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Dendrochronological study of Van Goyen´s panels and preliminary study of its painting technique

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Abstract This research employs a comprehensive methodology integrating dendrochronology, and the technical and material study of the painting´s pigments, and stratigraphy to further enhance our understanding of materials and techniques of the Dutch landscape painter of the seventeenth century, Jan van Goyen (1596–1656). The scientific examination of the eight panels housed in Medeiros e Almeida Museum (Portugal, Lisbon) aims to identify the wooden panels utilized by Van Goyen's workshop, exploring their assembly techniques and dates. Additionally, the integrated in situ approach also encompasses visible standard light photography, infrared reflectography and ultraviolet fluorescence photography imaging techniques and chemical analysis by energy-dispersive X-ray fluorescence and 2D macro-energy-dispersive X-ray fluorescence. The scientific results from the *Village Scene*, the earlier work known by Van Goyen in the collection, dated 1623, revealed that the artist executed an expressive underdrawing to set out the painting composition and applied a rich palette in the artistic expression, based on lead white, lead tin yellow, smalt blue, ochres, vermillion and a copper green pigment. This ongoing research provides a unique perspective on the relationship between materials and artistic intent in Van Goyen's work, offering valuable insights into the broader cultural and historical context of Dutch painting of the period.

1 Introduction

1.1 The painter Jan van Goyen and the scientific analysis

Van Goyen was born in 1597 and is reported to have started working in 1620. Known for his naturalistic landscapes, for which he is considered one of the pioneers, he had a significant influence on later painters. He has created approximately 1200 paintings and 800 drawings. The Medeiros e Almeida Museum has a collection of 8 paintings from different phases of his long artistic life (Fig. 1).

The study of Jan van Goyen and Dutch painting of the seventeenth century is a rich and varied field of research, with a long tradition of scholarship and inquiry. Over the years, scholars, and researchers from a range of disciplines have contributed to our understanding of van Goyen's life and work, as well as the broader cultural and historical context of Dutch painting from that period. Slive [1] is one of the most significant contributions to the literature about Jan van Goyen, providing a comprehensive analysis of van Goyen's life and work, as well as his use of materials and techniques. Several scholars have focused on the technical analysis of Dutch paintings of the seventeenth century—"Historical Painting Techniques, Materials, and Studio Practice" provides an overview of the pigments and binders used by Dutch landscape painters, including Van Goyen [2]; "Vermeer and the Art of Painting" issues a detailed analysis of the materials and techniques [3]. In addition to these key works, there are also numerous articles, essays, and monographs that provide detailed analysis of Dutch painting of the seventeenth century, including the work of Jan van Goyen. By example, Sutton et al. [4] analyse landscape as a subject, identifying the main themes and patterns of style and provides insight into the broader cultural context of Dutch painting of the period. Another important contribution is "Still Lifes of the Golden Age:

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Fig. 1 Jan van Goyen's paintings from the Medeiros e Almeida Museum (Lisbon) include *Landscape with Fair Weather* (FMA 391), *Landscape with Stormy Weather* (FMA 392), *Village Scene* (FMA 390), *View of The Hague* (FMA 376), *View of the Maas* (FMA 355), *The Ferry* (FMA 374), *View of Scheveningen* (FMA 373), and *View Near Dordrecht* (FMA 372). (@PMora, Museu Medeiros e Almeida)

Northern European Paintings from the Heinz Family Collection" with chapters on a range of painters and styles, including Jan van Goyen [5].

The most extensive dendrochronological study of paintings attributed to the Dutch painter Jan Van Goyen comprises 38 artworks from German, American, Swedish, and Dutch museum collections. The analysis of the dendrochronological data revealed the use of 100 to 300-year-old oak planks from the Baltic regions, Poland, Germany, and the Netherlands, covering a time span from 1294 to 1636 [6, 7]. Besides dating the wood supports of the eight van Goyen's paintings, a crucial goal of the proposed research is the strengthening and temporal expansion of the dendrochronological database developed in the last decades in Portugal, based on the study of Portuguese and Flemish paintings from Portuguese public and private collections [8]. The actual database (covering the period 1149–1599) has a gap in the dendrochronological data for the seventeenth century due to the lack of Portuguese studies on wooden artworks spanning this period [8]. The proposed project will be the first dendrochronological study to cover part of seventeenth century, increasing the database, in numbers and time scale. It will become an asset for the future dating of a wide range of historical objects from the Portuguese heritage (e.g. paintings, sculptures, historic building structures and furniture), from the seventeenth century.

This research builds on these earlier works, focusing specifically on materials and techniques used by Jan van Goyen in his small paintings. The interdisciplinary approach, which brings together art historians, materials scientists, and dendrochronologists, will contribute to the ongoing development of the field of heritage science. By combining scientific analysis with historical research, the project will provide a unique perspective on the relationship between materials and artistic intent in Van Goyen's work.

