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Depth estimation of pre-Kalahari basement in Southern Angola using seismic noise measurements and drill-hole data

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ABSTRACT

The remote Southern region of Angola is covered by siliciclastic Kalahari Cenozoic formations that host underground aquifers of great importance to local populations affected by water scarcity problems. These aquifers are well developed where Kalahari sands reach appropriate thicknesses. On the other hand, at the eastern end of this area, regional aeromagnetic data recently acquired suggested the possibility of the continuity of the geological structures of the Lufilian Arc, sited in the nearby Zambia and Congo, southwestwards into Angola under the Kalahari formations. Once the Lufilian Arc is associated with the presence of the so-called Central African Copperbelt, this possibility increased the interest in determining the depth to Pan-African rocks under the Kalahari basin. To estimate the thickness of Kalahari formations in this area of difficult access and poor logistics, an expedited and non-invasive geophysical method was needed. Seismic noise and the single-station Nakamura technique were chosen, but due to the large distance of the study area from the ocean, one of the major sources of seismic noise, a test survey was acquired in the Cuvelai region to assess the signal quality, where the data was calibrated using available drill-holes. >170 points of seismic ambient noise were later acquired and the horizontal/vertical (HVSR) amplitude versus frequency curves were 1D inverted for the best velocity/density model for each station. The results were compared with 1D inverted legacy vertical electrical soundings reprocessed and validated in this work, showing similar depth-to-basement, while interpreted velocities/densities of geological formations were sampled and confirmed with measurements. A depth-to-basement map was produced using seismic information, mechanical soundings, and geological information. Despite the relatively reduced geographical area covered, the map presents valuable information for hydrogeology and mineral exploration purposes and agrees with a previously available coarser map of Kalahari thickness and with observations from geological surveys simultaneously conducted at the time of the seismic surveys.

1. Introduction

Recent studies in the south and southeast of Angola indicate that the bedrock covered by Cenozoic units of the Kalahari basin (sensu Haddon, 2005) may be the continuation of the so-called Lufilian Arc present in the neighboring countries of Zambia, Congo, Namibia and Botswana

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(e.g., Laznicka, 2010; Arnaud et al., 2011; Rankin, 2015). The Lufilian Arc is a Neoproterozoic, 800 km long, fold-and-thrust structure that hosts the Congo-Zambia Copper Belt, with approximately 220 Mt. of estimated reserves (Selley et al., 2005; Hitzman et al., 2012) of mainly of copper and cobalt, and also zinc and lead (e.g., Laznicka, 2010; Ray et al., 2011). The Central African Copper Belt was estimated to contain 80% of the world's cobalt reserves and 25% of copper (Laznicka, 2010). It is considered as the largest, sediment-hosted stratiform copper province in the world (Sillitoe et al., 2015). The ore host rocks are siliciclastic and carbonate metasediments of amphibolite facies (e.g. Laznicka, 2010; Sillitoe et al., 2015). The location of the Lufilian Arc and the Central African Copper Belt relatively to the study area is presented in Fig. 1a.

Using the aeromagnetic regional surveys recently acquired under the scope of the governmentally funded Plano Nacional de Geologia de Angola (PLANAGEO) project, and the magnetic surveys of nearby countries, it was inferred that the magnetic anomalies related to the Lufilian Arc (see e.g., Williams and Nisbet, 2017) may prolong south-westwards. This hypothesis, also based on geological outcrop data, has been admitted previously (e.g., De Wit, 2009; Rankin, 2015), and has received further support from the aeromagnetic data acquired within the scope of the PLANAGEO project. Therefore, it is of paramount importance to assess the depth of basement in the region, for further geophysical exploration followed by eventual exploitation. Our primary study area is marked in both Fig. 1a and b.

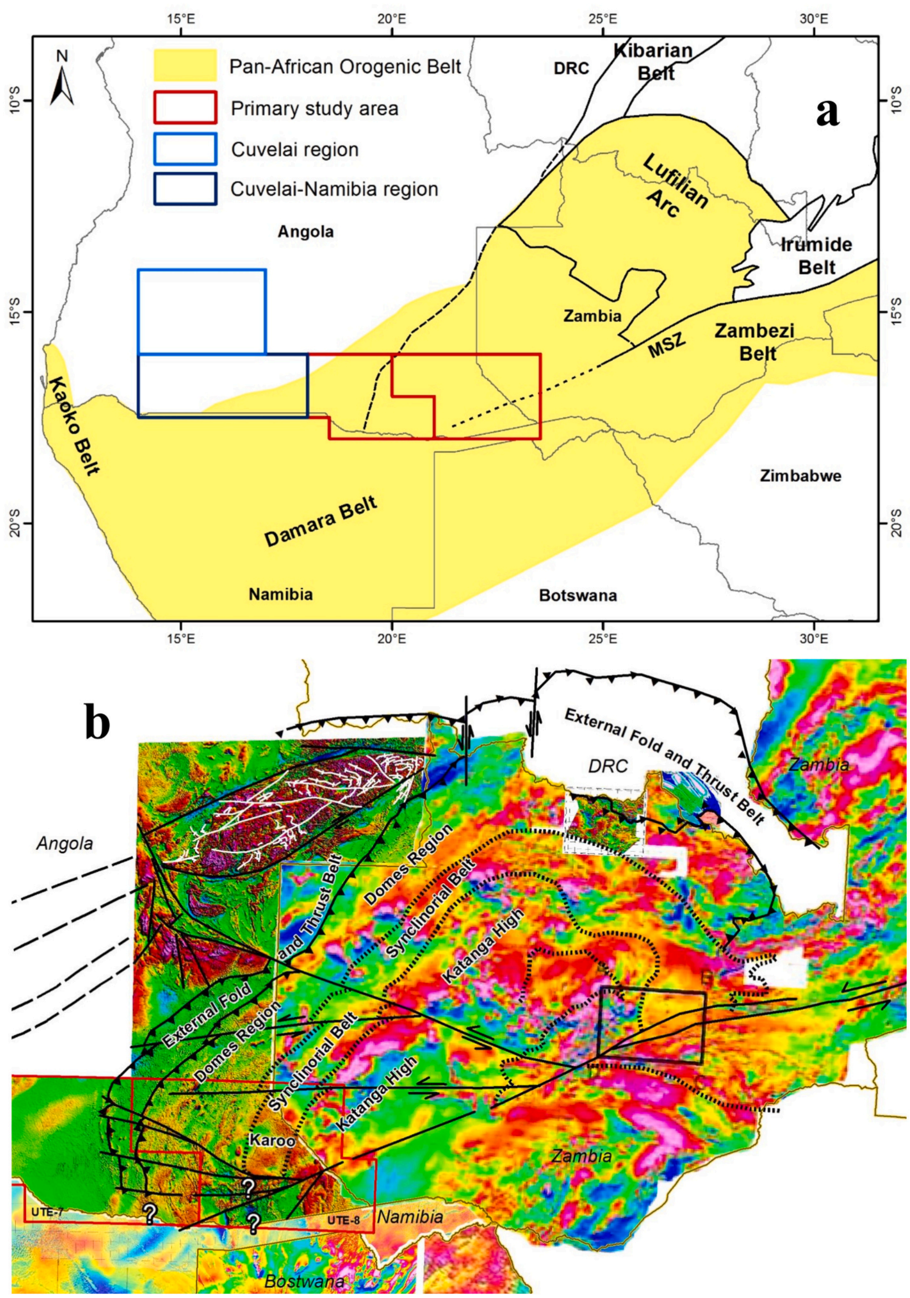

Fig. 1. a) Southern African Orogeny tectonic map showing the Lufilian Arc structure and b) its possible prolonging southeastwards into southeastern Angola, suggested by aeromagnetic data UTE unpublished report in portuguese) Red polygon delimits Blocks 7and 8 of the PLANAGEO UTE zone, the primary study area of this work. The region is covered by Cenozoic sediments that do not allow identifying the geological nature of the basement (see Fig. 2). MSZ- Mewmbeshi Shear zone; DRC- Democratic Republic of Congo. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Drill-hole data could be used for this purpose, but in this part of the region under study drill-holes are not available, mostly due to the lack of investment in hydrogeological studies in the last decades. Nevertheless, the region between Cuvelai and the border with Namibia, suffers from periodical severe droughts, and groundwater resources are scarce and with poor quality, and systematic hydrogeological studies were retaken after a several decades pause (Ramalho et al., 2023). The Kalahari sedimentary cover contains the large transboundary Kalahari-Ohangwena (KOH, hosted in the deposits of the Cubango Megafan) and Oshana (KOS, hosted in the deposits of the Cunene Megafan) aquifer systems (Ramalho et al., 2023) that are the major groundwater resources for the area.

The KOS aquifer system covers the westernmost part of the Cuvelai-Namibia region (Fig. 1a), and so far, it has been poorly studied either on the Namibian or the Angolan side. On the other hand, the KOH, covering southern Angola and northern Namibia, has been extensively studied in its Namibian side for the last two decades (c.f. Lindenmaier et al., 2014), but in Angola, only recently has been readdressed (Ramalho et al., 2023). It is generally composed of thick intercalations, sometimes with dozens of meters, of sands and clays and contains groundwater with highly variable chemical quality and two major aquifers in very distinct depths. According to Lindenmaier et al. (2014), the deepest aquifer occurs often deeper than 200 m, in the depocentric areas of the basin. This aquifer, with a regional dimension, is confined, and composed of fine to medium sands with very low hydraulic conductivities (Lindenmaier et al., 2014). Usually containing low mineralized water, it may be considered the most permanent source of water supply to this remote and often inaccessible area.

To obtain more information of both aquifers, it requires the drilling of more deep drill-holes, which is expensive and of considerable technical complexity (Ramalho et al., 2023), once the geophysical studies involving the electrical properties of the geological formations (Schildknecht, 2012; Lindenmaier et al., 2014; Ramalho et al., 2023; Francés et al., 2024) and the drill-holes drilled within the scope of PLANAGEO (Francés et al., 2024) didn't reach the basement in the depocentric area of the basin. Basement and Upper-Lower Kalahari interface depths can thus provide valuable information to the understanding of these aquifers. Some sparse drill-holes are available in the Namibia-Cuvelai region, while northwestwards, in the Cuvelai region (see location in Fig. 2), multiple drill-holes have been drilled, although their depth generally does not exceed 100 m.

Therefore, it was decided to extend the primary study area in Southeastern Angola to the Cuvelai region and the area south of it until the border with Namibia (Cuvelai-Namibia region). In Fig. 2 is displayed the primary, initial study area in the Southeastern part of Angola with possible interest to mineral exploration, and the Cuvelai and Cuvelai-Namibia regions, where major concern is the lack of water supply to local populations.

Some unpublished potential-field modeling studies suggested depths-to-basement of the order of 1 km, while a thickness map of the Kalahari Basin in Namibia and Angola previously produced by Haddon (2005) and Haddon and McCarthy (2005) for the entire Kalahari Basin comprehending Southern Angola, Namibia and Botswana suggested much shallower depths in the Southeastern part of the study area. However, Haddon (2005) does not mention what data and how the map was produced, which led us to carry out the present study.

To estimate the depth-to-basement in the entire study area, it was necessary to apply an expedited and economical geophysical method without the need of heavy logistics and possible to acquire in remote areas, with very difficult accesses and without any infrastructures. Seismic reflection, drilling or aerial gravimetry or electromagnetic surveys were too expensive and difficult to carry out, particularly in the Southeastern part of the study area, where logistic conditions are even poorer.

