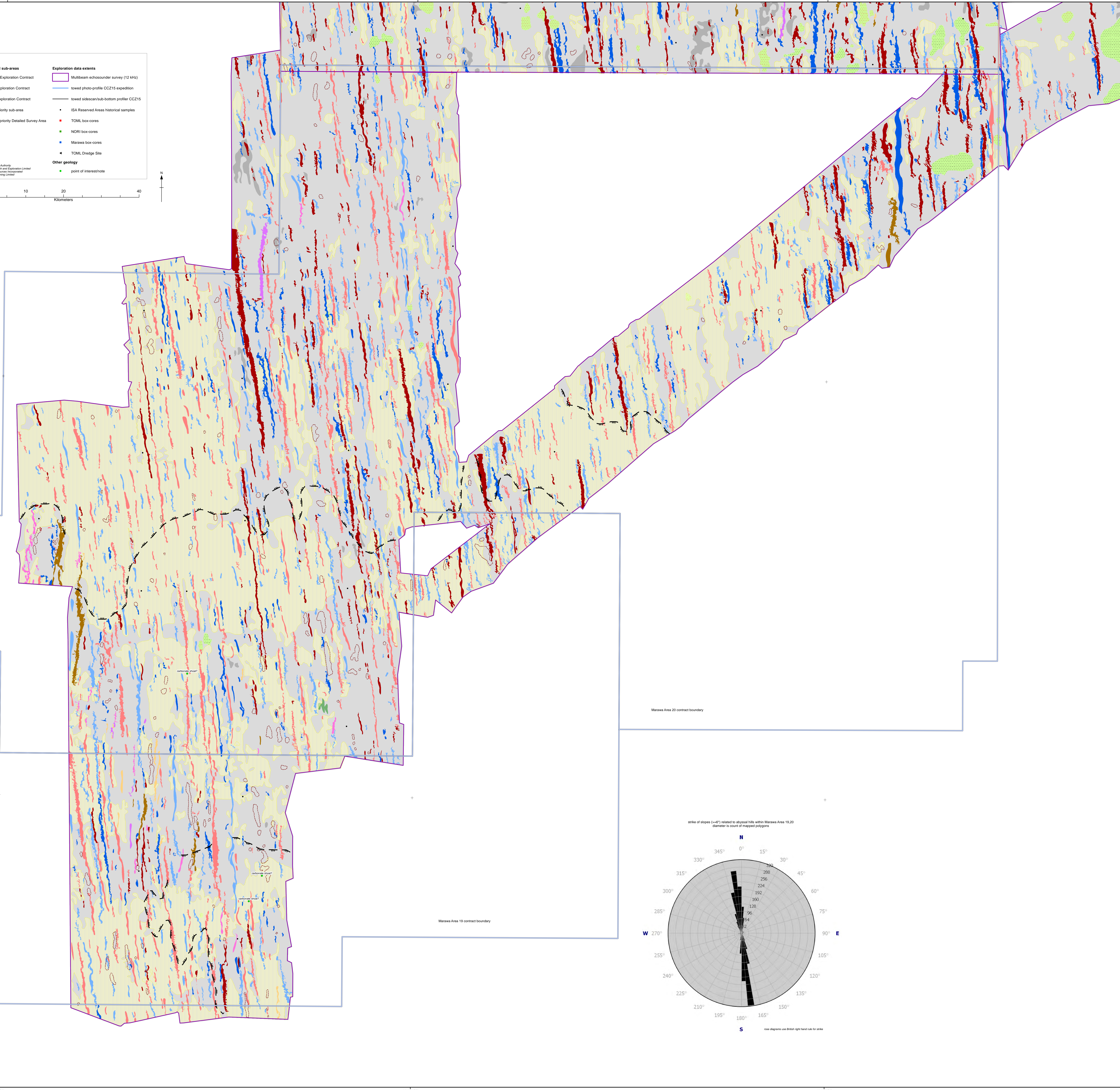
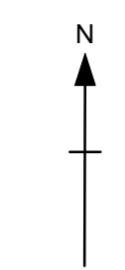
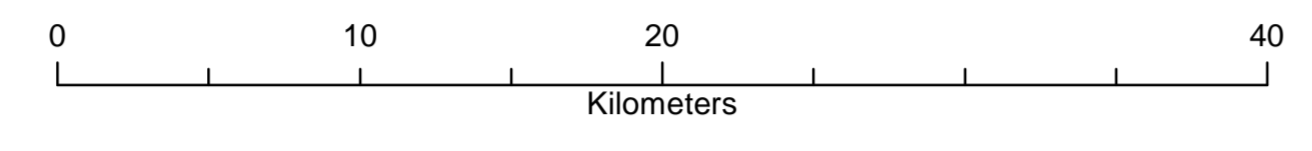
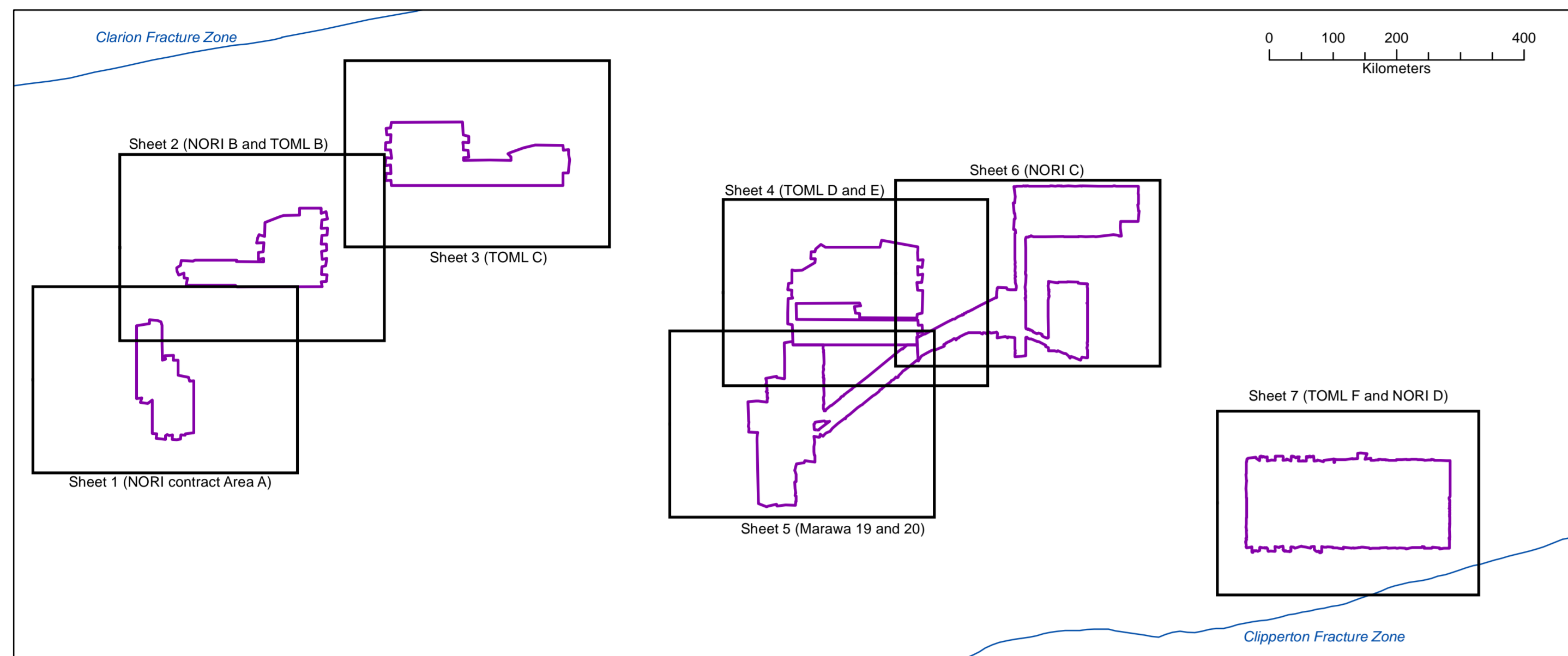
Surface Geology of part of the Clarion Clipperton Zone, tropical North Pacific Ocean - Sheet 5