1.2 Dating paintings through a dendrochronological approach

Dendrochronology is the scientific discipline of dating woody material to the precise year of each tree ring, thereby providing the *terminus post quem* through the most recent year identified. This process also enables the extraction of information regarding environmental events and changes. The biological study of dendrochronology uses wood tree-ring structures. It can be applied to different kinds of artwork: paintings, musical instruments, sculptures, furniture, archaeological artefacts, historical buildings, and ships. The scientific study of panels that have emerged over the past century has fundamentally altered the way an artwork is

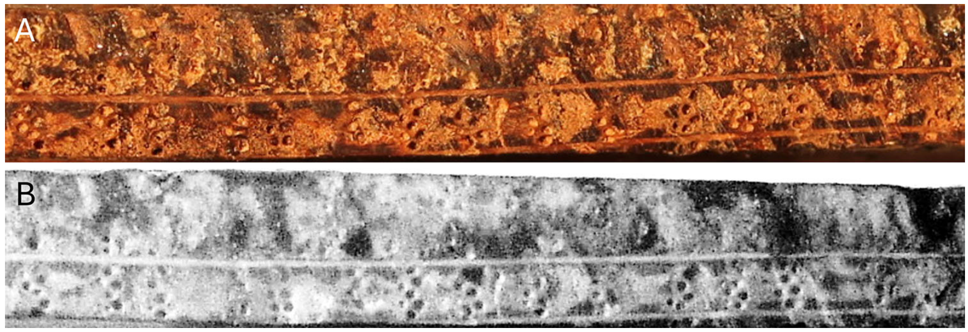

Fig. 2 Macro-photographs of the cross section of an oak board (**A**) visible light and (**B**) infrared

evaluated. Using various analytical instruments, researchers in art history, conservation and computer science, chemistry, physics, and biology highlight the successful performance of interdisciplinary work. Initially referred to as "technical studies", interdisciplinary collaboration has proven to be a growing area of research called "technical art history" [9] or even "heritage science". Dendrochronology applied to paintings is now considered one of the standard techniques. The main testimonies of the significance and validity of dendrochronology are the various studies that have been developed worldwide and published over the last decades [10–19]. The principal outcomes of these research endeavours are focused on the identification and provenance of wood species, the determination of the *terminus post quem* of the panel, the artistic attribution, and the panel manufacturing technology. A more thorough investigation can involve questions concerning timber and artworks international trade [15, 18, 20–22]. This science may provide an important contribution to answering such geographical, technological, and cultural issues that cannot be addressed by historical and philological methods alone. In addition, it can serve other purposes, such as upholding authentication, detecting potential forgeries, establishing the original link between separated wooden planks, and obtaining a more precise dendrochronological dating for a collection of artworks made in a specific workshop.

A dendrochronological dating is obtained for the last whole ring preserved and identified (i.e. the outer growth ring) on the wooden piece. However, Baillie [23] claims that the sapwood ring number is the biggest single problem in the interpretation of tree ring data. The complete or partial absence of sapwood rings in paintings is quite common, reducing the usefulness of dendrochronological details. Sapwood, like pith, is part of the wood that is not ideal for quality support because it is susceptible to warping and decay [24]. For this reason, the rules for their removal were well established since the fifteenth century [25, 26], although exceptions have been found in some Flemish paintings [27] including works by Jan van Goyen.

2 Experimental

2.1 Dendrochronological analysis

The dendrochronological analysis applied in this research project was performed on the wooden support of each painting through direct observation, as it is impossible to take samples of the work of art. The dating technique was based on obtaining high-resolution photographs of the transversal of each of the boards to measure the growth rings with the Image J software and subsequent dating with the TSAPWin Scientific 4.64 software. Macro-photographs were experimentally taken using visible light (digital camera Canon EOS 1100D, and Canon Zoom Lens EF-S 60 mm f/2.8 Macro USM) and infrared (Sony DSC-F828 2–2,8/7,1–51 T Carl Zeiss Vario-Sonnar Compact Digital Camera) to assess their quality and effectiveness in measuring growth rings. In some cases, infrared images were found to provide a clearer distinction between the limits of the tree rings, i.e. a clear ring-porous structure characteristic of certain oaks (Fig. 2).

A comparative statistical and visual analysis was conducted between the dendrochronological series obtained from the planks and a set of European oak chronologies. Furthermore, dendrochronological series provided by the Netherlands Institute for Art History (RKD) were considered, with access provided via the following link: https://rkd.nl/en/.

2.2 Imaging and analytical in situ approach

In situ analysis started with the painting´s direct examination and imaging techniques, that included the technical photography (in the visible light range, ultraviolet induced visible fluorescence and near infrared at 1000 nm). Visible (Vis) imaging and ultraviolet fluorescence (UVF) imaging were performed by using a Nikon D3200 digital single-lens reflex camera with a 24 MP sensor and a Nikkor 18–55 mm f/3.5–5.6 GII lens. Near-infrared (NIR) images were captured using a Nikon D3100 camera, modified for full-spectrum sensitivity, and equipped with high-pass filters (X-nite 780, 850, and 1000 nm). Infrared reflectography was performed with an Osiris camera equipped with a high-resolution infrared detector based on two-dimensional InGaAs sensor arrays. This setup allows the acquisition of high-resolution images (4096 × 4096 pixels) in response to radiation within the 900–1700 nm range. The

Table 1 Characterization of the boards that compose the supports of the eight paintings attributed to Jan van Goyen from the Medeiros e Almeida Museum (Lisbon) [Type of cut—FR: full radial (or full quarter); R: radial (or quarter); SR: semi-radial (or false quarter); T: tangential [24]