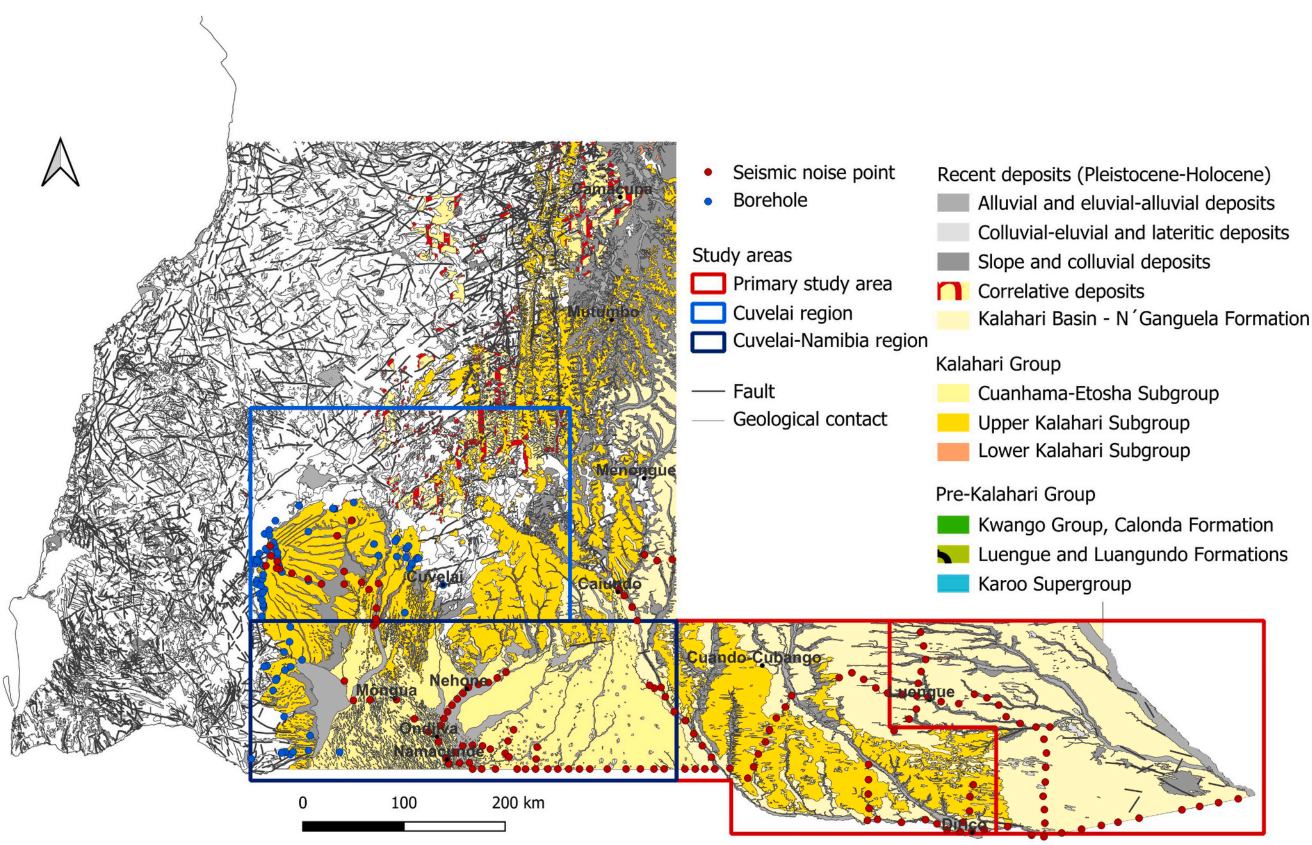

Fig. 2. Geological map of the study area (PLANAGEO, 2022), with the locations of the test survey and the total study area, available drill-holes and the seismic noise stations acquired in the scope of this work overlaid.

To achieve the above-mentioned goal, the single-station passive seismic method was chosen, since it allows the coverage of large areas in a fast and cost-effective way. Several studies showed that the thickness of soft sediments can be mapped using the seismic noise approach (Ibs-von Seht and Wohlenberg, 1999; Parolai et al., 2002; Borges et al., 2016; Scheib et al., 2016). The horizontal-to-vertical spectral ratio technique (Nakamura, 1989) was applied for the analysis of the seismic noise data. In this work, results of two passive seismic campaigns are presented and discussed, aiming to estimate the thickness of Kalahari sedimentary rocks in the south and southeast of Angola (Fig. 2). The Cuvelai and Cuvelai-Namibia regions, where drill-holes were available were used to test and calibrate the method, while the area with possible interest to the mineral exploration (Southeastern Angola) was the target of a second survey. About 200 ambient seismic noise data points were acquired and using available drill-holes and geological information, a coarse depth-to-basement map was produced.

2. Geological setting

The study area is largely covered by the Cenozoic Kalahari Formations. A recent geological map of the study area at the 1: 1 M scale produced by the PLANAGEO project is shown in Fig. 2., where the proterozoic basement is represented as a single undifferentiated unit. The location of the seismic noise stations acquired during the test survey in the Cuvelai and Cuvelai-Namibia regions (blue rectangles) and the survey in the region with interest to mineral exploration (red polygons) is overlaid. The map also displays the location of available drill-holes that were used in the work.

The region is covered by the predominantly sandy succession of the upper part of the Kalahari Group sediments. Pre-Kalahari units rarely outcrop and are randomly distributed, being mostly intersected in drill-holes. Therefore, its lateral continuity and geographical extension are difficult to establish. A flat topography and the weak fluvial incision are the main reasons for the poor direct knowledge on the stratigraphy of the intracratonic sedimentary successions. Nevertheless, seismic data interpretation requires that even under these conditions, a regional framework is established, therefore opening the need to resort to the knowledge of the sedimentary successions of the intracratonic regions of this part of Africa. For reference and framing of the pre-Kalahari Group unit's correlation, several geological columns presented in recent works carried out in Congo Basin are considered (e.g., Daly et al., 1992; Catuneanu et al., 2005; Kabongo et al., 2015; Linol et al., 2015a), namely for the Democratic Republic of Congo (DRC) and NE Angola (Table 1). Regarding the Kalahari Group, several works can be consulted, namely Cahen (1954), Cahen and Lepersonne (1954), Haddon (2005), or the regional geological mapping carried out by the PLANAGEO project (Table 2).

Table 1
Pre-Kalahari stratigraphy.

	RDC (Linol et al., 2015a, 2015b)		NE Angola (Pereira et al., 2003)	SE Angola (PLANAGEO)
Upper Cretaceous		Kwango Group	Calonda Fm.	Luangundo Fm.
Lower Cretaceous	Congo Supergroup	Bokungu Group		
		Loia Group	Continental Intercalate	
Midlle - Late Jurassic		Stanleyville Group		
Lower Jurassic			Cassange Group	Caiundo & Luengue Fms.
Triassic	Karoo Supergroup	Haute-Lueki Group		
Carboniferous Permian		Lukuga Group	Lutôe Group	?

Table 2
Correspondence of the Kalahari Group stratigraphy of Pereira et al. (2003) and PLANAGEO.

	NE of Angola (Pereira et al., 2003)		SE Angola (PLANAGEO)	
Pliocene	Kalahari Group		Cuanhama-Etosha Subgroup	Paleo-Cuvelai Paleo-Cunene Paleo-Cubango
Miocene-Pliocene		Areias ocres Fm.	Upper Kalahari Subgroup	Areias ocres Fm.
Oligocene-Miocene		Grés Polimorfos Fm.	Lower Kalahari Subgroup	Grés Polimorfos Fm.

2.1. Pre-Kalahari Group units

Basement units comprehend siliciclastic and carbonated rocks at the southeastern region, which outcrop in very reduced areas in the Dirico region (Fig. 2) and are related to the Karoo Supergroup, intersected by drill-hole data in NW Botswana. At the west the basement is composed by igneous, proterozoic rocks associated with the Kunene Anorthositic Complex (KAC). To the north, metasedimentary and igneous units of Proterozoic age also outcrop.

2.2. Karoo supergroup

Geological units correlated with the Karoo Supergroup in South Africa are well known in deep drill-holes located in the Congo Basin (DRC) and in outcrops along the main fluvial valleys of NE Angola and Cassange lows (N of Angola) (Catuneanu et al., 2005). Two major sedimentary sets are referred: the lower set, of Carboniferous-Permian age is defined by glacial and periglacial facies that include essentially siltstones e blackshales – Lukuga Group (Table 1). The stratigraphy is defined by recent studies in deep drill-holes in the DRC (Linol et al., 2015b) and by geological surveys in northern and northeastern Angola – Grupo Lutôe (e.g., Pereira et al., 2003 and references therein). The upper set is mainly a *red beds* set with fine detrital intercalations that compose the Haute Lueki Group in the DRC and the Cassange Group in N and NE Angola. In NW Botswana, several facies associated with two major units of the Karoo Supergroup are crossed by drill-holes (Linol et al., 2015b). In SE Angola, though with reduced geographical expression in outcrop (therefore not visible at the scale of Fig. 2, two lithostratigraphic units below the Lower Kalahari Group (Grés Polimorfos Fm.) were defined and mapped (Labaredas and Oliveira, 2020).

These units are correlated with the Karoo Supergroup: Caiundo Fm. (South of Caiundo city, see Fig. 2, Lopes et al., 2020), and Luengue Fm., North of Luengue municipality (Labaredas and Oliveira, 2020, see Fig. 2). In SE Angola, in the Cuando-Cubango province (see Fig. 2), a drill-hole intersected basalts that were interpreted as being of Karoo age. In the study area, Karoo Supergroup sediments are only expected to be present closer to the border with Namibia, as they are not seen in outcrop or drill-holes further North in Angola, except the above-mentioned drill-hole and another drill-hole in the Cuvelai region that intersected a few meters of unidentified basalts (Labaredas and Oliveira, 2020). Aeromagnetic data interpretation also available from the PLANAGEO project suggests however that the basalts are widespread east of the Cuvelai region.

2.3. Congo supergroup

This unit is defined in the Congo Basin (DRC), where it was recently studied by the lithostratigraphic and chronostratigraphic point of views (Roberts et al., 2015), receiving the name of Congo Supergroup (ibidem). In NE Angola, the Kwango Group is represented by the Calonda Fm. (South of Mutumbo and Camacupa, see Fig. 2). This is a detritic unit hosting important diamond mineralization, which is well studied and whose schematic column is shown in Table 1. Its presence in S and SE Angola (as Luangundo Fm.) is plausible, but so far it has not been proved. Also, North of Luengue, a unit above the Grés Polimorfos Fm. that has been correlated with the Kwango Group, the Luangundo Fm. (Labaredas and Oliveira, 2020) was defined and mapped.

2.4. Kalahari Group units

The Kalahari Group is divided into two main sets, generally designated by Upper Kalahari and Lower Kalahari, according to classical works (e.g., Cahen, 1954; Cahen and Lepersonne, 1954). Using this scheme, the lithostratigraphy in Angola considers the Grés Polimorfos Fm. and the Areias Ocre Fm. as representatives of the Lower Kalahari and Upper Kalahari, respectively (Sousa et al., 2021). Works recently carried out in the Central and Southern Angola under the scope of the PLANAGEO project allowed to improve the lithostratigraphic setting of the Kalahari group in this region, establishing a discontinuity separating the Grés Polimorfos Fm. and the Areias Ocre Fm. Another discontinuity separates the latter formation from the sandy units of the great paleofans of South Angola/North of Namibia (Paleo-Cunene, Paleo-Cuvelai e Paleo-Cubango megafans). Therefore, a lithostratigraphic reformulation of the geological mapping in South Angola considered a subgroup rank for the units limited by discontinuities of basin extension inside the Kalahari Group: Lower Kalahari Subgroup, Upper Kalahari Subgroup and Cuanhama-Etosha Subgroup. With this reformulation, the lateral variations between each of these large sets are absorbed by formation rank. For the study area (in Southern Angola), the scheme is summarized in Tables 1 and 2.

2.5. Recent deposits (Pleistocene - Holocene)

After the deposition of the above-mentioned paleo megafans, the Pleisto-Holocene eolic remobilization must be considered. This remobilization generates extensive dunal fields which constitute the N'Ganguela Fm., as well as Holocene deposits associated with the present-day hydrographic network.

3. Methodology

Passive seismic approach uses ambient vibrations (Bonnefoy-Claudet et al., 2006; Fäh et al., 2001a, 2001b) characterized by weak oscillations that propagate under the Earth's surface as seismic waves, with frequencies usually under 10 Hz. The interpretation of the seismic noise is a complex task due to the controversy surrounding the origin of the wave field and its precise composition. This complexity arises because the wavefield may include a mix of surface waves, body waves, and other seismic noise sources, making it challenging to isolate and analyze specific components. It is, however, generally agreed that the composition of the seismic noise wavefield is predominantly composed of variable proportions of Rayleigh and Love waves (Bonnefoy-Claudet et al., 2006). The horizontal to vertical spectra ratio (HVSR or H/V) method (Nakamura, 1989) applied to the data is based on the calculation of the ratio between the Fourier spectra of the averaged horizontal and vertical components of the seismic noise. This technique has been successfully applied to estimate the thickness of cover sequences over the bedrock (Ibs-von Seht and Wohlenberg, 1999; Parolai et al., 2002; Lane et al., 2008; Scheib et al., 2016, Bao et al., 2019; Vijayan et al., 2022).