1:250,000 scale
map is projected to UTM 10N WGS84

Legend

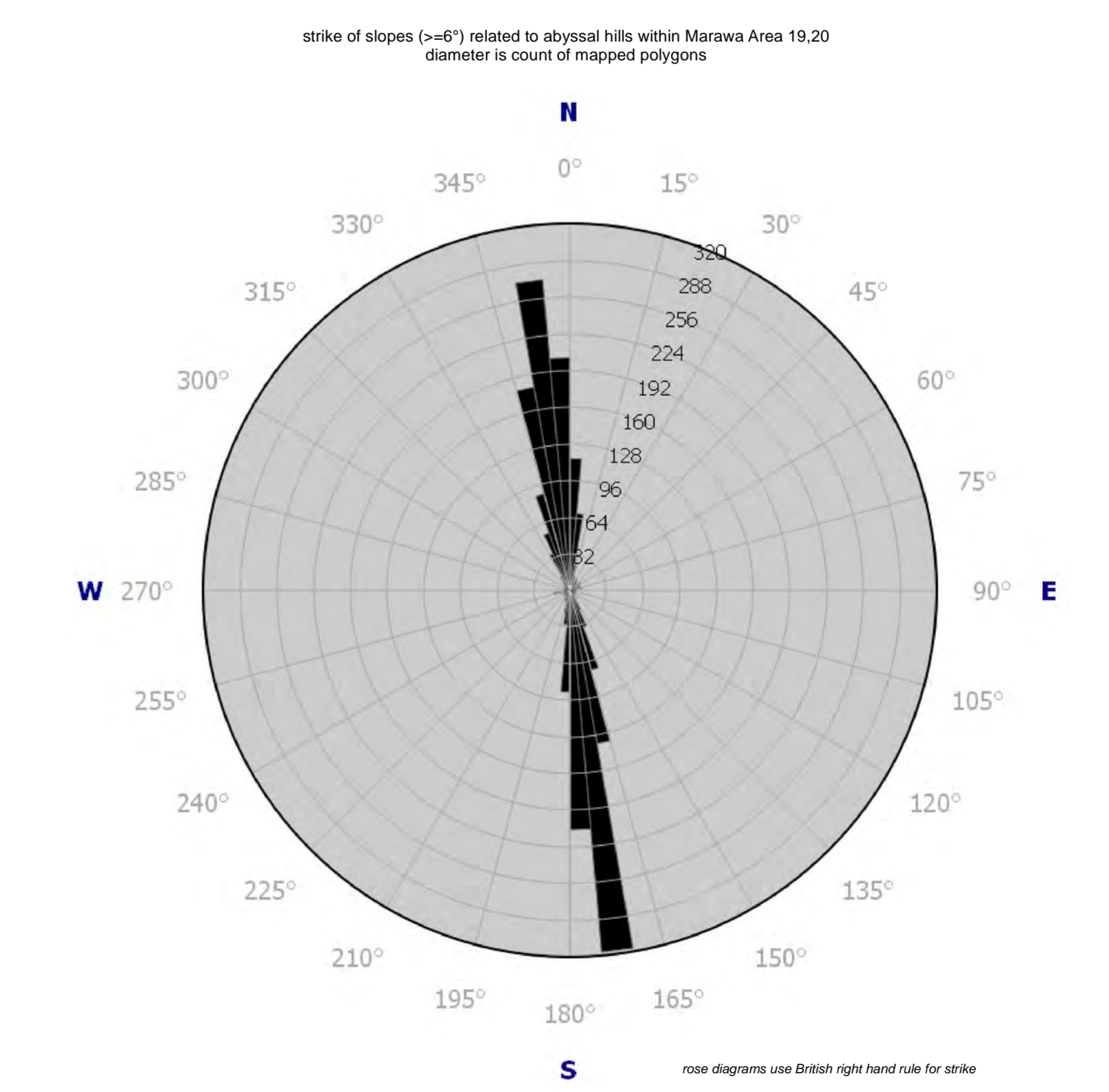
Surface clay-coats and nodules	Volcanic edifice and other units	Abyssal hill slopes (±4°)	Contract areas and sub-areas	Exploration data extents
HN: likely nodule bearing clay-coats with high reflectance	V1_m: seamount lava	S1_ne_h: NE facing high reflectance	Marawa Exploration Contract	Multibeam echosounder survey (12 MHz)
AB_k: likely shoaling carbonate chalk	V2_s: seamount talus	S1_ne_s: NE facing low reflectance	NORI Exploration Contract	lowed photo-profile CCZ15 expedition
AB_d: likely clay-coats with no or very low nodules	V1_s: very low aspect coherent	S1_sw_h: SW facing high reflectance	TOML Exploration Contract	lowed sidescan/sub-bottom profiler CCZ15
PH: area of pot holes and troughs	V1_k: knoll/mound high reflectance	S1_sw_s: SW facing low reflectance	TOML priority sub-area	ISA Reserved Areas historical samples
AB_c: clay-coats on abyssal hills, likely some nodule s- lower reflectance	V1_c: composite knoll high reflectance	S2_ne_h: second orientation NE facing high reflectance	NORI D priority Detailed Survey Area	TOML box-cores
AB_l_c: clay-coats on flatter area, likely some nodules - lower reflectance	V1_f: fissure breccia/dike	S2_ne_s: second orientation facing low reflectance		NORI box-cores
AB_s: clay-coats on abyssal hills, likely some nodules	V2_k: knoll/mound low reflectance	S2_sw_h: second orientation SW facing high reflectance		Marawa box-cores
AB_l_s: clay-coats on flatter area, likely some nodules	V2_c: composite knoll low reflectance	S2_sw_s: second orientation SW facing low reflectance		TOML Dropge Site
				Other geology
				point of interest
				topographic break-line

Organization: USA: International Seabed Authority
MORAWA: MORAWA Resources and Exploration Limited
NORI: NORI Ocean Resources and Exploration Limited
TOML: TOML Ocean Resources and Exploration Limited
TOML: TOML Ocean Resources and Exploration Limited



Marawa Area 20 contract boundary

Marawa Area 19 contract boundary



Surface Geology of part of the Clarion Clipperton Zone, tropical North Pacific Ocean - Sheet 6