Painting [inventory number]	Number of planks	Dimensions, cm (height × width x thickness)	Type of cut
Village scene [FMA 390]	2	36.5 × 72.0 × 0.40	R/R
Landscape with fair weather [FMA 391]	1	22.0 × 44.5 × 0.30	SR
Landscape with stormy weather [FMA 392]	1	22.0 × 44.5 × 0.30	SR
View near dordrecht [FMA 372]	1	41.0 × 64.0 × 0.40	R
View of the maas [FMA 355]	1	33.0 × 54.0 × 0.65	R
View of Scheveningen [FMA 373]	1	39.5 × 59.7 × 0.70	R
The ferry [FMA 374]	2	34.5 × 51.5 × 0.40	FR/R
View of the Hague [FMA 376]	1	24.5 × 36.0 × 0.60	R

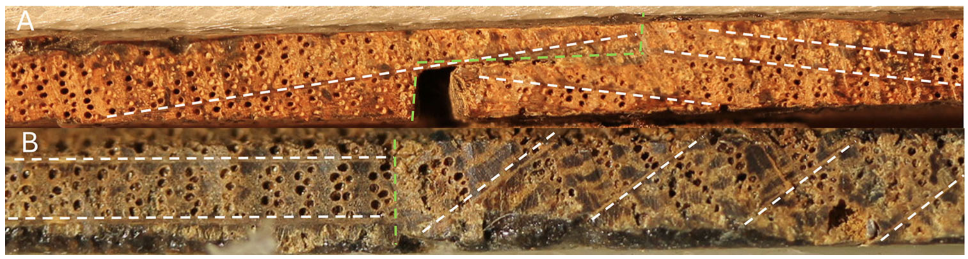

Fig. 3 Planks joints. (**A**) Lip join in *Village Scene* (FMA 390) (**B**)) butt join in *O ferry* (FMA 374) [white dashed lines represent the orientation of the medullary rays; green dashed lines delimit the junction of the boards]

camera features an internal filter (Schott RG850) that blocks radiation with wavelengths below 850 nm. It is designed for use with tungsten-halogen lamps, and for this investigation, two such lamps were employed (OSRAM 64575 Halogen lamp 1000W-230 V, colour temperature: 3400 K), positioned at an illumination angle of 30–60° relative to the object. The complete reflectographic coverage of each painting was conducted in areas measuring 30–50 cm.

The EDXRF analysis was performed by using a Bruker Tracer 5i handheld X-ray fluorescence spectrometer equipped with a rhodium X-ray tube and a X-Flash SDD detector. The spectra acquisition was obtained with 40 kV, 4 µA and an acquisition time of 30 s. The spectra processing was made through the ARTAX (Bruker) software.

The 2D chemical elemental mapping (MA-XRF) analysis was made with a CRONO Bruker spectrometer. The system consists of a measurement head mounted on a motorized stage, capable of scanning areas up to 60 cm × 45 cm at a speed of 42 mm/s, achieving a lateral imaging resolution of 0.5 mm (focal distance of 5–7 mm). The spectrometer features a rhodium X-ray tube and a large-area 50 mm^2 SDD detector with CUBE technology. Spectra acquisition was performed at a voltage of 50 kV and a current of 200 µA. Data acquisition and analysis were carried out using CRONO and ESPRIT software packages from Bruker.

3 Results and discussion

3.1 Wooden panels: nature, structure, and dating

All the paintings are crafted from deciduous oak (*Quercus* sp.), the most preferred wood support for paintings during the sixteenth and early seventeenth centuries [28]. Most of the paintings are constructed from a single plank, positioned horizontally (Table 1). However, there are two exceptions: *Village Scene* (FMA 390) and *The Ferry* (FMA 374). These are composed of two planks, with lip and butt joints, respectively (Fig. 3). It was traditional to glue two or more boards together, with heartwood joined to heartwood and sapwood to sapwood [29]. The boards were typically joined with the heartwood on the outer edges, as seen in the painting *Village Scene* (FMA 390). However, *The Ferry* (FMA 374) definitively does not show any of these assembly criteria.

In selecting oak boards for a panel, the medullar ray's orientation of each plank is a fundamental quality parameter (Fig. 4). On a full quarter (or full radial) oak plank, the medullar rays are visible throughout the entire width, thus offering high-quality planks [30]. Some authors consider them to be the highest-performing planks due to the reduced risks of wood fractures under environmental conditions [24, 26]. In the quarter (or radial) cut, the medullar rays are visible with a slight slope at an angle of less than 45°. The classification of the cut as false quarter (or semi-radial) is made when the medullar rays exhibit an angle greater than 45° [24]. Most of the planks from the eight Van Goyen panels show a radial cut.; however, one notable exception is the board featuring the painting *The Ferry* (FMA 374) (Fig. 2), which exhibits a full-radial cut. Additionally, the paintings *Landscape with Fair Weather* (FMA 391) and *Landscape with Stormy Weather* (FMA 392) exhibit a semi-radial cut (Table 1). Dendrochronological studies of paintings from the fifteenth and sixteenth centuries frequently yield boards with thicknesses ranging from 8 to 30 mm [30]. However, given the