It is important to note that due to the complexity and strongly nonlinearity between HV curves and the parameters of the model it relies on (such as the velocity of body waves and the thickness of the layers), the solution to the inverse problem is not unique. It should generally be solved using intensive exploration of space models and the imposition constraints (e.g. borehole, geology, and geophysical data) (Piña-Flores, 2017). Sharma et al. (2024) explored the variability in the inverted shear-wave velocity depth profile by the importance of identification of the wave contributions of the noise wavefield for the proper estimation of VS depth profiles.

There are several methods to model the seismic noise HVSR curves, among which the calculation of the response of a viscoelastic medium to the incidence of vertical body waves stands out (Herak, 2008). Other recent methods to model noise response are based in the assumption that microtremors are originate from a diffuse field containing all types of body (P and S) and surface waves (Sánchez-Sesma et al., 2011; Piña-Flores, 2017). Other authors, using noise recorded by single triaxial seismic stations, calculate the Rayleigh wave ellipticity as a function of frequency and, from that, invert the underground structure in terms of shear wave velocity (e.g., Hobiger et al., 2009). However, results in a very short time frame and an expedited procedure to apply in a remote region with severe logistic conditions were needed. Therefore, the Nakamura technique was chosen. Maghami et al. (2021) e.g., employed a similar methodology to the one used in this work (see also forward this section), including a priori information obtained from boreholes and inversion of the HV curves with OpenHVSR program, to obtain the V_S structure of the first layers of a sedimentary basin. In this work, novel geological information was added to borehole data, legacy geoelectric data was reprocessed and density and velocity measurements were carried out in selected samples to assist the interpretation.

In an initial phase, aiming to interpret the HVSR, we used a single-layer model formed by a low velocity layer over semi-infinite space. In this model, the relation between the resonance frequency fz is a function of the thickness of the sedimentary layer H and S-wave velocity (V_S) of the sedimentary layer (Ibs-von Seht and Wohlenberg, 1999) and is given by:

$$fz = V_S/4^{*}\ H \tag{1}$$

An impedance contrast results from a change in shear-wave velocity due to changes in elastic properties across a lithological boundary, while the peak frequency from HVSR indicates a change in impedance. The depth of the boundary can then be related to the peak frequency obtained from the HVSR and the lower the resonance frequencies the deeper the boundary (Fig. 3). So, knowing the S-wave velocity, Vs, allows an estimation of the thickness H. When the subsurface structure of the studied place is formed by several layers above the bedrock with contrasting impedance, the HVSR curves show extra peaks with greater frequency. The interpretation of these peaks can make it possible to detect the presence of these layers and make an estimate of their depths (Piña-Flores, 2017).

In the south of Angola, there was no information about S-wave velocities so, to calibrate the method for the study region, it was very important to plan the acquisition points near the location of known drill-holes and/or geophysical soundings, so we could obtain information about the depth of the sedimentary layers. From here, the velocities could be estimated, and the thickness of the sedimentary cover could be estimated in areas without information from drill-holes. However, if the variation of velocity with depth is complex, although an approximation can be made considering constant velocity to obtain an initial model, we had to introduce an inversion process to solve a finer stratification.

Analyzing the HVSR can provide qualitative information regarding the nature of the impedance contrast. If the peak is sharp and high in amplitude, it indicates that there is a high velocity contrast between the layers. If the peak is broader and lower in amplitude, it shows that the contact between the layers is gradational. This can happen when the bedrock is very weathered (Lane et al., 2008; Scheib, 2014), or when the sedimentary layer becomes gradually consolidated with depth. In this study, only peaks with amplitude above 2 were modelled.

4. Data acquisition

The distribution of the stations of the seismic noise (SN) survey was

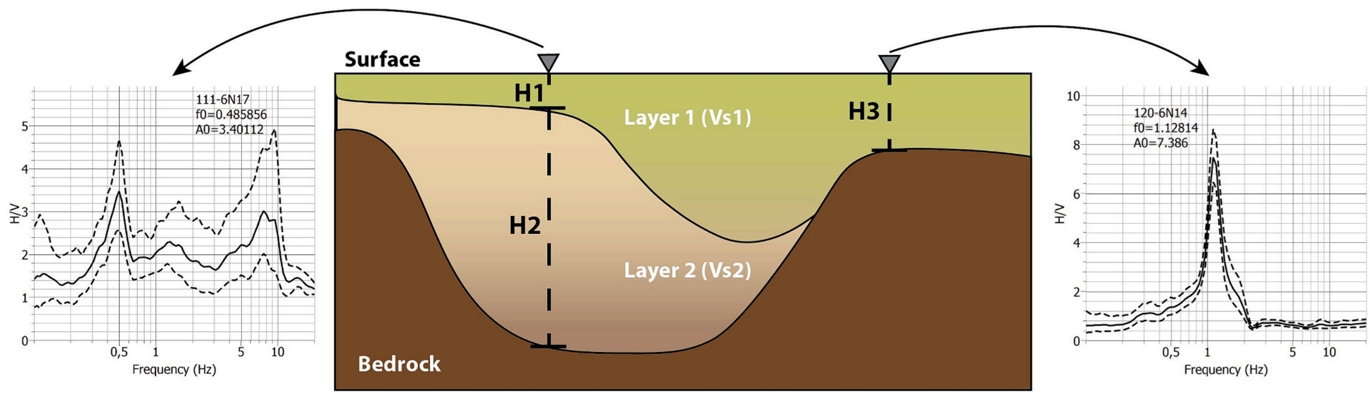

Fig. 3. Relationship between the frequency of the amplitude peak of H/V curve, related to layer i (fzi), average velocity to layer i (V_S), and thickness of layer i (Hi).

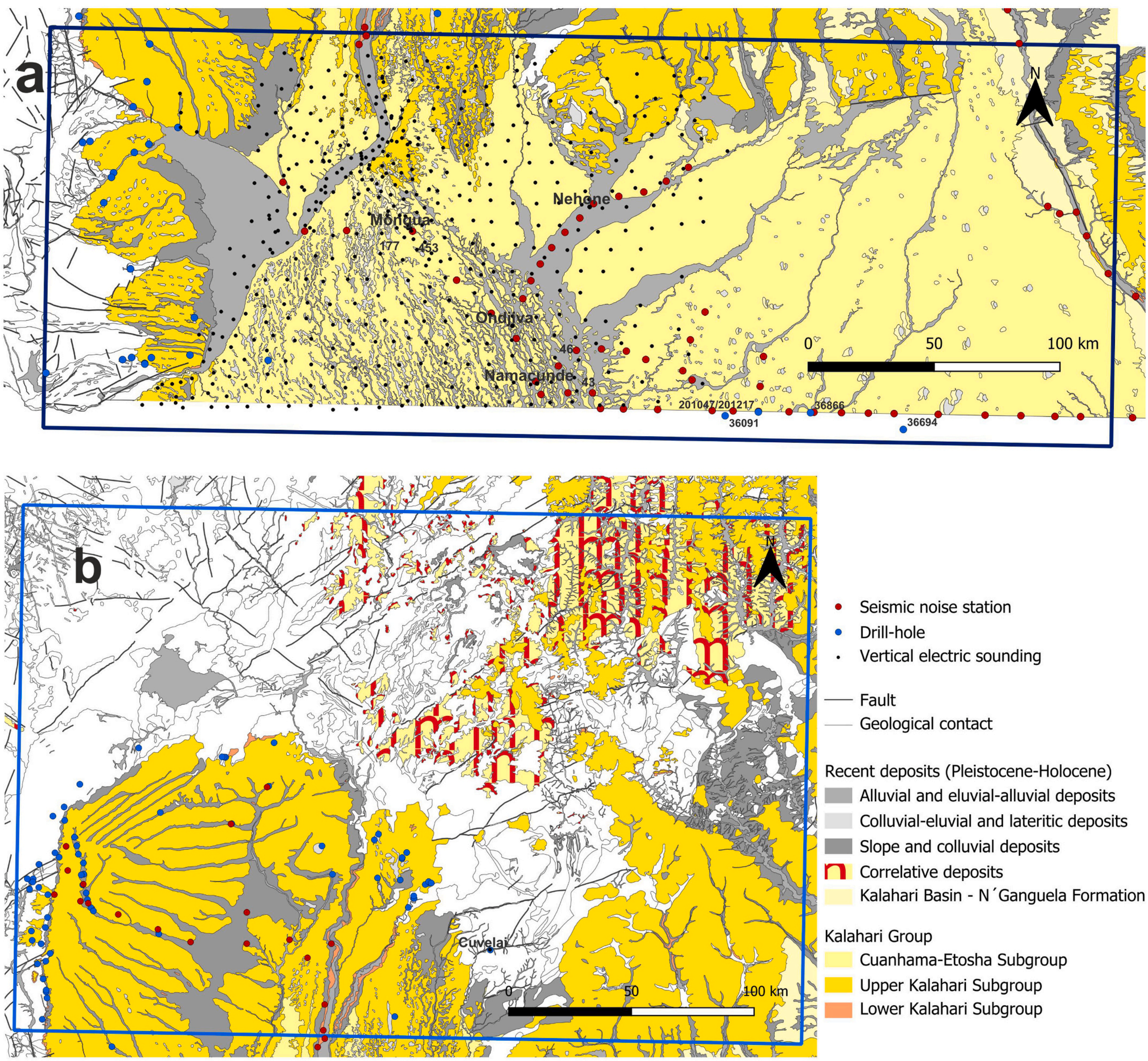

Fig. 4. Zooms of Cuvelai-Namibia and Cuvelai regions, presented in Fig. 2, showing details of a) vertical electrical soundings acquired by LNEC in the 1960's, that were reprocessed and used in this work to corroborate seismic noise measurements; b) location of drill-holes used to calibrate seismic noise measurements in the test survey in the Cuvelai region.

planned considering several important aspects: 1) the locations of drill-holes and also vertical electrical soundings that were acquired during the 1960's, by the Portuguese Mining Service and National Laboratory for Civil Engineering of Portugal (LNEC), respectively (see Fig. 4a); both legacy data were needed to constrain the starting models for the H/V inversion, and 2) also the accessibility of the places. The lack of accessible roads and the existence of land and tank mined areas in the region of study limited in part the geographical distributions of the acquisition points.

As stated in the Introduction section, the seismic noise measurements were carried out in two different campaigns. The first campaign, in October of 2017, started out as a test campaign so we could attest to the data quality. Several studies suggested that the most common source of seismic noise are ocean waves, rain, wind, and distal anthropogenic activities (Claprood, 2012; Ibs-von Seht and Wohlenberg, 1999; Lane et al., 2008; Okada, 2003) and according to Acerra et al. (2004), the ocean noise is the primary source of seismic ambient noise. As the test area is far from the coastal zone (>500 km away), we wanted to primarily experiment the method and then to verify if the data had a minimum quality for the proposed goals. Bearing this in mind, 20 test points were planned in this region near several drill-holes, and an additional 40 more stations were planned outside the drill-hole area.

The study of the seismic structure in southern Angola, where there is a vast unexplored area, requires the use of a cost-effective and efficient method. The HVSR method meets these requirements as the inversion of H/V curves is done with the introduction of constraints obtained through borehole data. Moreover, the modeling at the borehole points, using OpenHVSR program, very closely reproduces the field curves obtained at these points.

The measurements were made using a Guralp (UK) CMG-6Td (30 s) compact triaxial broadband seismometers, with a recording length of 1 h to 1 h30 m and a sampling frequency of 100 Hz (flat response in velocity between 0.03 and 50 Hz). According to Borges et al. (2016), performance tests to these broadband seismometers revealed that it takes 15 min (from the beginning of the logging) to stabilize the seismic registrations, so these first 15 min were discarded from the data. The data were acquired and processed following the recommendations of the SESAME European project (Bard, 2004). Most of the study area had little human occupancy, but the small villages in the region were avoided to eliminate strong sources of proximal noise, and some of the stations were placed at some distance from the unpaved roads, to avoid any rare passing vehicle.