1:250,000 scale
map is projected to UTM 10N UTM WGS84

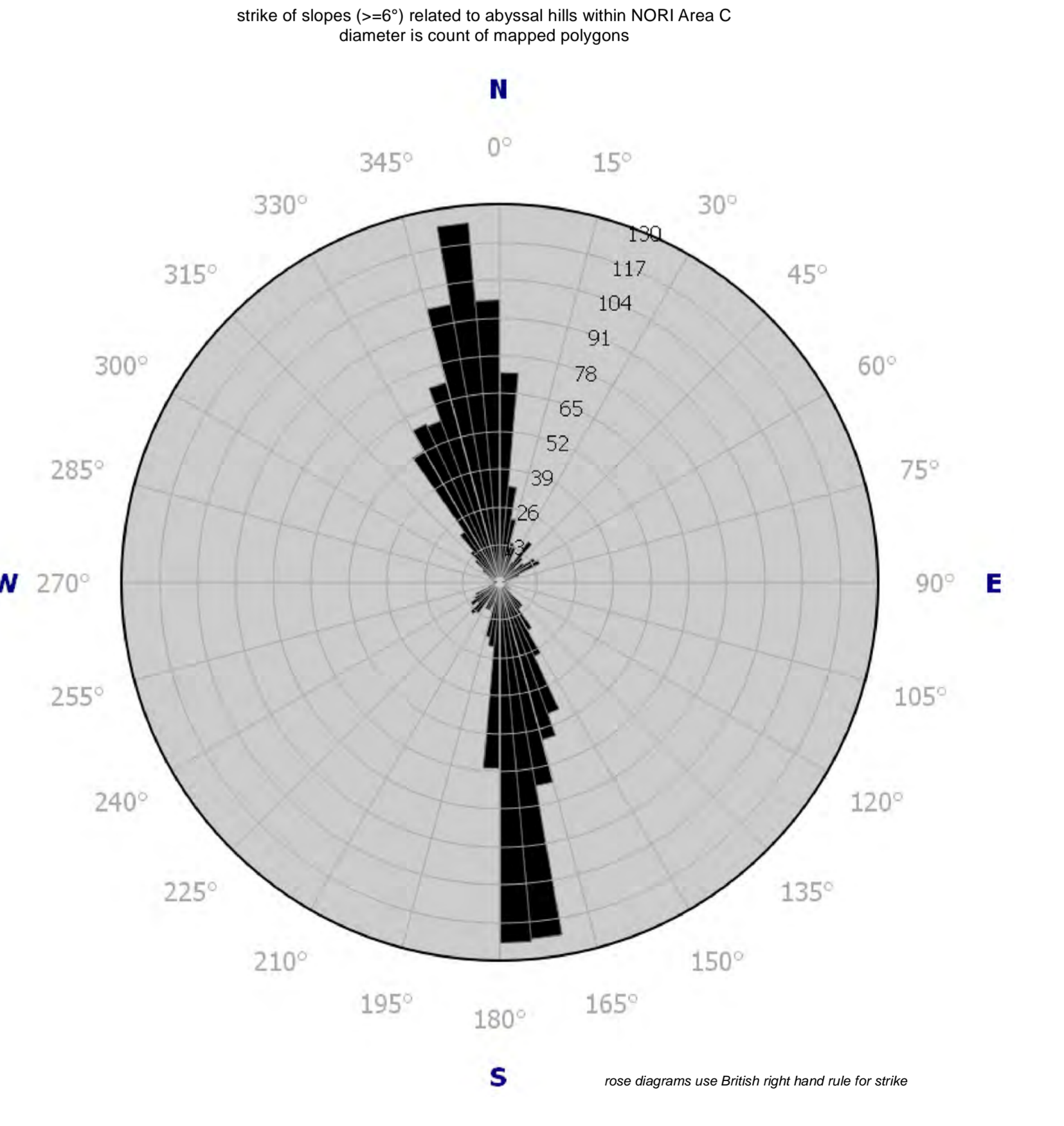
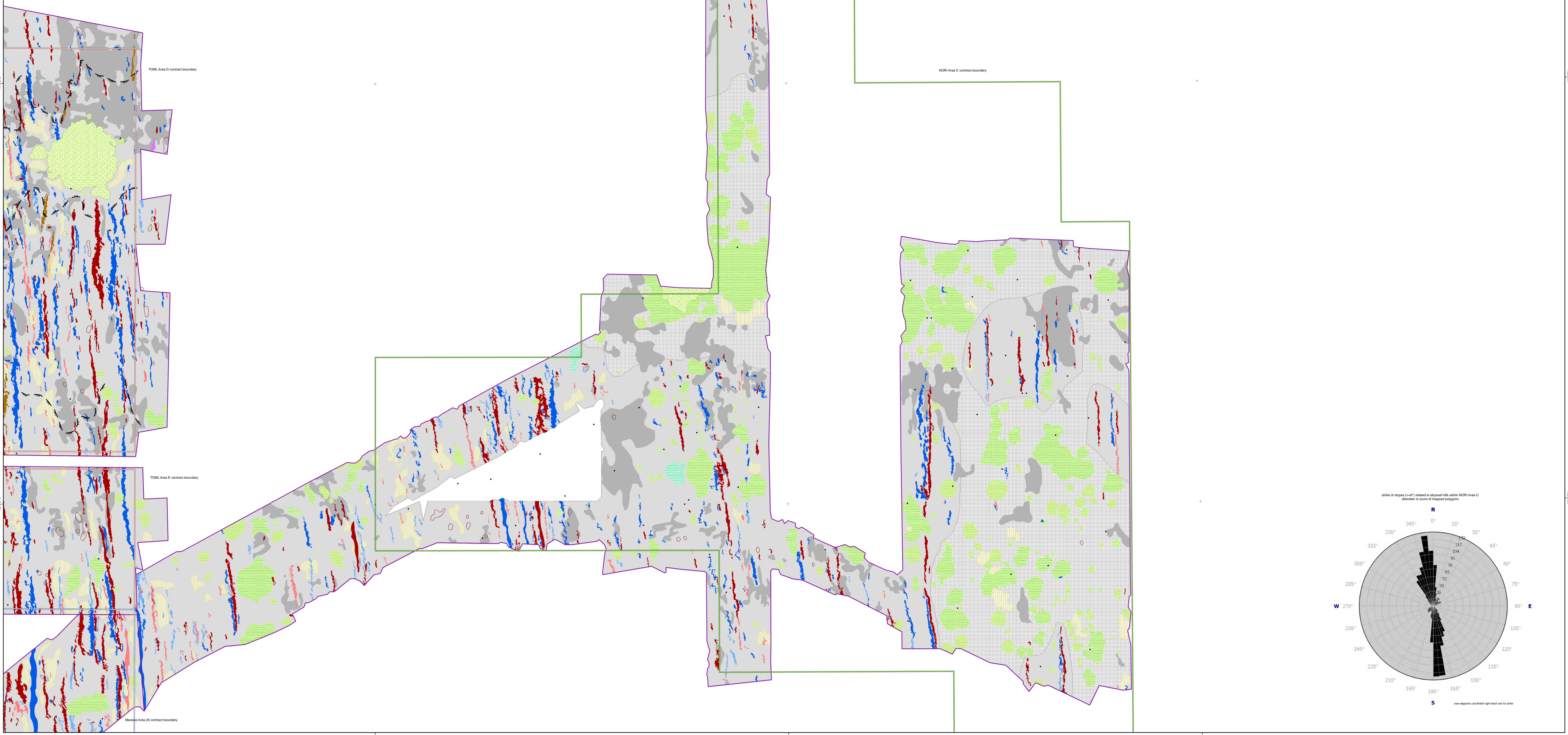
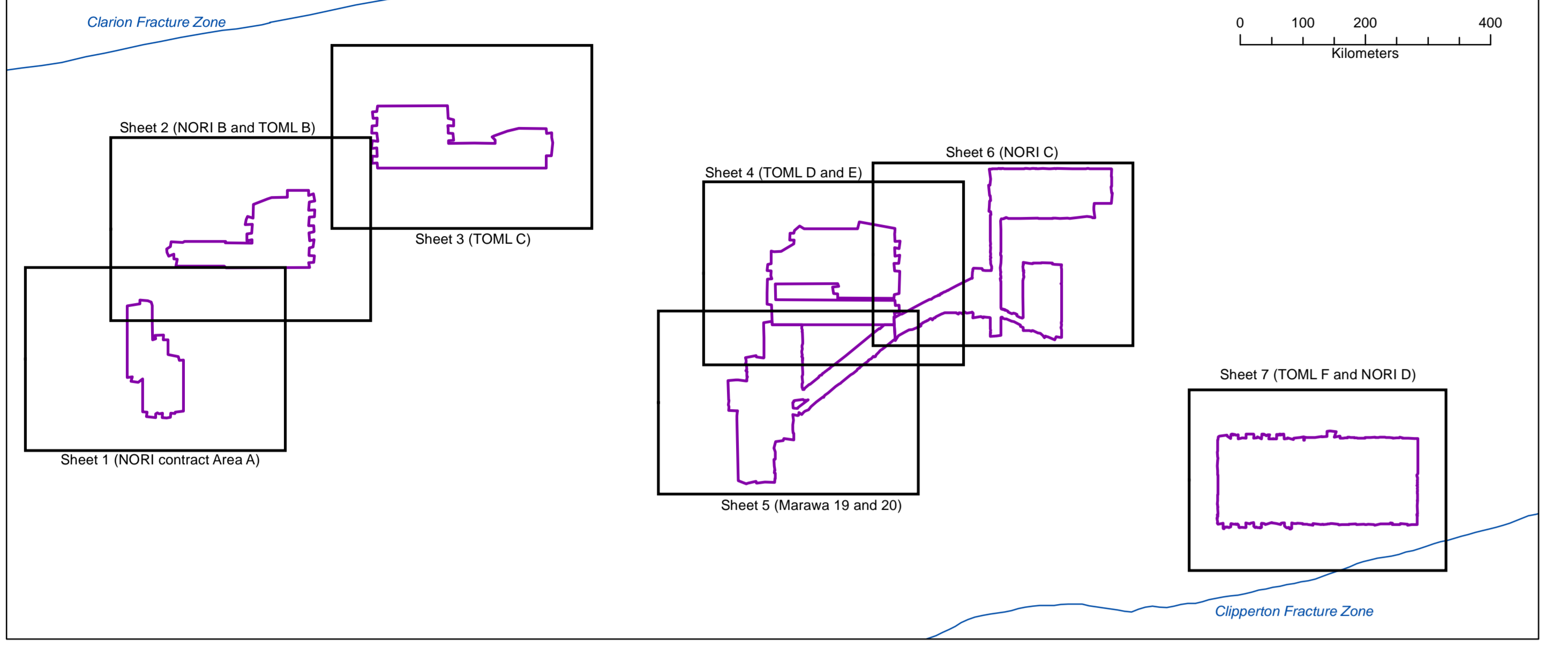
Legend