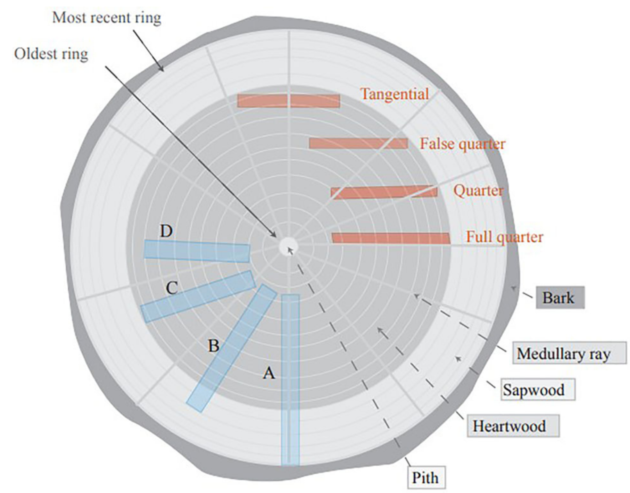

Fig. 4 Transverse section diagram of an oak wood trunk. Red rectangles represent the different possible cutting directions of the boards: FR_full radial (or full quarter); R_radial (or quarter); SR_semi-Radial (or false quarter); T_tangential. Blue rectangles represent the different cutting options of the boards according to/without sapwood and/or heartwood removal: **A** board with complete sapwood; **B** board with partial sapwood; **C** board without only sapwood; and **D** board without sapwood, as well as some heartwood rings [11]

Table 2 Dendrochronological dates of the 8 chronological series/combination of chronological series obtained in the eight paintings attributed to Jan van Goyen from the FMA collection

Laboratory filename (chronological series/combination of series)	Total rings measured	First preserved ring	Last preserved ring*	Sapwood rings (estimated number)	Terminus post quem		Historical date
					Earliest possible tree felling	For the support manufacture	
PFMA390001	115	–	–	–	–	–	–
PFMA390002	213	–	–	–	–	–	–
PFMA390000	215	1373	1587	+ 15	1602	1604	1623
PFMA391000	110	–	–	–	–	–	1625
PFMA392000	112	–	–	–	–	–	1625
PFMA391-PFMA392	118	1460	1577	+ 9	1586	1588	–
PFMA372000	304	1314	1617	+ 15	1632	1634	1639
PFMA355000	291	1330	1620	+ 15	1635	1627	1643
PFMA373000	319	1309	1627	+ 15	1642	1644	1643
PFMA374001	127	1475	1601	–	–	–	1644
PFMA374002	235	1389	1623	+ 15	1638	1640	
PFMA376000	174	1465	1638	+ 9	1647	1649	1652

[Laboratory filename—internal identification of each board; total rings—number of growth rings measured; sapwood rings (estimated number)—number of sapwood rings according to the tree's age (boards with less than 200 years—add 9 rings; boards with more than 200 years—add 15 rings); *terminus post quem* earliest possible tree felling—last preserved ring plus sapwood rings (estimated number); *terminus post quem* for the support manufacture—*terminus post quem* earliest possible tree felling plus 2 years of seasoning]

gradual scarcity of high-quality wood suitable for use in paintings, artworks from the seventeenth century commonly possess thinner planks, as evidenced in the set of eight paintings by Van Goyen, exhibiting thickness variations between 3 and 7 mm (Table 1).

As is typically observed in such art objects, no indications of sapwood were discernible in any of the paintings (see cutting types C and D in Fig. 4). This part of the trunk is known to be particularly susceptible to biological degradation by insects and fungi. However, some paintings by Jan van Goyen with sapwood have already been identified (see cutting types A and B in Fig. 4), namely in three paintings from the National Museum Stockholm collection—'Resting at a tavern' (NM442), 'River sight with an older tower' (NM441) and 'River landscape' (NM2416) (RKD).

The boards of the paintings *Landscape with Fair Weather* (FMA 391) and *Landscape with Stormy Weather* (FMA 392) belong to the same tree (Glk 78***/t_{BP} 9.3), and thus the two patterns have been synchronized and combined into a single time series (PFMA391-PFMA392) of 118 tree rings. A similar conclusion was reached regarding the two planks of the painting *Village Scene* (FMA 390) (Glk 74***/t_{BP} 9.9). As a result, the two patterns were synchronized and combined into a single chronological series (PFMA390000) spanning 215 tree rings (Table 2).

The wood supports of all paintings have been precisely dated, i.e. the year of the last ring preserved on each plank has been identified (Table 2). Table 3 details the three highest statistical correlations obtained for each time series, which provide supporting evidence for the respective dendrochronological dating. The highest correlations are identified for the paintings *The Ferry* (FMA 374) and *View of Scheveningen* (FMA 373) (Glk [67*** − 75***]/t_B [6.6–13.1] and Glk [63*** − 67***]/t_B [7.4–10.5], respectively).

