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17th-century copies of a 15th-century early Netherlandish painting uncovered through technical and art-historical research

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ABSTRACT

Studies of Early Netherlandish panel paintings have long implemented techniques such as dendrochronology, pigment analysis and infrared reflectography. However, knowledge about the production of workshop replicas from fifteenth century paintings, and later copies, remains limited. As a result, the attribution of such paintings poses a challenge to art historians. Here, we present a multidisciplinary investigation into two copies of an Early Netherlandish panel painting attributed to the fifteenth-century Flemish painter Pieter Cristus (or Petrus Christus), active in Bruges (Belgium) between c. 1445 and 1460 CE. Earlier research dated these works to the late 15th century based on dendrochronology and pigment analysis, although alternative hypotheses suggested a 17th-century origin or even modern forgery. To resolve this debate, we applied dendrochronology, radiocarbon dating, MA-XRF, infrared reflectography, Raman spectroscopy, and stylistic analysis. The new dendrochronological results, supported by radiocarbon dating, proved key in refuting the hypothesis of the 15th-century date, revealing that the trees were cut around the mid-17th century. Furthermore, while the pigments identified were largely consistent with 15th-century painting practices, the stylistic characteristics and the presence of the inscription “I.P.C” (*invenit Petrus Cristi*) in one of the paintings supports a production in the mid-17th century or shortly afterwards. These findings challenge the reliability of earlier dendrochronological assessments and illustrate that pigment analysis alone cannot securely date paintings, as historical materials and techniques persisted over time. Overall, our research highlights the practice of copying Early Netherlandish paintings in the 17th-century and the importance of integrated technical and art-historical approaches for accurate attribution.

1. Introduction

The production of copies from Netherlandish paintings is a phenomenon known to scholars in the field of Early Netherlandish art. For example, it is well established that in the second half of the 15th century, some workshops produced copies for the apprentices to acquire painting skills or to meet the market’s demands [1–3]. In later centuries, copies of 15th-century panel paintings were made with the same purposes, and thus, without any intention to deceive [2]. Even in the early 20th century, skilled restorers have produced imitations of Early Netherlandish panel paintings [4,5]. However, the existence of such workshop replicas, as well as both contemporary and later copies, complicates the discourse surrounding the attribution of artworks up to the point where, in contentious authenticity cases, paintings have sometimes been assumed to be 20th-century forgeries (e.g. [6]).

This study focuses on a composition attributed to the Early Netherlandish painter Pieter Cristus (c. 1420 – 1475/1476), sometimes referred to as Petrus Christus, of which three versions are known: the *Virgin and Child in an Archway*. The version held by the Museum of Fine Arts in Budapest under inventory number 4324 (Fig. 1a), is dated to around 1450 based on a stylistic analysis [7], and is regarded as the original because of a composi-

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Fig. 1. The three versions of *Virgin and Child in an Archway*. **a)** Pieter Cristus, *Virgin and Child in an Archway*, c. 1450–55, 55.5 × 31.5 cm. Szépművészeti Múzeum/ Museum of Fine Arts, Budapest. **b)** After Pieter Cristus (RCE painting), *Virgin and Child in an Archway*, 57.5 × 32 cm. Amersfoort, Collection Cultural Heritage Agency Netherlands, inv. NK1841. **c)** After Pieter Cristus (Goudstikker painting), *Virgin and Child in an Archway*, 60.7 × 44.6 cm. Collection Jacques Goudstikker, inv. BB2719 (former inv. 1297).