<p>Surface clay-coze and nodules</p> <ul style="list-style-type: none"> HN: likely nodule bearing clay-coze with high reflectance AD_k: likely shoaling carbonate chalk AD_d: likely clay-coze with no or very few nodules PH: area of pot holes and troughs AB_c: clay-coze on abyssal hills, likely some nodule s- lower reflectance AB_l: clay-coze on flatter area, likely some nodules - lower reflectance AB_s: clay-coze on abyssal hills, likely some nodules AB_f: clay-coze on flatter area, likely some nodules 	<p>Volcanic edifice and other units</p> <ul style="list-style-type: none"> V1_m: seamount lava V2_s: seamount talus V1_s: very low aspect coherent V1_k: knoll/mound high reflectance V1_c: composite knoll high reflectance V1_f: feature brachiopod V2_k: knoll/mound low reflectance V2_c: composite knoll low reflectance 	<p>Abyssal hill slopes (=>f)</p> <ul style="list-style-type: none"> S1_ne_h: NE facing high reflectance S1_ne_s: NE facing low reflectance S1_sw_h: SW facing high reflectance S1_sw_s: SW facing low reflectance S2_ne_h: second orientation NE facing high reflectance S2_ne_s: second orientation NE facing low reflectance S2_sw_h: second orientation SW facing high reflectance S2_sw_s: second orientation SW facing low reflectance 	<p>Contract areas and sub-areas</p> <ul style="list-style-type: none"> Marawa Exploration Contract NORI Exploration Contract TOML Exploration Contract TOML priority sub-area NORI D priority Detailed Survey Area 	<p>Exploration data extents</p> <ul style="list-style-type: none"> Multibeam echosounder survey (12 MHz) lowed photo-profile CCZ15 expedition lowed sidescan/sub-bottom profiler CCZ15 ISA Reserved Areas historical samples TOML box-cores NORI box-cores Marawa box-cores TOML Drift Site
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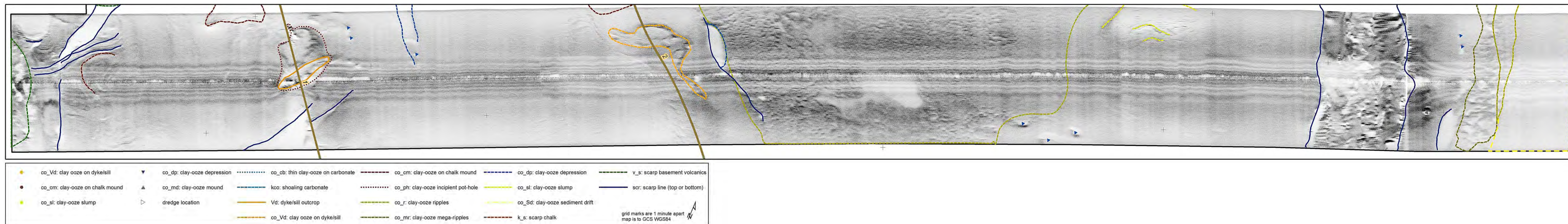
Other geology

- point of interest

Topographic break-line



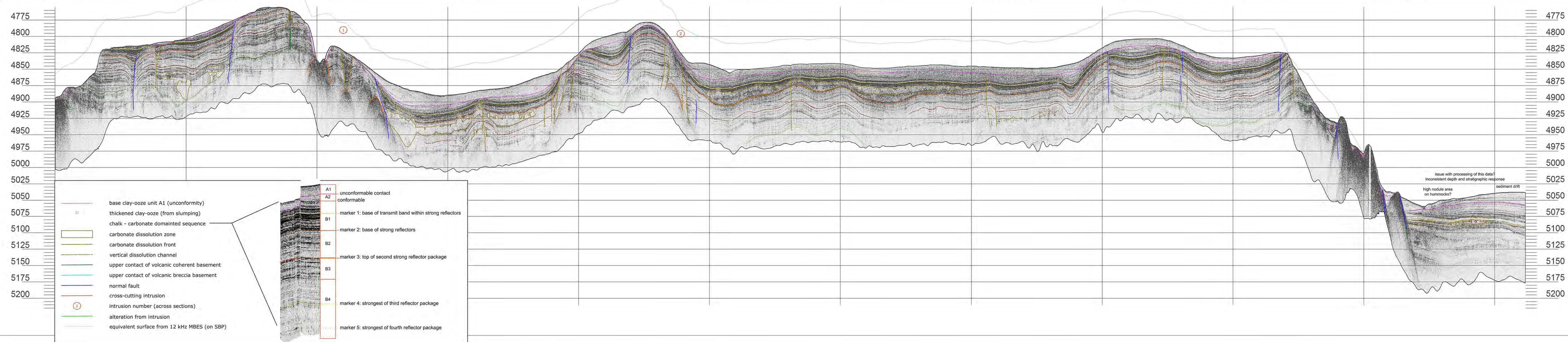
CCZ15-M01 30 kHz towed sidescan sonar response