Table 3 Three best statistical matches between the final series and independent chronologies in the eight paintings attributed to Jan van Goyen from the FMA collection

Laboratory filename (sequence/combination of sequences)	Independent chronologies	OVL	Glk/GLS	t_{BP}	Publication reference
PFMA390000	2021BLT2	215	66***	7.5	Daly and Tyers [31]
	0520006 M	119	59***	4.1	Eckstein et al. [36]
	2920301A	140	67***	3.5	RKD Database [34]
PFMA391-FAM392	MEMEL	118	66***	4.4	Brazauskas [32]
	NLARTP02	118	63***	4.3	Jansma [33]
	2021BLT1	118	61**	4.2	Daly and Tyers [31]
PFMA355000	NL Baltic A	273	63 ***	5.3	Jansma [33]
	2999002A-2999002B	115	68 ***	5.2	RKD DATABASE[34]
	NLARTP02	291	61***	5.1	Jansma [33]
PFMA372000	0520006 M	178	60**	5.6	Eckstein et al. (1975)[36]
	VILQURO1	95	66***	5.0	PUKIENÉ [38]
	0520001 M	304	61***	4.5	Klein and Wazny [29]
PFMA373000	2021BLT3	319	67***	10.5	Daly and Tyers [17]
	0520003 M	319	63***	7.9	Klein and Wazny [29]
	0520004 M	265	66***	7.4	Klein and Wazny [29]
PFMA374001	2021BLT3	127	67***	7.3	Daly and Tyers (2022)[31]
	0520003 M	127	67***	6.9	Klein and Wazny [29]
	BTV0M001_B3	127	67***	6.6	Daly and Tyers [21]
PFMA374002	2021BLT3	235	75***	13.1	Daly and Tyers [21]
	0520004 M	235	73***	12.2	Klein and Wazny [29]
	0520003 M	235	75***	11.1	Klein and Wazny [29]
PFMA376000	2021BLT1	162	63***	4.5	Daly and Tyers [31]
	5205401B	152	67***	4.3	RKD database [34]
	0520004 M	174	62***	4.3	Klein and Wazny [29]

[Laboratory filename—internal identification; OVL—number of overlapping tree rings between the final series and the chronology; Glk/GLS—percentage of parallel variation, also termed *Gleichläufigkeit* [36]; t_{BP}—t-value Baillie-Pilcher [37]

The research was supported by several Baltic region chronologies, with the most relevant cross-reference provided by the updated version (2021BLT3)[31], 0520003 M and 0520004 M [29] and BTV0M001_B3 [21]. The lowest correlations were identified in the PFMA391-FAM392 series (Glk [62 $***$ −66$***$]/t_{BP} [4.2–4.0] and the painting *View of The Hague* (FMA 376) (Glk [62 $***$ −67$***$]/t_{BP} [4.3–4.5]), also with the Baltic oak chronologies, namely MEMEL [32], NLARTP02 [33], 2021BLT1[31], and 0520004 M [29]. The wood's provenance is consistent with that established in the various dendrochronological studies conducted on the van Goyen paintings, yet there are instances of Western German/Dutch woods (RKD) [34].

To determine the *terminus post quem* of each painting, tree rings must be included, as there is no sapwood in any of the planks. As the provenance of the trees used for the wood support structures is associated with the Baltic region, the criteria for the number of sapwood rings, should be adhered to: 9 and 15 are to be considered the minimum and median number of sapwood rings, respectively. Furthermore, according to Klein [29], it is more appropriate to add the median value of the sapwood rings rather than the minimum value when the boards come from trees over 200 years old. In all instances, the year in question is prior to the corresponding historical date inscribed on the painting. It is necessary to make a minor adjustment to the dating of the painting *View of Scheveningen* (FMA 373), as the *terminus post quem* for the wood support manufacture (1644) is one year later than the date inscribed on the painting itself (1643). In essence, the calculation of the *terminus post quem* is based on the addition of an estimated number of years of sapwood (in this case, 15 years). This estimate is based on inter- and intra-tree variability, namely the age of the tree, the geographical area and the fact that the sapwood/heartwood boundary is not consistent throughout the tree's cross section [35]. Accordingly, as previously proposed by Baillie [23], the application of dendrochronology can assist in corroborating the veracity of the attributions made to Jan Van Goyen with respect to the paintings studied in this project.

Fig. 5 Imaging techniques (*Village Scene*, inv. 390): **a** standard light photography and **b** and infrared reflectography

3.2 On Van Goyen's painting technique—in situ analysis of the earlier work *village scene* (dated 1623), by imaging techniques and MA-XRF

Another aim of this project is to analyse the technical and material aspects of this set of eight paintings by Van Goyen and to understand the elements of his artistic evolution. In this article we present the results of one of the earliest works by this artist which dates back to 1623 and depicts a village scene. The landscape features a mid-level horizon, a windmill near two houses on the right, and clouds in the sky.

In order to establish further details about the techniques and materials used by Van Goyen, an integrated in situ approach was developed, based on direct observation of the painting, imaging techniques and non-invasive 2D chemical elemental mapping by MA-XRF [39]. The application of X-ray fluorescence (XRF) and macro-X-ray fluorescence (MA-XRF) in the study of paintings has proven to be a fundamental tool for technical art history and heritage science, allowing for non-invasive elemental analysis of painted surfaces. These techniques provide critical insights into the materials used by artists, aiding in the identification of pigments and fillers and the detection of underlying compositions. In the case of seventeenth-century Dutch painting, such as the works of Jan van Goyen, MA-XRF mapping can reveal the distribution of key elements associated with pigments contributing to a deeper understanding of the artist's palette and painting techniques.