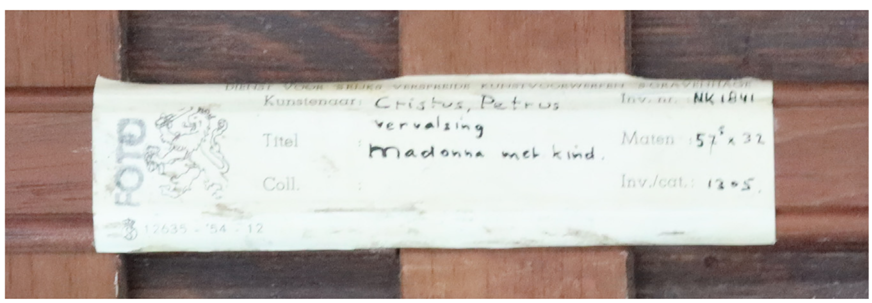

Fig. 2. Label on the reverse of the RCE painting. Probably dating from 1954, the label presents it as a falsification (*vervalsing*).

tion change observed in the underdrawing. From the two versions of this painting, one is nearly identical to the original. It is part of the collection of the Cultural Heritage Agency of the Netherlands (RCE) under inventory number NK1841 (Fig. 1b), and housed at CollectieCentrum Nederland (CCNL), the government depot for Dutch state-owned artworks. The other version (Fig. 1c), was part of the famed collection of Jacques Goudstikker in 1940 and has recently been restituted to the heirs. The chronology and true nature of these two versions—hereafter referred to as the RCE and the Goudstikker paintings—remains a subject of ongoing scholarly debate.

The art historian Max Friedländer referred to them as weaker copies, not painted by Pieter Cristus himself, suggesting the work of a workshop assistant or a later follower [8]. In 1952, the RCE panel was even considered a 20th-century forgery, and it was exhibited with this designation in shows held in Amsterdam and Basel. To this day, the panel bears a label on its reverse reading: "Petrus Cristus. Forgery. Virgin and Child" (Fig. 2). However, the provenance history of these two paintings can be traced back to the late nineteenth century (see Supplementary Information), discarding them as 20th century forgeries. In 1967, the chemist Hermann Kühn analysed paint samples of the RCE painting alongside the Budapest version and identified only historical pigments, including lead-tin yellow. On this basis, he concluded that the RCE panel must predate 1750. Kühn's report is preserved in the curatorial files of the painting at the Museum of Fine Arts in Budapest. The museum's curator of Early Netherlandish Painting, Suzanne Urbach, hypothesised in 1971 that both the Goudstikker and RCE paintings might be 17th-century copies after the Budapest original [9], whereas the art historian Maryan Ainsworth suggested that they could be copies dating from the 15th century [7]. None of these two hypotheses was supported by material evidence or stylistic analysis though. The physicist Dolf Van Asperen-de Boer, who was a pioneer in technical art history, went a step further, proposing that both paintings may in fact be authentic workshop replicas [10,11]. His hypothesis found additional support for the RCE painting in the dendrochronological research conducted by Peter Klein (University of Hamburg) in 1994, as Klein reported a likely felling date for the oak between 1432 and 1438 (https://rkd.nl/technical/5005409; [10], p. 153; [11], p. 43). This sparked considerable art historical interest, given that Pieter Cristus was documented as having produced multiple versions of a single composition in 1454 [7,10,12]. In 1995, the art historian Didier Martens, possibly unaware (or maybe sceptical) of the dendrochronological results, contributed to the scholarly discourse with a stylistic argument identifying subtle features in the two versions that, in his view, pointed to a 17th-century origin—thus aligning with Urbach's earlier position [13]. Therefore, the dating and production context of these versions remained unresolved.

2. Research aim

This study aimed to resolve the historical debate around these paintings by establishing the chronology and production context of the two disputed versions through minimally invasive analytical methods and art historical analysis. Therefore, rather than undertaking a comprehensive technical reconstruction of their painting technique, the technical examination included dendrochronology on both panels, plus radiocarbon dating on the Goudstikker one, and pigment analysis (using MA-XRF scans and IRR on the Goudstikker painting, and MA-XRF plus Raman spectroscopy on the RCE panel), to reach an empirically-based conclusion concerning the dating and the potential context of the production of the paintings.