5 kHz towed sub-bottom profiler response

V/H = 10

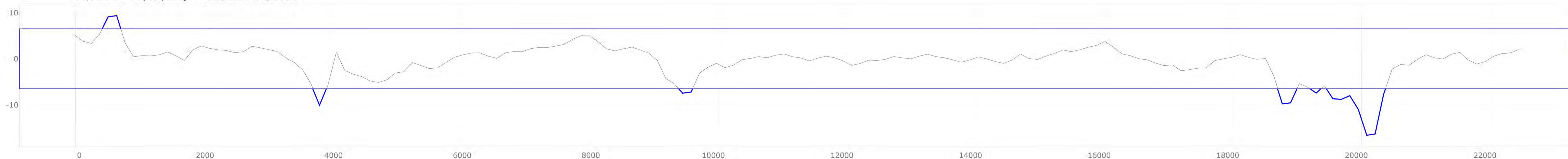
Пикет, м	0	2000	4000	6000	8000	10000	12000	14000	16000	18000	20000	22000
Глубина, м	4894	4802	4835	4889	4826	4842	4841	4845	4817	4832	4979	5039
Широта	13°34.76'N	13°35.20'N	13°35.63'N	13°36.08'N	13°36.53'N	13°36.97'N	13°37.41'N	13°37.84'N	13°38.26'N	13°38.68'N	13°39.08'N	13°39.51'N
Долгота	132°57.58'W	132°56.56'W	132°55.55'W	132°54.54'W	132°53.53'W	132°52.52'W	132°51.50'W	132°50.49'W	132°49.47'W	132°48.44'W	132°47.41'W	132°46.40'W



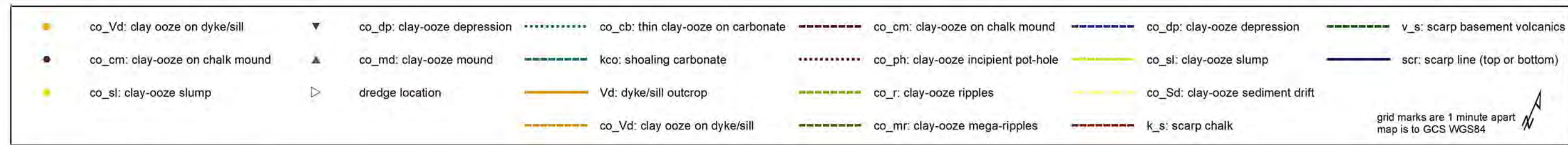
V/H = 1

slope of 12 kHz bathymetry in degrees

negative numbers are slope to the NE
positive numbers are slope to the SW

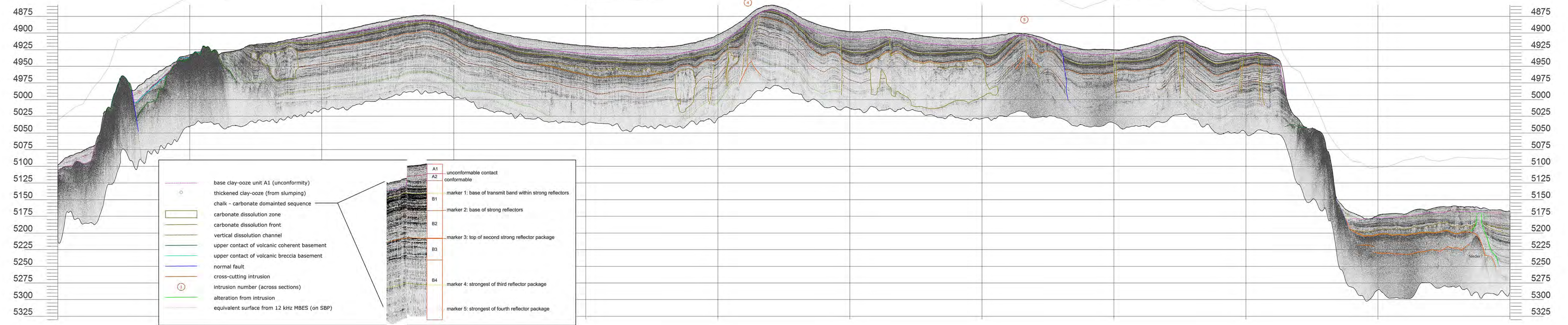


CCZ15-M03 30 kHz towed sidescan sonar response



5 kHz towed sub-bottom profiler response
V/H = 10

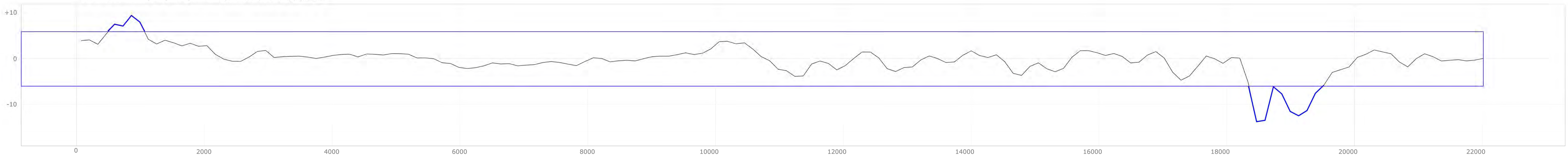
Пикет, м	0	2000	4000	6000	8000	10000	12000	14000	16000	18000	20000	22000
Глубина, м	5098	4932	4899	4880	4918	4902	4897	4907	4925	4930	5173	5167
Широта	13°36.85'N	13°37.32'N	13°37.76'N	13°38.20'N	13°38.64'N	13°39.08'N	13°39.51'N	13°39.94'N	13°40.36'N	13°40.77'N	13°41.19'N	13°41.61'N
Долгота	132°58.21'W	132°57.22'W	132°56.20'W	132°55.19'W	132°54.18'W	132°53.16'W	132°52.14'W	132°51.13'W	132°50.11'W	132°49.08'W	132°48.06'W	132°47.04'W



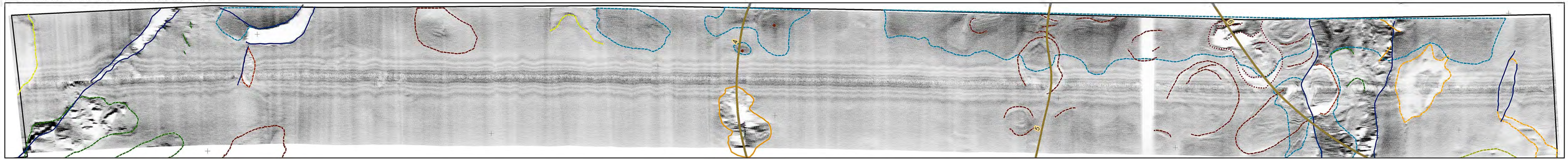
V/H = 1



slope of 12 kHz bathymetry in degrees
negative numbers are slope to the NE
positive numbers are slope to the SW