In the Cuvelai area there are several drill-holes with log information available. The available drill-holes in this region between Chibia and the border with Namibia, were drilled during the project "Coordenation Plan for Southern Angola Pastureland Water Supply" (Plano de coordenação de Abastecimento de Água às Regiões Pastoris do Sul de Angola, Direcção Provincial dos Serviços de Geologia e Minas), and the respective logs constitute the Hidrominas database (National Society for Underground Waters). Besides the information from this database the soundings from Pacheco (1976, Geological Survey of Portugal report, in Portuguese) and Gomes (1972, National Directorate for Geology and Mining report, in Portuguese) were also used, the latter also containing electrical and clay content logs. The logs contain a simple lithological description, so we had to reinterpret them taking into consideration the geological units from the new stratigraphy established during the PLANAGEO project (Tables 1 and 2).

After analyzing these data, we found that most of the drill-holes did not reach the bedrock and the ones that did, showed that the bedrock was very shallow (a couple of meters to a few tens of meters). For this reason, only 4 drill-holes, Tchimbolelo 1, Muve, Bossi and Bandarra that reached 38 m, 124 m, 100 m and 125 m depth, respectively (see Fig. 4b), were used to calibrate the method. None of the soundings to the east of Muve reached the bedrock, but most of them reached >100 m depth. The report from Gomes (1972, National Directorate for Geology and Mining report, in Portuguese) mentioned several soundings other than Môngua (NE of Ondjiva with 280 m depth, see Fig. 2), with a few of them reaching >300 m depth, but their reports are lost so far. In northern Namibia, near the border with Angola, some drill-holes with logs reached around 400 m depth, without however reaching the Karoo formations, or the bedrock. These mechanical soundings are located near the SN points 137, 138, 140, 146 and have been identified by Lindenmaier et al. (2014) with references 36,091, 201,047 and 201,217, 36,866 and 36,694. However, the stratigraphy in Namibia (e.g., Rankin, 2015) is distinct from that of Angola, and additional efforts were needed to homogenize them (see Labaredas and Oliveira, 2021; Ramalho et al., 2023 and references therein).

Schildknecht (2012) and Lindenmaier et al. (2014) also provided electrical resistivity information on several transects of time-domain electromagnetics carried out in northern Namibia. These transects comprised 440 stations with an approximate maximum depth of investigation of 400 m. The information from vertical electrical soundings (VES) acquired during the 1960's by LNEC (Nascimento and Moura Esteves, 1966, LNEC report in Portuguese; Nascimento et al., 1967, LNEC report in Portuguese) was also available, including 482 VES conducted in the Cunene-Namibia region (Fig. 4a) with maximum AB/2 spacing ranging from 350 m to 1200 m, with high-resistivity basement being reached in most of them. The resistivity curves were recovered from paper documents; the data were 1D reprocessed using with software IP2Win (Bobachev et al., 2000) and a 3D model based on electrical resistivity data was constructed and validated with the information from Schildknecht (2012), Lindenmaier et al. (2014) and drill-hole logs (Ramalho et al., 2023). Therefore, several of these 1D VES resistivity models based on legacy field data that had been acquired near the SN stations were safely compared with the SN models. The comparison is described in detail later, but generally, the VES corroborated the basement depth estimated with SN, though with a slight overestimation.

The second campaign was carried out between May and June of 2018 using the same equipment, with a total 101 stations acquired. First, the area near the border with Namibia was covered and afterwards the survey continued eastwards. Most of the acquisition points are located in the southeast of Angola, where there are no VES or drill-hole information available. A total of 173 points were acquired in both surveys.

5. Data analysis and processing

Using the software SeisGram2k (http://alomax.free.fr/seisgram/SeisGram2K.html), all the registries were analyzed to identify any possible acquisition problems and for both campaigns 9 points were discarded from the 173 surveyed. The HVSR curves were calculated using the GEOPSY program developed by the SESAME team (Geopsy, 2006 http://geopsy.org/). The spectral ratio H/V curves calculation followed the methodology described by Furtado (2010). For each measurement point, the HVSR was computed using time windows with 100 s length. After obtaining the H/V spectral ratio curves (see Fig. 5 examples), quality control was done to check if the peaks were clear. For some points, the H/V traces were not clear and those were excluded from our analyses.

The inversion of the HVSR calculated was achieved using the OpenHVSR (Bignardi et al., 2016) program. It is a Matlab® program capable of obtaining the 1D model of the elastic properties of a subsurface. There are 5 parameters to invert for each layer, the P- and S-wave velocities, density, layer thickness and attenuation factor Q (V_P, V_S, ρ, H and Q, respectively).

If the thickness can be estimated from the drill-holes and using the frequency of the amplitude peaks observed in the H/V curves, then Vs can be obtained from eq. 1. On the other hand, if the layer thickness is not known, using again the peaks observed in the H/V curves, Vs values can be obtained from the literature for geological analogs. The other parameters can also be taken from the literature (Sheriff and Geldart, 1995; Johnston, 1981; Carvalho et al., 2018; Jeng et al., 1999).

Both programs used for H/V inversion create a synthetic curve trace

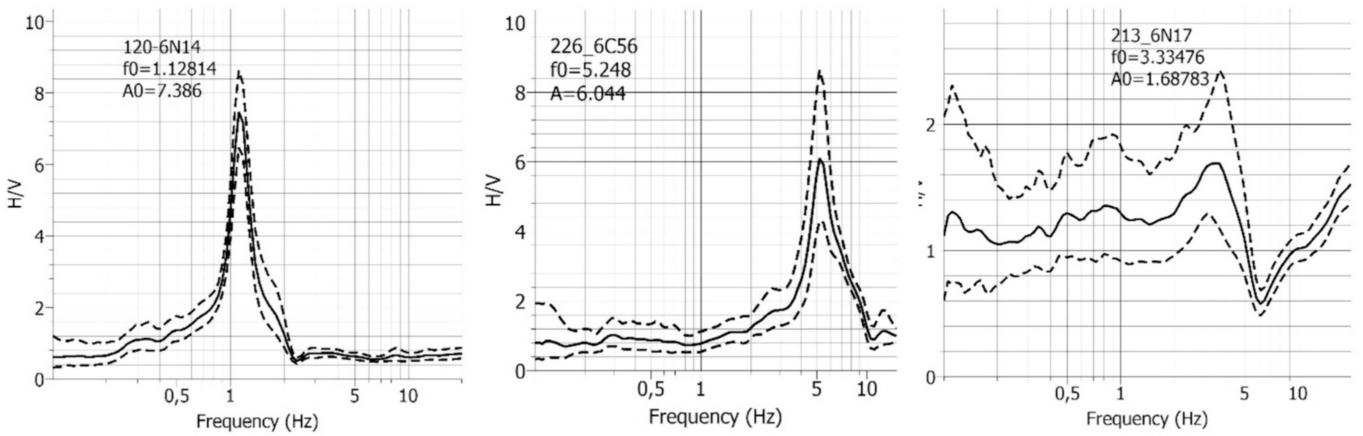

Fig. 5. The two curves from the left and center represent good examples of a H/V curve. The right curve represents an excluded H/V curve as it doesn't show a clear peak.

using a starting model of V_P, V_S, ρ, H and Q. The synthetic curve is compared with the observed H/V curve in a Euclidean distance metric and the misfit is minimized until a satisfactory fit is achieved (Bignardi et al., 2016; Herak, 2008). Generally, the inversion algorithm, based on the guided Monte Carlo method limited by using a priori constraints, converges after 50,000 iterations. The inversion was carried out for all the SN stations and the obtained model was saved. The software is most sensitive to S-wave velocities and layer thicknesses. For those points close to drill-holes, the starting layer thicknesses were fixed, while the other parameters were left free within a certain range of velocities and densities, in agreement with velocities found for analogue lithologies and ages (Carvalho et al., 2018; Jeng et al., 1999; Dobrin and Savitt, 1988; Sheriff and Geldart, 1995; Johnston, 1981). Starting models for stations far away from drill-holes were calculated using the V_S and V_P from the models obtained for the stations calibrated with drill-holes and eq. 1 was used to obtain the thickness of each layer. The velocities were allowed to vary by 30%, while the other parameters were again set free with expectable values from geological analogues. Fig. 6 shows an example of output from the inversion code for one of the SN stations.

6. Data interpretation and map of the Kalahari Basin thickness

The models obtained from inversion of the HVSR curves consist in a stacking of several layers, each one characterized with different

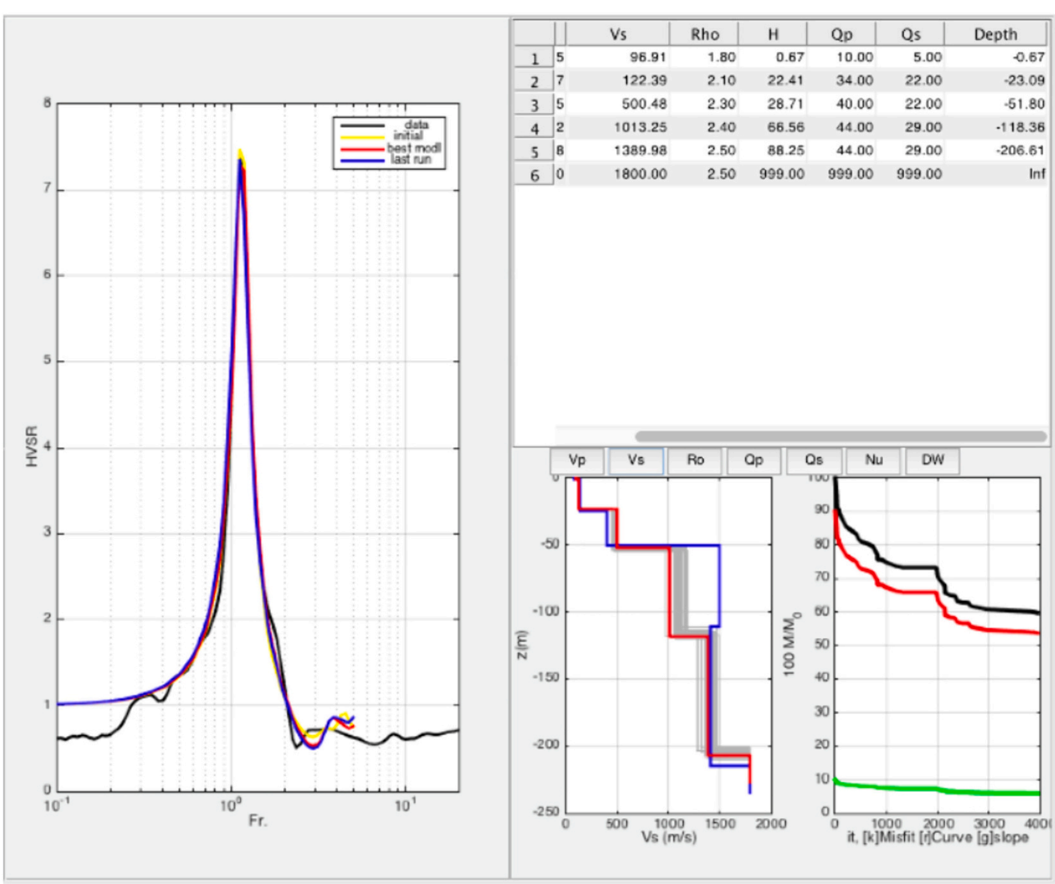

Fig. 6. Screenshot representing the inversion results using OpenHVSR (right).

Table 3
Average (Av) and end values of seismic wave velocity and density, and average layer thickness in the study area, for the three geologically distinct regions.