One of the major advantages of these methods is their ability to analyse paintings without causing damage, making them ideal for studying delicate and historically significant artworks. The use of MA-XRF, in particular, has enabled the visualization of hidden layers, *pentimenti*, and compositional changes, offering valuable information about the artist's creative process. However, these techniques also have limitations, such as their inability to provide molecular data, requiring complementary methods like Raman or FTIR spectroscopy for a complete characterization of materials. Additionally, the penetration depth of XRF is limited, meaning that some deeper layers may not be fully detected, requiring careful interpretation of the results. Despite these challenges, the integration of XRF and MA-XRF with other analytical tools continues to enhance the study and preservation of historical paintings, offering unprecedented access to the material and technical aspects of artworks.

Fig. 6 Album containing drawings by Jan van Goyen in[40] b) and d) that may have inspired the composition in a) *View of Hague* and c) *Village Scene* (RIV detail), respectively

Fig. 7 Details of brushstrokes and layers thickness in **a** *Village Scene* (dated 1623) and **b** *View of The Hague* (dated 1652)

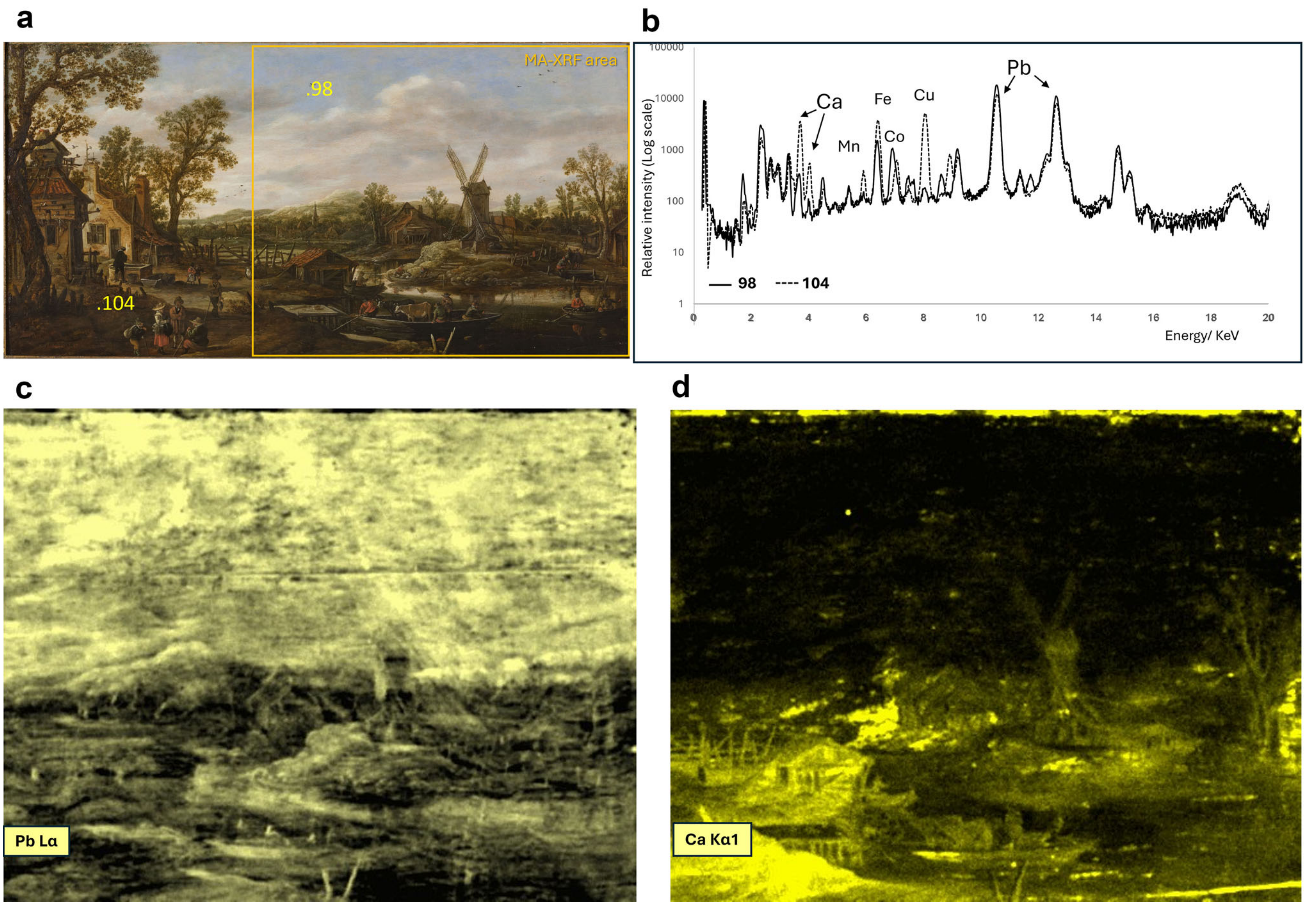

Fig. 8 Chemical elemental analysis of a) *Village Scene* (dated 1623) by combined EDXRF and 2D MA-XRF: b) EDXRF spectra of the area of the sky and a darker area of the painting; and MA-XRF revealing the mapping distribution of Pb and Ca

3.3 Underdrawing

What is particularly curious is that, through infrared reflectography analysis, we detected underdrawing only in this panel, dated 1623, created during the initial period of his artistic activity. This raises new questions, making it crucial to understand these constructive processes. For instance, why was a drawing detected only in this work? Could it be related to the materials used for the underdrawing, the nature of the preparation, or the artistic process itself, which might reduce or eliminate this creative phase of the work, as his contemporary artists?