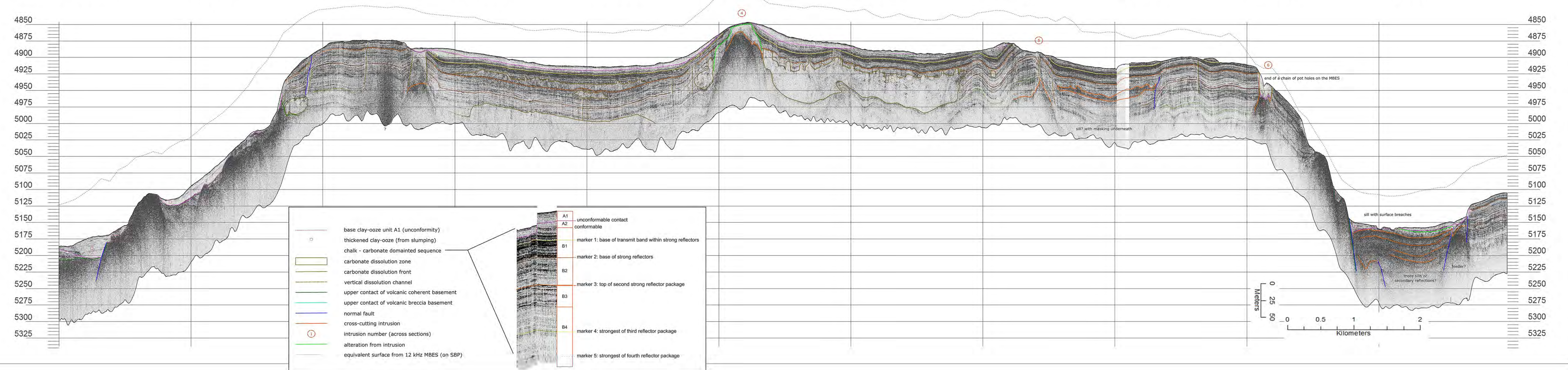
CCZ15-M04 30 kHz towed sidescan sonar response



- co_Vd: clay ooze on dyke/sill
 - ▼ co_dp: clay-ooze depression
 - co_ob: thin clay-ooze on carbonate
 - co_cm: clay-ooze on chalk mound
 - co_dp: clay-ooze depression
 - v_s: scarp basement volcanics
 - co_cm: clay-ooze on chalk mound
 - ▲ co_md: clay-ooze mound
 - kco: shoaling carbonate
 - co_ph: clay-ooze incipient pot-hole
 - co_sl: clay-ooze slump
 - v_d: dyke/sill outcrop
 - co_r: clay-ooze ripples
 - co_Sd: clay-ooze sediment drift
 - co_sl: clay-ooze slump
 - ▷ dredge location
 - co_Vd: clay ooze on dyke/sill
 - co_mr: clay-ooze mega-ripples
 - k_s: scarp chalk
- grid marks are 1 minute apart
map is to GCS VGS84

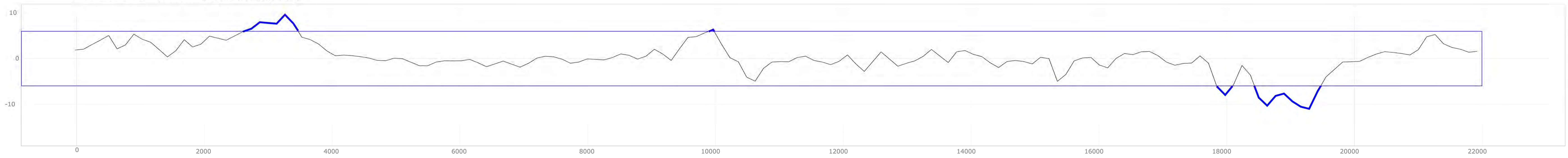
5 kHz towed sub-bottom profiler response
V/H = 10

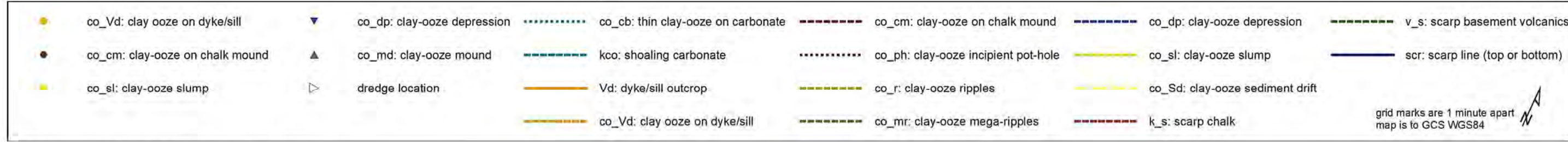
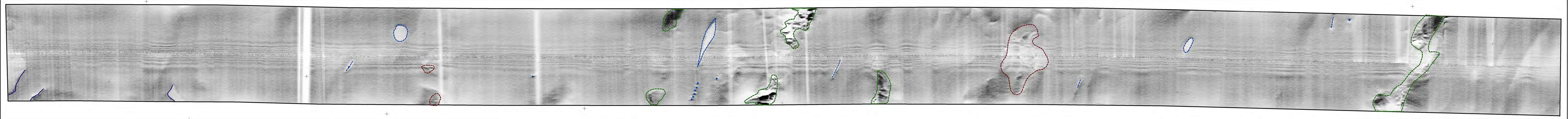
Пикет, м	0	2000	4000	6000	8000	10000	12000	14000	16000	18000	20000
Глубина, м	5186	5095	4885	4888	4914	4865	4882	4888	4916	4911	5159
Широта	13°37.89'N	13°38.38'N	13°38.83'N	13°39.25'N	13°39.68'N	13°40.09'N	13°40.51'N	13°40.92'N	13°41.34'N	13°41.76'N	13°42.18'N
Долгота	132°58.59'W	132°57.60'W	132°56.59'W	132°55.57'W	132°54.55'W	132°53.53'W	132°52.51'W	132°51.48'W	132°50.46'W	132°49.43'W	132°48.42'W



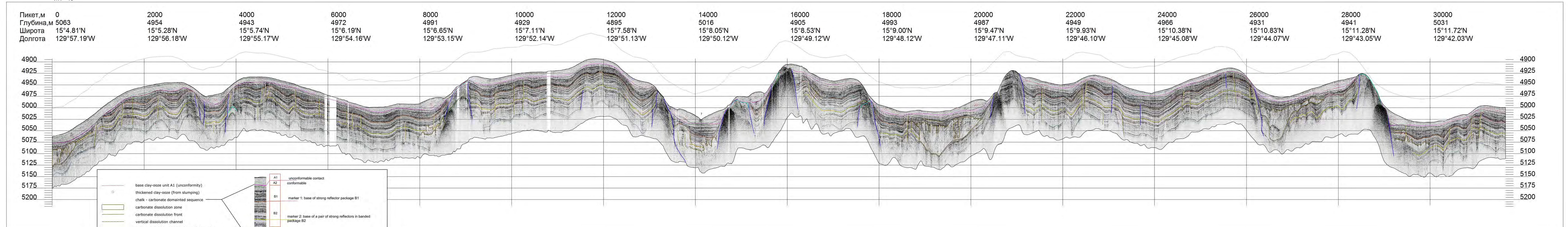
V/H = 1

slope of 12 kHz bathymetry in degrees
negative numbers are slope to the NE
positive numbers are slope to the SW