Region	Layer	Vp (m/s)			Vs (m/s)			H (m)	rho (g/cm^3)		
		Min	Max	Av	Min	Max	Av		Min	Max	Av
Cuvelai	Layer 1	105	1787	523	50	458	186	9	1.7	2.3	1.9
	Layer 2	888	2488	1720	429	982	679	90	2.1	2.6	2.3
	Bedrock	2110	4954	3046	764	1800	1410	–	2.1	2.8	2.6
Cuvelai-Namibia	Layer 1	100	2594	587	50	983	251	158	1.7	2.6	2.0
	Layer 2	659	3125	1544	446	1358	777	207	1.9	2.7	2.5
	Bedrock	2200	4606	3183	1013	2000	1677		2.4	2.8	2.6
SE	Layer 1	100	3778	385	50	1259	155	26	1.7	2.6	2.0
	Layer 2	392	2646	1365	298	904	621	84	1.8	2.8	2.3
	Bedrock	1494	5600	3019	838	2606	1289	–	2.1	2.9	2.5

Vp- P-wave velocity; Vs- S-wave velocity; H- average layer thickness; rho- density.

velocities and density contrasts, which agreed with the several amplitude peaks observed in the HVSR curves. These models can be useful to help identify the depths of the different outcropping geological formations and are expected to be present beneath the study area. The first step was to analyze, for each SN station, the values of seismic velocity and densities obtained from the 1D inversion, and group them in different layers according to common velocity and density intervals. Each geophysical layer was then associated with a specific geological formation according to its expected velocity and density ranges taking into consideration composition, age and depth. Table 3 represents the velocities and density ranges for each of these layers in the different regions of the study area. The latter, as explained above, was divided into three subareas taking into consideration their geological characteristics, drill-hole availability and the distance between groups of SN stations: the eastern region, Cuvelai and Cuvelai-Namibia regions (see Fig. 2).

6.1. Cuvelai area

In the Cuvelai area, where the acquisition tests were carried out and where drill-holes were available, two layers of sediments were interpreted from the HVSR curves and their inversion. Layer 1, the shallowest, with S-wave velocities varying from 50 to 460 m/s, very possibly corresponds to several geological formations, taking into consideration their compositions and position in the stratigraphic table: recent continental deposits, Upper Kalahari formations and the upper sandy lithologies from the Lower Kalahari Fm. This layer has an S-wave medium velocity of 186 m/s and density of 1.9 g/cm^3. The most compacted lithologies in Lower Kalahari, most likely correspond to the 2nd layer of the models and its average S-wave velocity and density are approximately 679 m/s and 2.3 g/cm^3, respectively.

As stated in the Geological Setting section, the Upper Kalahari is characterized by less compact and sandy lithologies, while the Lower Kalahari is topped by a more compact sandy-clayey lithology and below by harder, compact silicified sandstones and carbonated rocks. Because of the presence of this more compact layer, a strong velocity density contrast between the boundaries of the Upper and Lower Kalahari is expected in the areas where the Grés Polimorfos Fm. is present. This geological formation has been interpreted as a continental fan facies, and its positioning can be anticipated in the borders of the Kalahari Basin.

6.2. Cuvelai-Namibia area

In the Cuvelai-Namibia area, in the region of Ondjiva and Nehone, recent deposits and Upper Kalahari Fm. (Fig. 2) outcrop. The average S-wave velocity in this region for Layer 1 is approximately 250 m/s, and the average density of 2 g/cm^3 (Table 3). Both are compatible with the composition of outcropping units. Layer 2 in this region has an average S-wave velocity and densities of 777 m/s and 2.5 g/cm^3 respectively, from which results a sharp velocity/density contrast with Layer 1. The Môngua drill-hole, located in this region (Fig. 2), has intersected carbonated rocks at depths of about 190 m (see Ramalho et al., 2023 or Francés et al. 2024 for a more detailed description and study), that may represent the Lower Kalahari lithologies (Gomes, 1972). Also, according to geological data presented by other authors (e.g., Miller, 1997; Haddon, 2005; Lindenmaier et al., 2014), rocks from the Karoo Fm. may be present in this area at depths greater than a few hundreds of meters. We have not found in the literature S-wave velocities measurements in the Karoo Fm. Taking into consideration the composition, age and burial depth of Karoo units, it is expected that they present a similar velocity and densities range to that of the harder Lower Kalahari Sub-group facies. As the Lower Kalahari is composed of silicified sandstone and carbonated rocks, and the Karoo sediments from Paleozoic are composed of consolidated but porous sandstones and claystones, it's not expected to exist a big contrast between the Karoo and the Lower Kalahari. Therefore, we have interpreted Layer 2 of the Namibia region in Table 3 as a representation of a group of geological formations composed of the Lower Kalahari lithologies and the Karoo.

6.3. SE Angola

In the southeastern region of Angola, the outcropping geological units are also, as in the Cuvelai-Namibia region, recent continental sediments and the lithologies of the Upper Kalahari. The average S-wave velocities for layer 1 are 155 m/s and for density 2 g/cm^3 (Table 3). The second layer is characterized by average S-wave velocity and density of 621 m/s and 2.3 g/cm^3, respectively. Available geological information (Lindenmaier et al., 2014; Hoak et al., 2014), includes lithologies from the Lower Kalahari Sub-group and possibly from sediments of the Karoo Supergroup. In the Luengue area (see Fig. 2), outcrop Mesozoic sedimentary units: the Luengue and Luangundo Formations. These units, composed of coarse sands with clay matrix and quartzite sandstones with conglomeratic intercalations, deposited prior to the Lower Kalahari Sub-group. Outcrops of this unit have a reduced thickness (< 50 m), so it is possible that it may not be detected in depth, either due to the limited resolution of the SN method, or simply due to the lack of density/velocity contrast with Karoo or Lower Kalahari.

Analyzing Table 3, we can check that the velocities for each layer don't change much between the three distinct regions. The big disparity between minimum and maximum values in Layer 1 is due to the fact that the inversion models often detected thin, shallow layers with low seismic velocities, which were included in this table. We can also verify that the S-wave velocities and densities are higher in the southern study area (Cuvelai-Namibia region). This may be explained by the greater depth of the sedimentary column and/or the compactness and composition of the sediments.

In the Cuvelai-Namibia and Southeastern part of the study area, the sedimentary layers may include Phanerozoic units that don't exist in the Cuvelai region, but they may not be detected due to small thickness and similar characteristics with the upper layers. This is the case of Karoo units, known to outcrop in Namibia and in the southeastern part of the study area.

Finally, the third and deepest layer presents an average S-wave velocity and density of 1460 m/s and 2.6 g/cm^3 for all regions, clearly indicating a crystalline nature that we associate with the Proterozoic basement. In the Cuvelai region, where drill-holes were available and reached the basement, this association is clear, but in the Cuvelai-Namibia region, where drill-holes did not reach the basement, and in the Southeastern region where no drill-holes are available, we used other information to check this possibility.

As mentioned in the Data Acquisition section, we had available hundreds of VES acquired in the Cuvelai-Namibia region. The results from the VES study showed that many of them did not detect the bedrock, because of the short AB value, but a large number of them did reach a very high-resistivity layer that most likely corresponds to the basement. Within the scope of reprocessing and reinterpretation of Ramalho et al. (2023), some of these VES were compared to the closest SN station, such as the nearest VES to the drill-hole of Môngua (n^{er} 464 and n^{er} 199, SN station n^{er} 104).

These AB/2x$\rho_{apparent}$ curves and their inversion results are shown in Fig. 7. The two VES and the single-point-resistance (SPR) log indicate the presence of a high resistivity layer around 145 and 187 m which, according to the drill-hole, seems to correspond to the carbonated rocks of the Lower Kalahari Fm. Their 1D inverted model shows an interface at approximately 200 m depth that may be the top of this carbonated layer.

Other pair of VES (n^{er} 127 and n^{er}130), close to SN station 130 near Namacunde, indicate a high-resistivity layer at about 580 and 700 m (not shown here). The depth-to-basement obtained for SN station is 429 m. Again, the electric basement depth seems to be overestimated relatively to the seismic basement. This happened to a few other reprocessed VES and SN stations, and we therefore assumed that the electric and seismic basements correspond to the Proterozoic rocks. In the Southeastern region, neither VES nor drill-holes were available.

6.4. Physical properties measurements

To consolidate our interpretation, several velocity and density measurements were performed on 11 selected samples from the Lower Kalahari, Upper Kalahari and Proterozoic basement rocks. These

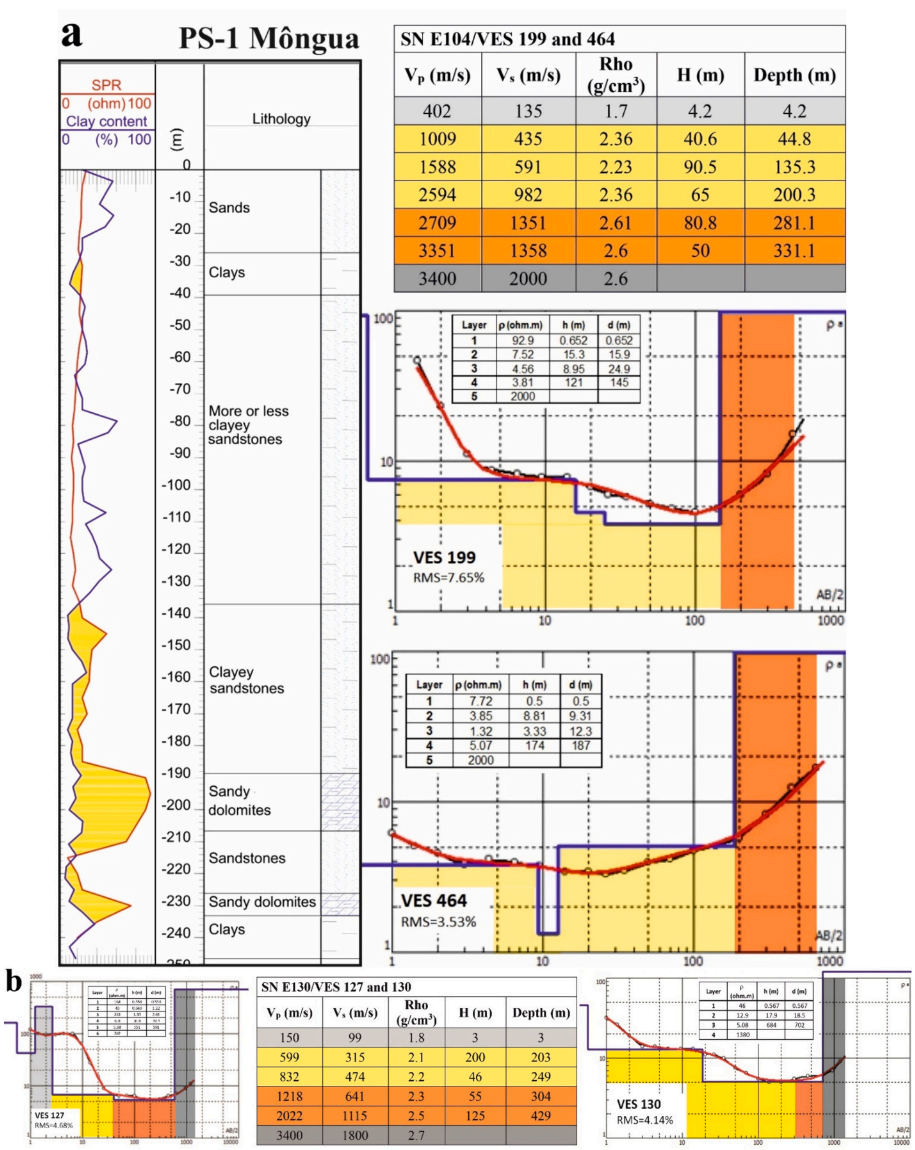

Fig. 7. a) Left: Vertical electric soundings, single point resistance (SPR) and geological logs from the Môngua drill-hole. Center top: Layered model obtain from inversion of seismic noise data from point 104, conducted over the Môngua drill-hole (Vp and Vs – P and S-wave velocities, Rho – density, H – Layer thickness, Depth – Bottom depth of the layer); Centre bottom: Reprocessing of VES 199 e 464 located in the drill-hole area. b) Layered model obtained from inversion of seismic noise data from point 130 (top) and reprocessed VES 127 and 130 located nearby the SN station.

Table 4
Longitudinal wave seismic and density measurements of selected samples of the study area.