The infrared reflectography is shown in Fig. 5, where a freehand technique for composition marking is quite evident.

In the album containing 182 sheets with drawings by Jan van Goyen and Esaias van de Velde, we can relate the underdrawing in this painting to a drawing made by Van Goyen in his sketchbook [40], which likely inspired the figures in this composition (Fig. 6).

3.4 Palette and layered structure

One of the references we have is that Van Goyen changed his construction processes, particularly at the preparation level, by significantly reducing its thickness and coloration over time. This aligns with his approach to summarizing chromatic tones. According to Petria Noble et al.[7], it is also mentioned that Van Goyen applied a preparation based on chalk and a priming made of lead white, chalk, and umber or charcoal. This serves as an important basis for comparison with the works we are currently studying.

Based on the direct observation of the paintings (Fig. 7) and taking the first and last works as a reference, it is visible the difference between the opacity of the painting layers. In his later work, *View of the Hague*, the brushstrokes are distinctly visible, revealing the wooden support underneath (Fig. 7, b), which reports to a technical simplification of the layered structure.

In the *Village Scene*, a beige layer is visible beneath even in the darker areas, suggesting the application of preparatory layers below the chromatic layers. This observation aligns with previous analyses of Van Goyen's panels, *Dilapidated Farmhouse with Peasants* (1631) and *River View* (c. 1644–1648), suggesting a consistent technique in his work [7].

Additionally, the detection of underdrawing through infrared reflectography aligns with the presence of this whitish layer underneath.

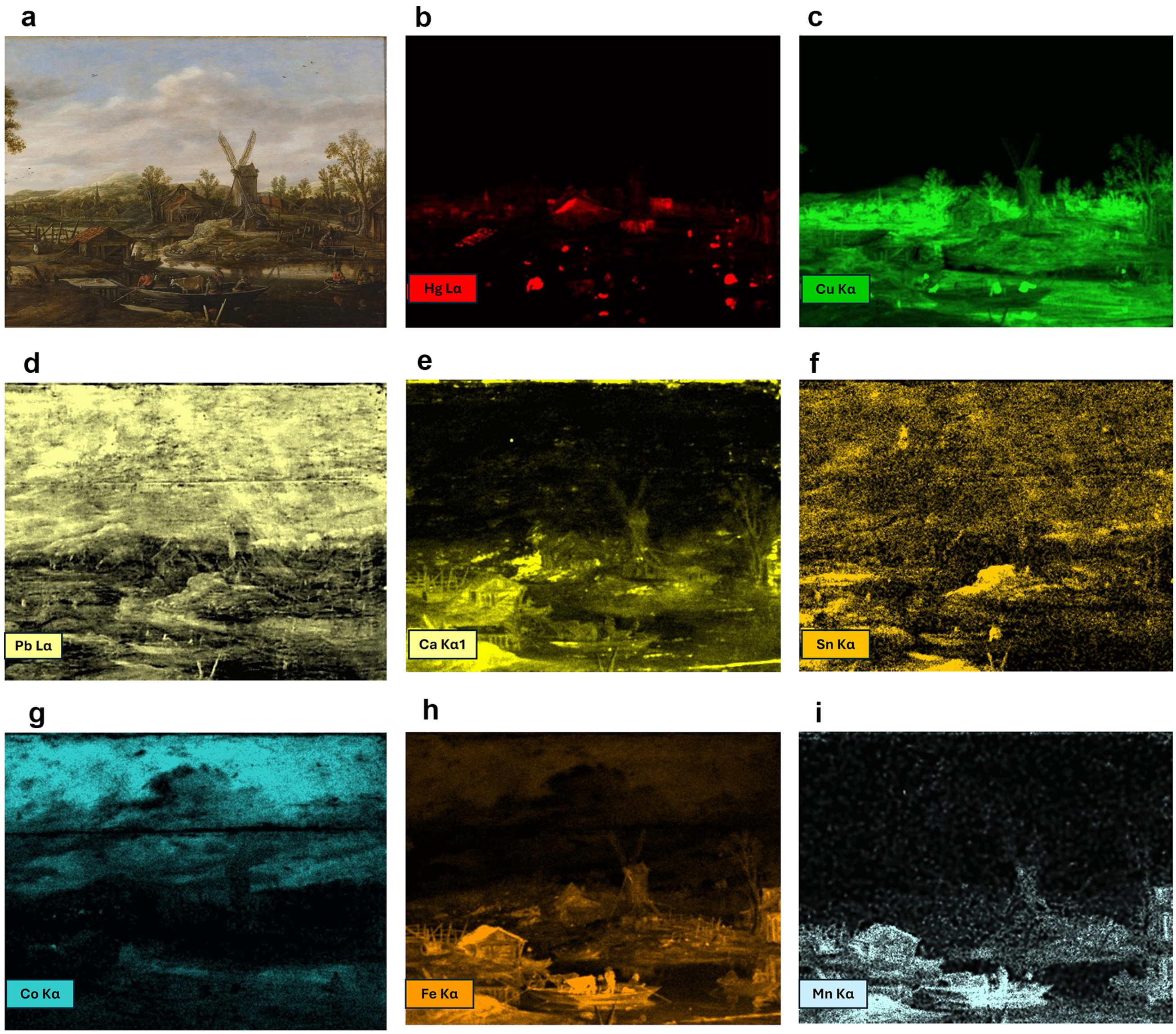

Fig. 9 2D MA-XRF analysis of *Cena de aldeia* (dated 1623): **a** detail of the area of the 2D scanning, **b** Hg Lα map; **c** Cu Kα map; **d** Sn Kα map; **e** Co Kα map; **f** Fe Kα map and **g** Mn Kα map

This layer provides the contrast necessary to reveal the underdrawing using this imaging technique (made with a material that absorbs the IV radiation, e.g. carbon black), despite being subsequently covered by the chromatic layers [41–43].