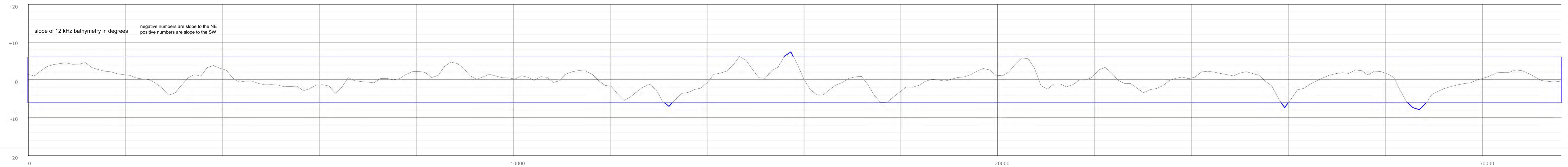




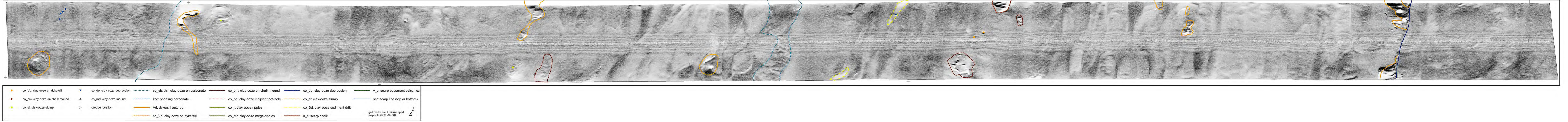
5 kHz towed sub-bottom profiler response
V/H = 10



V/H = 1

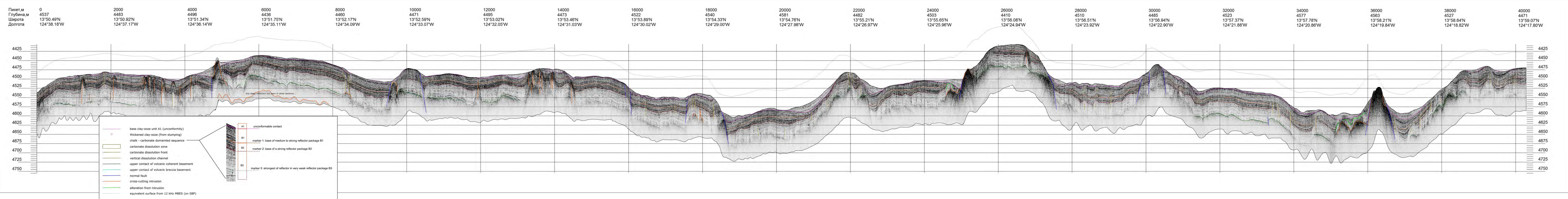


CCZ15-M06 30 kHz towed sidescan sonar response

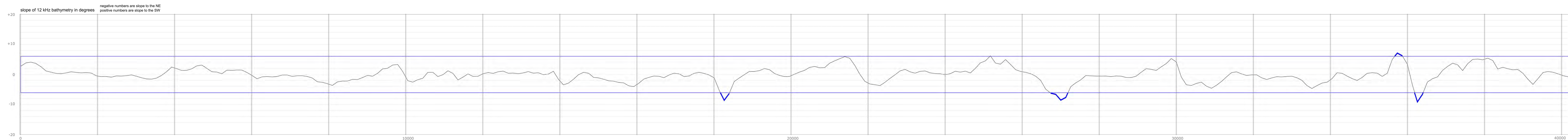


5 kHz towed sub-bottom profiler response

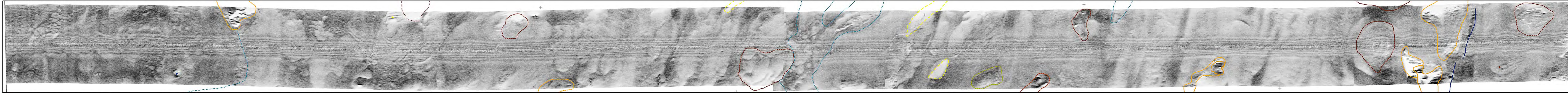
V/H = 10



V/H = 1



Line M07: 30 kHz towed sidescan sonar response

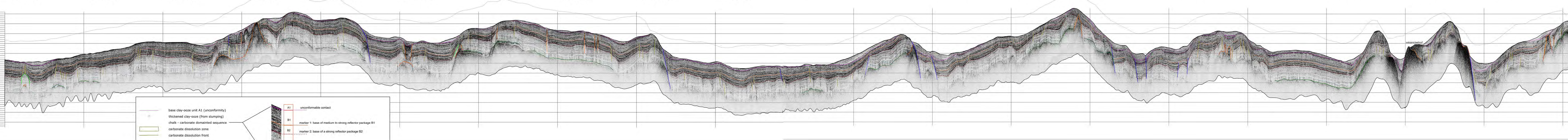


- co_Vd: clay ooze on dyke/sill
- ▼ co_dp: clay-ooze depression
- co_cb: thin clay-ooze on carbonate
- co_cm: clay-ooze on chalk mound
- co_dp: clay-ooze depression
- v_s: scarp basement volcanics
- co_cm: clay-ooze on chalk mound
- ▲ co_md: clay-ooze mound
- kco: shoaling carbonate
- co_ph: clay-ooze incipient pot-hole
- co_sl: clay-ooze slump
- scr: scarp line (top or bottom)
- co_sl: clay-ooze slump
- ▷ dredge location
- Vd: dyke/sill outcrop
- co_r: clay-ooze ripples
- co_Sd: clay-ooze sediment drift
- k_s: scarp chalk

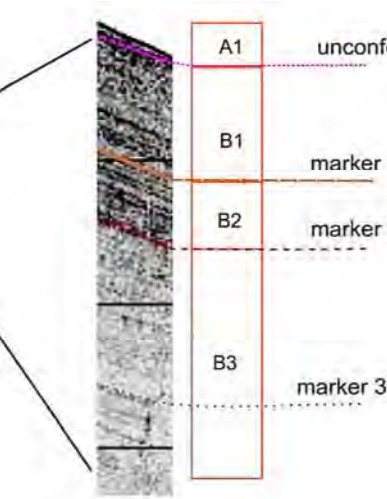
5 kHz towed sub-bottom profiler response