Geological formation/Sub-group	Age	Lithology	P-wave velocity (km/s)	S-wave velocity (m/s)	Apparent density (g/cm^3)
Maiongue Fm.	Pan-African	quartzite	3760	490	2.58
Cunene Anorthosotic Complex	Proterozoic	anorthosite	5590	730	2.7
Lower Kalahari-Grés Polimorfos	Paleogene	recrystallized sandstone w/ iron oxides	4650	600	2.25
Lower Kalahari-Grés Polimorfos	Paleogene	recrystallized sandstone	1470	190	–
Lower Kalahari-Grés Polimorfos	Paleogene	recrystallized white quartzite	–	–	2.09
Lower Kalahari-Grés Polimorfos	Paleogene	sandstones with chert levels	–	–	2.48
Lower Kalahari-Grés Polimorfos	Paleogene	sandstones with chalcedony	–	–	2.42
Lower Kalahari	Paleogene	quartzitic sandstone (whitish)	5140	670	2.34
Lower Kalahari	Paleogene	quartzitic sandstone (greenish)	5810	750	2.38
Lower Kalahari	Paleogene	compact limestone	5870	760	2.48
Lower Kalahari	Paleogene	limestone (recrystallized)	5100	660	2.44
Lower Kalahari	Paleogene	Compact limestone with fossils	–	–	2.06
Lower Kalahari	Paleogene	diatomite	900	120	–
Lower Kalahari	Paleogene	diatomite (weathered)	1520	200	–
Upper Kalahari	Paleogene	calcareous sandstone	1070	140	–

measurements are depicted in Table 4. Seismic velocities were measured in the laboratory of the University of Évora, while apparent densities were measured at the National Laboratory for Energy and Geology (LNEG) following international standards. Unfortunately, it was not possible to measure both velocities and densities for all the samples, as some broke during the transportation from Angola to Portugal and did not have the required size.

Apparent densities and open porosities were determined according to the European standard EN 1936:2006. However, given the high size of the tested specimens, the method used to saturate the test specimens was the one provided in the European standard EN 13755:2008. This standard was also followed to determine water absorptions at atmospheric pressure. In apparent density determinations, a value of 1000 kg/m^3 was assumed for the real density of water. The P-wave and S-wave seismic velocities were measured using 250 kHz transducers and a sampling interval of 0.1 μs, making direct measurements between the transducers and transmitters. The contact area of the transducers was of 1962.5 mm^2.

These measurements show that Upper Kalahari Sub-group formations do present lower densities and seismic velocities than most of the lithologies of Lower Kalahari sediments. Carbonated and some lithologies of Grés Polimorfos Lower Kalahari sediments present high velocities/densities that approach those of the samples from the Proterozoic or Pan-African basement. It is therefore realistic to assume that in areas where these lithologies are present, the depth-to-basement is in error. The maximum error is expected to be <50 m, as the thickness of the Grés Polimorfos Fm. thickness is generally below this number. See later, in the Discussion section, further discussion on the implications of the velocity and density measurements to the SN interpretation.

After data processing and interpretation, the depth to the high seismic velocity/density layer (possibly corresponding to the high-resistivity layer) was used to obtain a tentative depth-to-basement map. The drill-holes and geological outcrop information were also used to produce it. The depth-to-basement data was interpolated using the iterative weighting distance (IWD) method and a research radius of 5 km. The result is shown in Fig. 8. In the following section the results are discussed.

7. Discussion

The Kalahari Basin thickness contour lines from Haddon (2005) are also shown in Fig. 8, which was the only available map of Kalahari

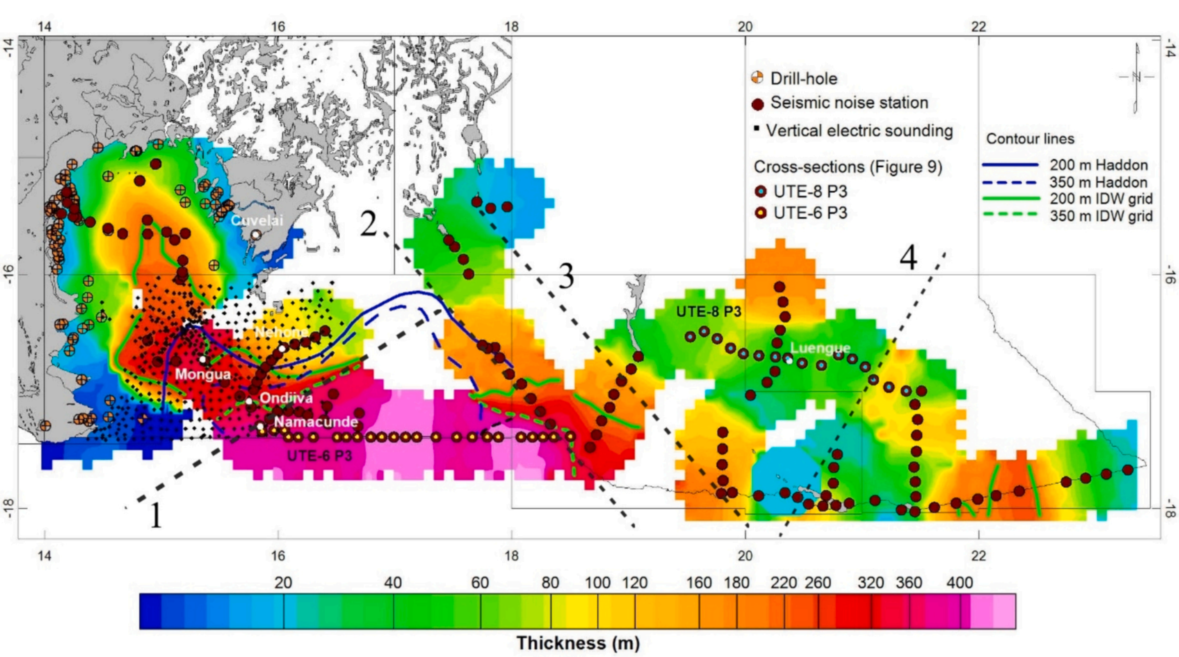

Fig. 8. Map with the representation of the thickness of the Kalahari basin according to this work using seismic noise, drill-hole and outcrop geological data. The contour lines represent the thickness values obtained from seismic noise data of this work and after Haddon (2005). 1- Opuwo lineament; 2- Okavango lineament; 3- Cuanavale lineament; Omaruru-Kudo lineament (see text).

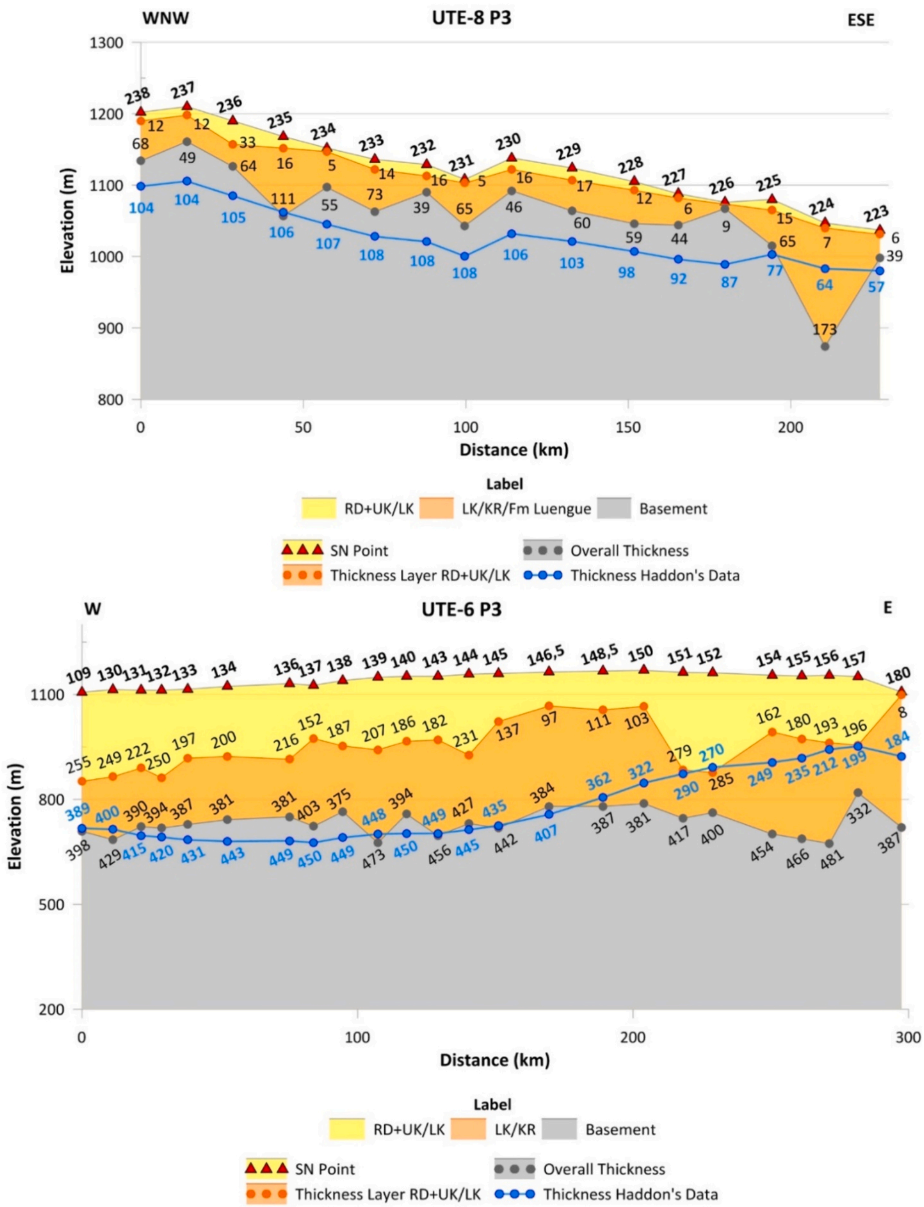

Fig. 9. Examples of representative depth-to-basement cross-sections built with SN and drill-hole data (see location in Fig. 8). Blue line represents depth-to-basement of Haddon (2005). UK- Upper Kalahari; LK- Lower Kalahari; KR- Karoo; RD- recent deposits. Numbers at the surface indicate SN stations number other numbers refer to the depth to the top of each layer. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

thickness in the study area before this study. Haddon's (2005) map was produced for the entire Kalahari Basin, and covers Southern Angola, Namibia, and Botswana. In Fig. 9 we show two representative cross-sections of the depth-to-basement obtained in this work and Kalahari thickness according to Haddon (2005). The comparison between our map and Haddon's (2005) shows a reasonable agreement between both maps in most of the study area.

Both the map and cross-sections show similar depth variations, but our study presents a rougher basement surface, while that of Haddon (2005) appears to be a smoothed version of our map. This is clear in the cross-section shown in Fig. 9. Some of the sharp features in our depth-to-basement map are supported by the geological surveys that were made simultaneously with the second SN campaign and later. For example, two paleo river channels in the Southeastern region are in agreement with basement lows detected with SN data. Our map is also more in agreement with a tectonically comparted area as the study area is expected to be.

According to the depth-to-basement map produce here (Fig. 8) and that of Haddon (2005), the thickness of the sedimentary cover thickens southwards towards the border with Namibia (near Ondjiva and Namacunde areas) reaching here around 450 m, according to Haddon (2005), and 490 m in our study. This value is consistent with some drill-holes in the area, with lost reports but according to IGEO (personal communication) and Gomes (personal communication and 1972) reaching >500 m depth without reaching the basement, and drill-holes located in Namibia (Lindenmaier et al., 2014).

Towards East, in the Southeastern region, the basement becomes much shallower in both maps. According to Haddon's (2005) work this transition is gradational, while our study shows a sharp transition, probably tectonically controlled. 3D modeling of the electrical resistivity data referred previously and covering the small area depicted in Fig. 8 also points out a gradational decrease of the thickness of the sedimentary cover towards SW and N in a large area (Ramalho et al., 2023).