First chemical approach by EDXRF analysis allowed to detect elements such as lead (Pb) and calcium (Ca) throughout this painting (Fig. 8b). The areas where Pb is most concentrated correspond to the lighter areas of the painting while the higher concentration of Ca seems to report to the darkest tones.

Meanwhile, 2D MA-XRF (Fig. 8c and d) enabled a correlation between the elemental composition and the pigments used in the artwork, showing that Pb (most likely lead white) was applied extensively across the painting. In contrast, the element Ca (likely linked to chalk) appearing more concentrated in darker areas may indicate the use of chalk as a filler in specific pigment mixtures. Nevertheless, one has to take into consideration that it could also result from X-ray attenuation by the heavy element Pb in lead-white-rich lighter areas, which may cover the signals from underlying layers, such as a chalk-based preparatory layer. According to published data on Van Goyen's work [7], this suggests a construction process that might involve a chalk-based preparation, followed by the application of a very thin layer containing Pb and Ca.

By using 2D MA-XRF (Fig. 9) we were also able to compare the paintings materials and the extension of its application over time. In the painting from the early period, we can confirm, for instance, the use of a rich palette based on: vermillion (HgS) for the bright red´s (detection of Hg Lα in red areas), iron based pigments for earth colours (Fe Kα also appears combined with Mn Kα in darker areas, suggesting that an Umber could also be used), the use of blue smalt mainly for the blue sky (Co Kα and As Kβ1 associated in bluish areas) [44, 45], lead tin yellow (Pb Lα and Sn Kα associated in more intense yellow motifs) and an extensively use of a copper green pigment (Cu Kα detected in vegetation areas).

On the other hand, ongoing research is now reporting that in the last work by Van Goyen there is a greater predominance of earth tones based on iron and manganese as well as smalt blue, as he seems to use it also in mixture with yellow earths to obtain greenish tones. The use of lead tin yellow also becomes more sporadic, employed selectively, for instance, in green tones. Vermillion wasn´t detected in this last work where the reddish hues seem to report to the use of iron-based pigments.

These changes are consistent with Jan van Goyen´s technical evolution, where he progressively moved away from the techniques of his master, developing a distinctive and more naturalistic approach to painting. From 1623 onwards, he began to cover the entire wooden panel with paint, marking a shift in his method. Recognized for his innovative techniques, Van Goyen employed thin oak panels as supports, which he prepared with multiple layers of animal glue. Using a blade, he spread a thin layer of tinted white lead across the surface, creating a translucent base that sealed the wood pores while allowing the grain to remain visible through the paint layers [7].

Despite his prolific output, Van Goyen's paintings rarely commanded high market prices. To maintain cost efficiency, he relied on inexpensive pigments, applying them sparingly and in thin layers [1–5, 7, 9, 25, 30, 39, 40]. Over time, his technique became increasingly refined, characterized by expansive skies, low horizons, and a monochromatic palette dominated by earth tones such as ochres and umbers. This evolution resulted in atmospheric compositions that captured the passage of time in its various dimensions, reinforcing his legacy as a master of tonal landscape painting.

4 Conclusion

The targeted implementation of dendrochronology in the examination of eight signed paintings by Jan van Goyen contributes with critical data confirming their dating and supporting the historical integrity of the works. One of the major advantages of undertaking dendrochronological analysis of a group of paintings produced by an artist is that it enables us to refine the chronological range of his activity, thereby extending our interdisciplinary knowledge base through the insights gained from future research. In the case of Jan van Goyen, the dating of Baltic oak panels used across several decades provides a comparative framework for assessing workshop practices, material sourcing strategies, and their alignment with the broader historical and economic context of seventeenth-century Dutch painting.

This study's findings corroborate earlier research indicating that oak sourced from the Baltic region was a primary support material employed in Jan van Goyen's workshop, as previously evidenced in other documented works.

Van Goyen's early production reflects the technical and stylistic influence of his master, Esaias van de Velde, notably in the use of a varied chromatic palette, detailed rendering, and compositionally active settings with multiple figures. The analytical data from this study confirm that, in his formative period, Van Goyen adopted not only the aesthetic but also the material strategies characteristic of Van de Velde's practice. Over time, however, the technical evidence supports a process of gradual synthesis in Van Goyen's method, marked by a systematic reduction in complex spatial arrangements, also reducing the palette complexity and employing a progressive thinning of paint layers—an evolution that reflects both conceptual refinement and workshop efficiency. These findings offer a nuanced perspective on the material dimension of Van Goyen's artistic development, contributing to a deeper understanding of authorship, chronology, and technical intentionality in Dutch seventeenth-century painting.

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Declaratons

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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