V/H = 10

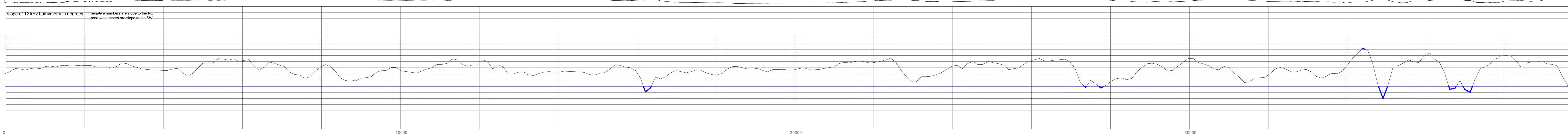
Пикет, м	0	2000	4000	6000	8000	10000	12000	14000	16000	18000	53	2000	4000	6000	8000	10000	12000	14000	16000	18000	20000
Глубина, м	4541	4526	4497	4465	4441	4484	4461	4466	4484	4546	55.72°N	4531	4519	4481	4438	4510	4487	4531	4528	4551	4447
Широта	13°51.62'N	13°52.05'N	13°52.48'N	13°52.88'N	13°53.28'N	13°53.69'N	13°54.12'N	13°54.57'N	13°55.02'N	13°55.46'N	4°28.74'W	13°56.17'N	13°56.60'N	13°57.04'N	13°57.48'N	13°57.91'N	13°58.36'N	13°58.79'N	13°59.24'N	13°59.69'N	14°0.14'N
Долгота	124°38.70'W	124°37.68'W	124°36.66'W	124°35.63'W	124°34.60'W	124°33.57'W	124°32.55'W	124°31.54'W	124°30.53'W	124°29.52'W		124°27.73'W	124°26.71'W	124°25.69'W	124°24.68'W	124°23.66'W	124°22.65'W	124°21.63'W	124°20.62'W	124°19.61'W	124°18.60'W



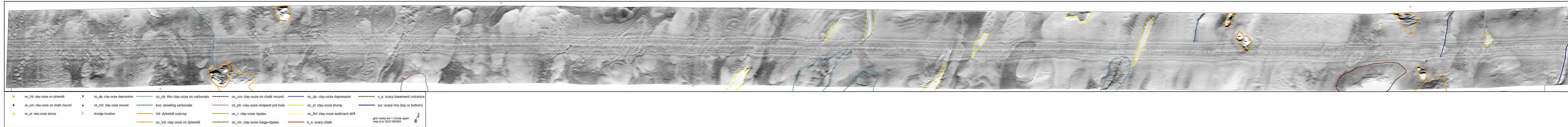
- base clay-ooze unit A1 (unconformity)
- thickened clay-ooze (from slumping)
- chalk - carbonate dominated sequence
- carbonate dissolution zone
- carbonate dissolution front
- vertical dissolution channel
- upper contact of volcanic coherent basement
- upper contact of volcanic breccia basement
- normal fault
- cross-cutting intrusion
- alteration from intrusion
- equivalent surface from 12 kHz MBES (on SBP)



V/H = 1



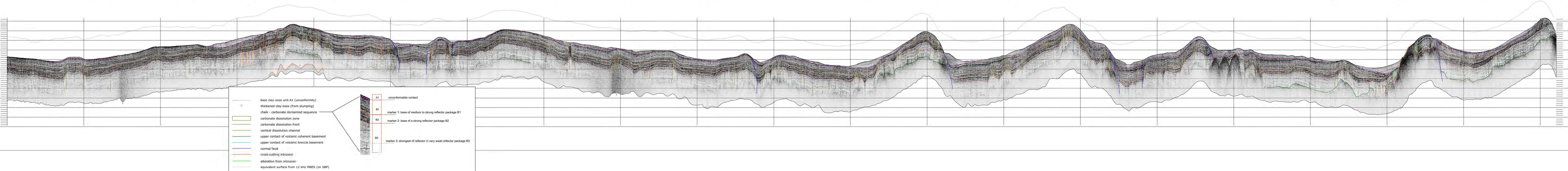
Line M08: 30 kHz towed sidescan sonar response



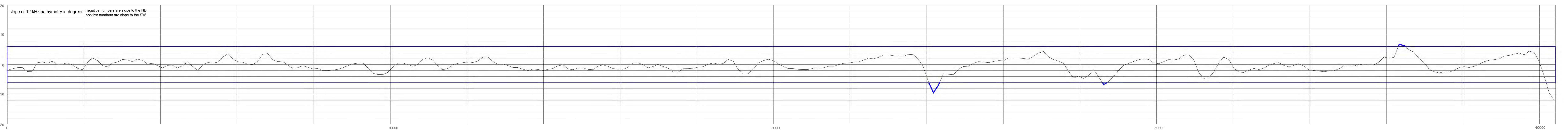
5 kHz towed sub-bottom profiler response

V/H = 10

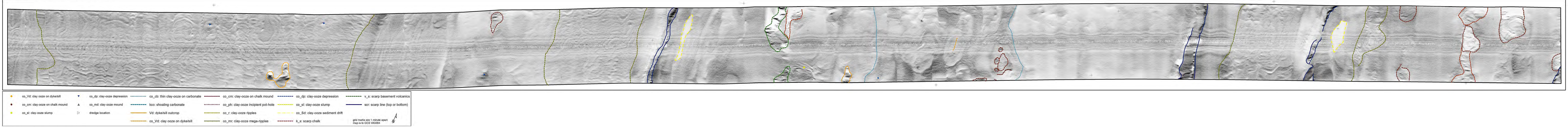
Пикет.м	0	2000	4000	6000	8000	10000	12000	14000	16000	18000	18000	20000	22000	24000	26000	28000	30000	32000	34000	36000	38000	40000
Глубина,м	4517	4523	4491	4471	4443	4473	4475	4463	4496	4522	4518	4541	4518	4451	4514	4447	4511	4498	4519	4542	4502	4421
Широта	13°52.66'N	13°53.10'N	13°53.55'N	13°54.00'N	13°54.45'N	13°54.88'N	13°55.30'N	13°55.74'N	13°56.15'N	13°56.57'N	13°56.99'N	13°57.41'N	13°57.82'N	13°58.24'N	13°58.67'N	13°59.08'N	13°59.51'N	14°0.37'N	14°0.74'N	14°1.11'N	14°1.48'N	14°1.85'N
Долгота	124°39.24'W	124°38.22'W	124°37.22'W	124°36.21'W	124°35.19'W	124°34.17'W	124°33.15'W	124°32.14'W	124°31.11'W	124°30.09'W	124°29.06'W	124°28.04'W	124°27.01'W	124°25.99'W	124°24.97'W	124°23.94'W	124°22.92'W	124°21.89'W	124°20.88'W	124°19.88'W	124°18.87'W	124°17.86'W



V/H = 1



CCZ15-M09: 30 kHz towed sidescan sonar response



5 kHz towed sub-bottom profiler response

V/H = 10

Пикет, м	0	2000	4000	6000	8000	10000	12000	14000	16000	18000	20000	22000	24000	26000	28000	30000	32000	34000	36000	38000	40000
Глубина, м	4679	4657	4657	4639	4631	4739	4760	4637	4638	4772	4693	4611	4594	4630	4581	4532	4705	4745	4711	4612	4620
Широта	13°26.29'N	13°26.70'N	13°27.11'N	13°27.53'N	13°27.95'N	13°28.39'N	13°28.84'N	13°29.30'N	13°29.76'N	13°30.18'N	13°30.63'N	13°31.06'N	13°31.51'N	13°31.95'N	13°32.40'N	13°32.83'N	13°33.26'N	13°33.68'N	13°34.10'N	13°34.51'N	13°34.94'N
Долгота	125°16.50'W	125°15.47'W	125°14.45'W	125°13.42'W	125°12.40'W	125°11.39'W	125°10.39'W	125°9.38'W	125°8.38'W	125°7.36'W	125°6.35'W	125°5.33'W	125°4.32'W	125°3.31'W	125°2.30'W	125°1.29'W	125°0.27'W	124°59.25'W	124°58.23'W	124°57.20'W	124°56.18'W