However, some areas can be interpreted as tectonically controlled, with low wavelength electrical resistivity contrasts. Overall, the southern area of study has a thicker sedimentary layer, also confirmed by Lindenmaier et al. (2014), Ramalho et al. (2023) and Francés et al. (2024), but becomes less deep moving southwestwards and northwards, with the basement reaching depths very close to the surface or outcropping. Although there are some drill-hole logs and geophysical information in the southwestern study area, in the southeastern area there are no mechanical soundings available. However, the presence of small outcrops from Proterozoic and Mesozoic rocks, recently mapped by the end of the PLANAGEO project (Labaredas and Oliveira, 2020) indicate that the basement is indeed quite shallow, which is also supported by Haddon (2005) data. This strongly suggests that drill-holes and other geophysical studies should be carried out to investigate the possibility of the presence of the prolonging of the Lufilian Arc and a possible extension of the Congo-Zambia Copper Belt in Southeastern Angola. The map presented here, and the aeromagnetic map produced under the scope of the PLANAGEO project (Fig. 1b) can be used as valuable tools to investigate this possibility.

Very recent geological surveys carried out under the scope of PLANAGEO mapped Karoo sediments in the eastern part of the study area. Velocity or density measurements were not possible in Karoo units, but taking into consideration the lithologies of these sediments, age and depth of burial, high seismic velocities are expected. Nevertheless, according to geological information, the thickness of the Karoo sediments appears to be reduced, as Pan-African basement rocks also outcrop in minor areas in nearby areas.

Our depth-to-basement map may be in error due to methodological or interpretation errors. The methodology used is expedited and possible to apply in a remote area, but is 1D and has limitations when compared with other seismic methods or more advanced ambient noise acquisition and interpretation methods (e.g., Hobiger et al., 2009; Sánchez-Sesma et al., 2011; Piña-Flores, 2017), which are very difficult to apply in the study region. In areas with sharp lateral velocity contrasts or gradational velocity changes these errors will be present. Interpretation errors are also present, due to the overlap of seismic velocities for some geological formations.

For example, in some areas where the Karoo or Grés Polimorfos Fm. are present beneath the Upper Kalahari. Nevertheless, as stated before, geological information suggests that the Grés Polimorfos Fm.'s thickness does not exceed 50 m. In areas where the Karoo Supergroup sediments are present, such as in the area near the border with Namibia, the depth-to-basement is very probably underestimated in our map. In Namibia, in the adjacent area to the study area, a thick column of Karoo sediments has been identified.

The geoelectrical basement can help to estimate depth-to-basement, as Karoo sediments are probably less resistive than Pan-African or Proterozoic basement, unless carbonated. Unfortunately, VES are only available in the Namibia-Cuvelai region and were not acquired in the eastern study area; nevertheless, either the individual 1D VES or the 3D electrical model (Ramalho et al., 2023) give a good idea of the electrical resistivities involved, and what to expect in the enlarged area.

Thick layers with very low electrical resistivities can be due either to the sandy aquifers containing highly mineralized water or clays from the KOH and KOS aquifer systems confirmed by the time domain electromagnetics W-E transect along the border Angolan-Namibian border from Lindenmaier et al. (2014) that covered the western half of the study area and did not reach the basement, although a depth of investigation of about 500 m (Schildknecht, 2012) was reached.

Despite the possible errors in the depth-to-basement estimates, and the reduced area covered, the basement map presented is a good approach to a realistic basement map and highly correlated with the electrical resistivity interpretations from Lindenmaier et al. (2014) or Ramalho et al. (2023), but can also be improved with future studies, given the scarcity of data. The major basement depth variations spatially agree with major lineaments/fault zones inferred from geological and geophysical data interpreted in Namibia, such as the Omaruru-Kudo, Opuwo, Okavango and Cuanavale lineaments, for example (e.g., Singletary et al., 2003; Corner, 2008; Rankin, 2015, see location in Fig. 8), adding further credibility to the interpretation carried out in this work.

8. Conclusions

The possible extension of the Lufilian Arc structure and of the Congo-Zambia Copper Belt beneath the Cenozoic cover into the southeastern corner of Angola led to the need to estimate the depth-to-basement in this area, in order to eventually carry out other mineral exploration activities. Due to the water scarcity in the region of south Angola, the study area was extended towards the west, to add some information to the study of several aquifers present in Namibia inside Kalahari Cenozoic formations. A first depth-to-basement map has been produced by Haddon (2005) but neither the data used, nor its accuracy were disclosed. The remoteness and lack of infrastructures in the study region required the use of an expedite geophysical method for that goal. The single-station horizontal to vertical ratio method offered a viable approach to obtain a first course estimate of depth-to-basement. Despite the large distance from the ocean, considered as one of the major sources of ambient noise, the quality of the signal was good and contained several high frequency peaks, showing that regional sources of noise contributed to the signal recorded.

Using 1D inversion of amplitude/frequency of horizontal to vertical curves, available drill-hole data and geological outcrop data, a depth-to-basement map was produced in this work. The result is similar to that of a previously available broader map containing the study area, which is a smoother, coarser version of our map. Our interpretation was constrained by seismic velocities and density measurements from selected samples from the study area, and drill-hole data. In some areas, where Karoo sediments are very probably present, our map is possibly in error due to the velocity similarity of these formations with Pan-African age or Proterozoic basements. In these areas, the basement depth is underestimated and the previously available map as well. Adding to the interpretation errors, the limitations of the 1D inversion method used have to be considered, particularly in areas with vertical gradual velocity increases or sharp lateral velocity changes. Due to the vastness, remoteness of the study area, and the need to obtain results in a short period of time, 2D or 3D seismic approaches were difficult to implement. Overall, the H/V method is a valid and expedited tool to estimate either the depth to pre-Cenozoic basement or Cenozoic sediments thickness.

The recent identification of small outcrops of Pan-African aged rocks, possibly related to the extension of the Lufilian Arc in southeastern Angola, confirms the result obtained in this work that the Pre-Kalahari basement is generally located at shallow depths in the part of the study area. As a tentative separation of Upper and Lower Kalahari was also achieved, the data collected in the scope of this work can also be used in hydrogeological studies in the Namibia-Cuvelai region, where several aquifers hosted by Kalahari formations and with great importance for groundwater supply are present.

CRediT authorship contribution statement

E.C. Ramalho: Software, Investigation, Formal analysis, Data curation, Writing – review & editing. **A. Oliveira**: Investigation, Formal analysis, Data curation, Writing – review & editing. **J.L. García-Lobón**: Validation, Writing – review & editing. **D. Alves**: Software, Formal analysis, Data curation, Writing – review & editing. **J. Borges**: Validation, Supervision, Software, Investigation, Formal analysis, Conceptualization, Data curation. **P. Ibarra**: Data curation. **J. Carvalho:** Writing – original draft, Validation, Supervision, Software, Investigation, Data curation, Conceptualization. **B. Caldeira:** Validation, Supervision, Software, Investigation, Formal analysis, Data curation, Conceptualization. **D. Cordeiro:** Writing – review & editing, Data curation. **A. Machadinho:** Writing – review & editing, Visualization, Validation, Investigation. **J.F. Rodrigues:** Writing – review & editing, Supervision, Investigation, Formal analysis. **J.M. Llorente:** Data curation. **M. Ditutala:** Writing – review & editing, Formal analysis, Data curation. **J. Máximo:** Writing – review & editing, Formal analysis, Data curation. **C. Carvalho:** Methodology, Investigation. **J. Labaredas:** Writing – review & editing, Investigation, Formal analysis. **J. Manuel:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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References

Acerra, C., Aguacil, G., Anastasiadis, A., Atakan, K., Azzara, R., Bard, P.Y., Bonnefoy-Claudet, S., 2004. Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations measurements, processing and interpretation. In: SESAME European Research Project WP12 – Deliverable D23.12, European Commission – Research General Directorate Project No. EVG1-CT-2000-00026 SESAME.

Arnaud, E., Halverson, G.P., Shields-Zhou, G., 2011. The Geological Record of Neoproterozoic Glaciations, Geological Society 36, London. https://doi.org/10.1144/M36.

Bao, F., Li, Z., Tian, B., Wang, L., Tu, G., 2019. Sediment thickness variations of the Tangshan fault zone in North China from a dense seismic array and microtremor survey. J. Asian Earth Sci. 185, 104045 https://doi.org/10.1016/j.jseaes.2019.104045.

Bard, P.-Y., 2004. The sesame project: An overview and main results. In: 13th World Conference on Earthquake Engineering, Vancouver.

Bignardi, S., Mantovani, A., Abu Zeid, N., 2016. OpenHVSR: imaging the subsurface 2D/3D elastic properties multiple HVSR modeling and inversion. Comput. Geosci. 93, 103–113. https://doi.org/10.1016/j.cageo.2016.05.009.

Bobachev, A.A., Modin, I.N., Shevnin, V.A., 2000. IPI2Win User's Guide. Moscow State University, Geological Faculty, Dept. of Geophysics, Geoscan-M Ltd, Moscow, Russia.

Bonnefoy-Claudet, S., Cornou, C., Bard, P.-C., Cotton, F., Moczo, P., Kristek, J., Fah, D., 2006. H/V ratio: a tool for site effects evaluation. Results from a 1-D noise simulation. Geophys. J. Int. 167, 827–837.

Borges, J.F., Silva, H.G., Torres, R.J.G., Caldeira, B., Bezzeghoud, M., Furtado, J.A., Carvalho, J., 2016. Inversion of ambient seismic noise HVSR to evaluate velocity and structural models of the lower Tagus Basin, Portugal. J. Seismol. 20, 875–887. https://doi.org/10.1007/s10950-016-9564-x.

Cahen, L., 1954. Geologie du Congo Belge. H. Vaillant-Carmanne, Liege.

Cahen, L., Lepersonne, J., 1954. État actuel des conaissances relatives aux séries mésozoïques de l'intérieur du Congo. Bulletin de la Société Belge de Géologie 77, 20–37.

Carvalho, J., Dias, R., Ghose, R., Borges, J., Narciso, J., Pinto, C., Leote, J., 2018. Near surface characterization of the Lisbon and lower Tagus Valley Area, Portugal for seismic hazard assessment: VS30 and soil classification maps. Bull. Seismol. Soc. Am. 108 (5A), 2854–2876. https://doi.org/10.1785/0120170340.

Catuneanu, O., Wopfner, H., Eriksson, P.G., Cairncross, B., Rubidge, B.S., Smith, R.M.H., Hancox, P.J., 2005. The Karoo basins of south-Central Africa. J. Afr. Earth Sci. 43 (1–3), 211–253.

Claprood, M., 2012. Ambient noise. In: Hunter, J.A., Crow, H.L. (Eds.), Shear Wave Velocity Measurement Guidelines for Canadian Seismic Site Characterization in Soil and Rock Ottawa, Geological Survey of Canada, Open File, vol. 7078, pp. 9–18.

Corner, B., 2008. Crustal framework of Namibia derived from an integrated interpretation of geophysical and geological data. In: Miller, R.M.G. (Ed.), The Geology of Namibia: Archean to Mesoproterozoic, Special Publication of the Geol. Survey of Namibia, vol. 1. Geological Survey of Namibia, Windhoek, pp. 1–19.

Daly, M.C., Lawrence, S.R., Diemu-Tshiband, K., Matouana, B., 1992. Tectonic evolution of the Cuvette Centrale, Zaire. J. Geol. Soc. Lond. 149, 539–546. https://doi.org/10.1144/gsjgs.149.4.0539.

De Wit, M., 2009. Tsodilo Resources Limited Drills Extension of Zambian Copper Belt-like Mineralisation in Pan African Basement of Northwest Botswana. Tsodilo Resources Limited Report. http://www.tsodiloresources.com/s/Home.asp.

Fäh, D., Kind, F., Giardini, D., 2001a. A theoretical investigation of average H/V ratios. Geophys. J. Int. 145, 535–549. https://doi.org/10.1046/j.0956-540x.2001.01406.x.

Fäh, D., Kind, F., Lang, K., Giardini, D., 2001b. Earthquake scenarios for the city of Basel. Soil Dyn. Earthq. Eng. 21 (5), 405–413. https://www.infona.pl/resource/bwmeta1.element.elsevier-a0bc5d87-67ba-3f22-b4cd-a7f73f12f3a/tab/jContent/facet?field=%5ejournalYear%5ejournalVolume&value=%5e_02001%5e_00021.

Francés, A.P., Ramalho, E.C., Monteiro Santos, F., Llorente, J.M., Mateus, T., Martin Banda, R., Cuervo, I., García Lobón, J.L., Dala, V., Ditutala, M., Famorosa, A., A.M. Victorino, 2024. Contribution of the time domain electromagnetic method to the study of the Kalahari transboundary multilayered aquifer systems in Southern Angola. Hydrogeology Journal. https://doi.org/10.1007/s10040-024-02822-x.

Furtado, J.A., 2010. Confirmação do modelo da estrutura 3D do Vale Interior do Tejo a partir de dados de ruído sísmico ambiente. Master Thesis (in Portuguese), Universidade de Évora (136 p).

Haddon, I.G., 2005. The Sub-Kalahari Geology and Tectonic Evolution of the Kalahari Basin, Southern Africa. Doctoral dissertation. https://wiredspace.wits.ac.za/server/api/core/bitstreams/3f64b798-a09a-405b-8cdf-d5d6444a1d14/content.

Haddon, I.G., McCarthy, T.S., 2005. The Mesozoic–Cenozoic interior sag basins of Central Africa: The Late-Cretaceous-Cenozoic Kalahari and Okavango basins. J. Afr. Earth Sci. 43 (1), 316–333.

Herak, M., 2008. ModelHVSR—A Matlab® tool to model horizontal-to-vertical spectral ratio of ambient noise. Comput. Geosci. 34 (11), 1514–1526. https://doi.org/10.1016/j.cageo.2007.07.009.

Hitzman, M.W., Broughton, D., Selley, D., Woodhead, J., Wood, D., Bull, S., 2012. The Central African Copperbelt: Diverse Stratigraphic, Structural, and Temporal Settings in the World's Largest Sedimentary Copper District, 16. Society of Economic Geologists Special Publication, pp. 487–514. https://doi.org/10.5382/SP.16.19.

Hoak, T.E., Klawitter, A.L., Dommer, C.F., Scaturro, P.V., 2014. Integrated exploration of the Owambo basin, onshore Namibia: hydrocarbon exploration and implications for a modern frontier basin. In: AAPG Annual Convention and Exhibition, Houston, Texas, April 6-9. http://the-eis.com/elibrary/search/12931.

Hobiger, M., Bard, P.-Y., Cornou, C., Le Bihan, N., 2009. Single station determination of Rayleigh wave ellipticity by using the random decrement technique (RayDec). Geophys. Res. Lett. 36, L14303. https://doi.org/10.1029/2009GL038863.

Ibs-von Seht, M., Wohlenberg, J., 1999. Microtremor measurements used to map thickness of soft sediments. Bull. Seismol. Soc. Am. 89, 250–259. https://doi.org/10.1785/BSSA0890010250.

Jeng, Y., Tsai, J.Y., Chen, S.-H., 1999. An improved method of determining near-surface Q. Geophysics 64 (5), 1608–1617. https://doi.org/10.1190/1.1444665.

Johnston, David H., 1981. Attenuation: state-of-the-art summary. In: Toksoz, M.N., Johnston, D.H. (Eds.), Seismic Wave Attenuation, SEG Geophys. Reprint Ser. No. 2, Tulsa, pp. 123–135.

Kabongo, E.K., Delvaux, D., Everaerts, M., Sebangenzi, M.N.S., Lucazeau, F., 2015. Neoproterozoic to lower paleozoic sequences of the Congo Shield: Comparisons between the Congo and its peripheral basins. In: de Wit, M.J., Guillocheau, F., de Wit, M.C.J. (Eds.), Geology and Resource Potential of the Congo Basin. Springer, pp. 97–109.

Labaredas, J., Oliveira, A., 2020. Geological Map of Angola at the 1:250 000 Scale, Sheet Sul E-33/C, Caiundo, (in Portuguese). UTE (IGME - LNEG - Impulso) - IGEO, Luanda.

Labaredas, J., Oliveira, A., 2021. Geological Map of Angola at the 1:250 000 Scale, Sheet Sul E-34/G (Cuangar) (in Portuguese). UTE (IGME, LNEG, Impulso) - IGEO, Luanda, p. 121.

Lane, J.W., White, E.A., Steele, G.V., Cannia, J.C., 2008. Estimation of bedrock depth using the horizontal-to-vertical (H/V) ambient noise seismic method. In: Proceedings of Symposium on the Application of Geophysics to Engineering and Environmental Problems. SEG, pp. 490–502. https://doi.org/10.4133/1.2963289.

Laznicka, P., 2010. Giant Metallic Deposits: Future Sources of Industrial Metals, second ed. Springer, New york.

Lindenmaier, F., Miller, R., Fenner, J., Christelis, G., Dill, H.G., Himmelsbach, T., Kaufhold, S., Lohe, C., Quinger, M., Schildknecht, F., Symons, G., Walzer, A., van Wyk, B., 2014. Structure and genesis of the Cubango Megafan in northern Namibia: implications for its hydrogeology. Hydrogeol. J. 22, 1307–1328. https://doi.org/10.1007/s10040-014-1141-1.

Linol, B., de Wit, M.J., Barton, E., Guillocheau, F., de Wit, M.C.J., Colin, J.P., 2015a. Paleogeography and tectono-stratigraphy of Carboniferous-Permian and Triassic "Karoo-like" sequences of the Congo Basin. In: de Wit, M.J., Guillocheau, F., de Wit, M.C.J. (Eds.), Geology and Resource Potential of the Congo Basin. Springer, New York, pp. 111–134.

Linol, B., de Wit, M.J., Guillocheau, F., de Wit, M.C.J., Anka, Z., Colin, J.P., 2015b. Formation and colapse of the Kalahari Duricrust ["African Surface"] across the Congo Basin, with implications for changes in rates of Cenozoic off-shore sedimentation. In: de Wit, M.J., Guillocheau, F., de Wit, M.C.J. (Eds.), Geology and Resource Potential of the Congo Basin. Springer, New York, pp. 191–210.

Lopes, R., Máximo, J., Sousa, J.C., 2020. Geological Map of Angola at the1:250 000 Scale, Sheet Sul D-33/Z, Caiundo (in Portuguese). UTE (IGME - LNEG - Impulso) - IGEO, Luanda, p. 166.

Maghami, Shahram, Sohrabi-Bidar, A., Bignardi, S., Zarean, A., Kamalian, M., 2021. Extracting the shear wave velocity structure of deep alluviums of "Qom"Basin (Iran) employing HVSR inversion of microtremor recordings. J. Appl. Geophys. 185, 104246 https://doi.org/10.1016/j.jappgeo.2020.104246.

Miller, R., 1997. The Owambo Basin of Northern Namibia African Basins, in Sedimentary Basins of the World. Elsevier Science B.V, pp. 237–268.

Nakamura, Y., 1989. A Method for Dynamic Characteristics Estimation of Subsurface Using Microtremor on the Ground, 30. Quarterly Report of Railway Technical Research Institute, Tokyo, pp. 25–30. http://worldcat.org/oclc/3127232.

Okada, H., 2003. The Microtremor Survey Method, Society of Exploration Geophysicists, Geophysical Monographs Series no. 12, Tulsa, Ok (USA) (135 p).

Parolai, S., Borman, P., Milkereit, C., 2002. New relationships between Vs, thickness of sediments, and resonance frequency calculated by the H/V ratio of seismic noise for the Cologne area (Germany). Bull. Seismol. Soc. Am. 92, 2521–2527. https://doi.org/10.1785/0120010248.

Pereira, E., Rodrigues, J., Reis, B., 2003. Synopsis of Lunda geology: implications for Diamond exploration. Comum. Instituto Geológico e Mineiro 90, 189–212. http://hdl.handle.net/10400.9/690.

Piña-Flores, J., 6 others, 2017. The inversion of spectral ratio H/V in a layered system using the diffuse field assumption (DFA). Geophys. J. Int. 208, 577–588. https://doi.org/10.1093/gji/ggw416.

Ramalho, E.C., Francés, A.P., Monteiro Santos, F., Victorino, A.M., 2023. D electrical structure definition of aquifer systems in the Kalahari basin in Southern Angola based on legacy data reprocessing. J. Appl. Geophys. 211, 104968 https://doi.org/10.1016/j.jappgeo.2023.104968.

Rankin, W., 2015. Cross-border correlation of the Damara Belt in Namibia and equivalent lithologies in northwestern Botswana from potential field and magnetotelluric interpretations. PhD Thesis. University of Witwatersand, Johannesburg, p. 542.

Ray, J., Sen, G., Ghosh, B., 2011. Topics in Igneous Petrology, first ed. Springer, New York.

Roberts, E., Jelsma, H.A., Hegna, T., 2015. Mesozoic sedimentary cover sequences of the Congo Basin in the Kasai Region, Democratic Republic of Congo. In: de Wit, M.J., et al. (Eds.), Geology and Resource Potential of the Congo Basin, Regional Geology Reviews. Springer-Verlag, Heidelberg, pp. 163–191. https://doi.org/10.1007/978-3-642-29482-2_9.

Sánchez-Sesma, F.J., Rodríguez, M., Iturrarán-Viveros, U., Luzón, F., Campillo, M., Margerin, L., García-Jerez, A., Suarez, M., Santoyo, M.A., Rodríguez-Castellanos, A., 2011. A theory for microtremor H/V spectral ratio: Application for a layered medium. Geophys. J. Int. 186, 221–225.

Scheib, A., Morris, P., Murdie, R., Delle Piane, C., 2016. A passive seismic approach to estimating the thickness of sedimentary cover on the Nullarbor Plain, Western Australia. Aust. J. Earth Sci. 63, 583–598. https://doi.org/10.1080/08120099.2016.1233455.

Schildknecht, F., 2012. Groundwater exploration with TEM soundings in the Cuvelai-Etosha Basin. In: Grundwasser für den Norden Namibias (Cuvelai-Etosha Becken), British Geological Survey, Report 2006.2073.2, 05–2326, 35p.+Annexes.

Selley, D., Broughton, D., Scott, R., Hitzman, M., Bull, S., Large, R., McGoldrick, P., Croaker, M., Pollington, N., Barra, F., 2005. A new look at the geology of the Zambian Copperbelt. In: Economic Geology, 100th Anniversary Volume, pp. 965–1000.

Sharma, Hema, Molnar, S., Sirohey, A., 2024. Techniques to identify microtremor wave contributions and impact to seismic site characterization. J. Seismol. 28, 345–372. https://doi.org/10.1007/s10950-024-10189-5.

Sheriff, R.E., Geldart, L.P., 1995. Exploration Seismology. Cambridge university press, Cambridge.

Sillitoe, R.H., Perelló, J., Creaser, R.A., Wilton, J., Dawborn, T., 2015. Two ages of copper mineralization in the Mwombezhi Dome, Northwestern Zambia: metallogenic implications for the Central African copperbelt. Econ. Geol. 110, 1917–1923. https://doi.org/10.2113/econgeo.110.8.1917.

Singletary, S.J., Hanson, R.E., Martin, M.W., Crowley, J.L., Bowring, S.A., Key, M., Ramokate, L.V., Direng, B.B., Krol, M.A., 2003. Geochronology of basement rocks in the Kalahari Desert, Botswana, and implications for regional Proterozoic tectonics. Precambrian Res. 121, 47–71. https://doi.org/10.1016/S0301-9268(02)00201-2.

Sousa, J.C., Oliveira, A., Máximo, J., 2021. Geological Map of Angola at the 1:250 000 Scale, Sheet Sul D-33/U, Chibemba, with Memoir (in Portuguese). UTE (IGME - LNEG - Impulso) - IGEO, Luanda, p. 199.

Vijayan, A., Agrawal, M., Gupta, R.K., 2022. Seismic Site Characterization using Ambient Noise and Earthquake HVSR in the Easternmost part of Shillong Plateau. India. J. Geol. Soc. India 98, 471–478. https://doi.org/10.1007/s12594-022-2004-3.

Williams, B.W., Nisbet, P.R., 2017. Structural framework of the Lufilian Fold Belt in the Domes region of North Western Province, Zambia from interpretation of geophysical data. J. Afr. Earth Sci. 129, 542–557. https://doi.org/10.1016/j.jafrearsci.2017.01.029.