3. Material and methods

3.1. Dendrochronological research

The inspection of the Goudstikker panel for dendrochronology was carried out at the dendrochronology laboratory of the Cultural Heritage agency of the Netherlands, whereas the RCE panel was inspected and researched at the CCNL, both in Amersfoort (the Netherlands).

In both cases, tree rings were photographed in a sequence of overlapping images with a macro lens, including a ruler to obtain absolute measurements. Ring widths were measured on the digital photographs with CooRecorder [14] and crossdating was carried out with PAST4 v. 4.3.1025 [15]. The t-values reported for the crossdating statistics were calculated using the Baillie-Pilcher algorithm [16] (TBP) coupled with the percentage of parallel variation [17] (%PV) and its significance level (### represents $p < 0.001$). To consider a statistical match good enough to be indicative of a date, it should return a TBP higher than 6 for overlaps longer than 100 years, and a significant (at least $p < 0.05$) %PV higher than 65%. To determine that two pieces of wood have been obtained from one single tree, there is not a strict parametric threshold [18]. While TBP values well above 10 for overlaps higher than 100 years are often indicative of a same-tree match, lower values can also occur (and similarly, higher values may arise from wood of trees growing close to each other, under very growth-limiting environmental conditions). Therefore, an outstanding visual match, possibly coupled with the direct observation of particular features in the wood, is crucial to decide that two pieces of wood originate from the same tree.

3.2. Radiocarbon (^{14}C) dating

In addition to dendrochronology, ^{14}C dating was carried out on the Goudstikker copy at the premises of Royal Institute of Cultural Heritage (RICH, Brussels). For practical reasons, the sample was taken from the outer edge of the wide board, where the oldest growth rings (closer to the pith) are located (Fig. 3a). The sample was pretreated following the protocol by [19], and was subsequently analysed by an AMS (Accelerator Mass Spectrometry) to determine the age of the sample [20]. IntCal20 was used to establish a calibrated date with a 95,4% confidence interval [21].

3.3. Macro-X-ray fluorescence (MA-XRF)

The MA-XRF spectroscopic analysis of the Goudstikker painting was carried out with a M6 Jetstream at the International Platform for Art Research & Conservation (IPARC) in Kampenhout, Belgium. This is a non-invasive technique that allows identifying and mapping the elemental composition of the paint in an artwork. The equipment consists of a Rh-target microfocus X-ray tube, operating at a voltage of 50 kV and a filament current of 600 μA. The measurement head is mounted on an XY motor-driven platform with a maximum range of motion of 80 × 60 cm, enabling measurement in one single scan. The spot size of the X-ray was 550 µm, and step size (pixel size) of 500 µm. Per spot, 35 ms was measured (dwell-time). The XRF spectra were collected, deconvoluted and examined with the Bruker M6 Jetstream software and with specialized software Datamuncher in conjunction with PyMca. The scans were done by David Lainé (IPARC) and interpreted in collaboration with Jan Verheyen (FWO/IPARC).

The MA-XRF scans of the RCE painting were executed at the CCNL with a CRONO 2D-micro-XRF scanner by Bruker. A 500 µm collimator was used with a spot size and step size of 500 µm. The instrument ran with an operating voltage of 40 kV and used a filament current of 200 µA. Scanning was executed in 11 separate scans, with a dwell time of 30 ms per spectrum. These separate scans were subsequently stitched into scans covering the entire image. One additional scan was performed on the face of the Virgin and Child using a 500 µm collimator with a 250 µm step size, 40 kV tube voltage, 200 µm current and 30 ms dwell time.

3.4. Infrared reflectography (IRR)

IRR was performed on the Goudstikker painting at IPARC with a Xenics Xeva InGaAs camera, sensitive up to 1700 nm, with a 100 mm Nikkor lens and a 1400 nm bandpass filter, mounted on a custom x-y-gantry. This non-invasive technique makes visible carbon-based underdrawings, overpainting, restorations and other modifications of the painting that are not visible to the naked eye. The individual images were merged with PTGui Pro.

3.5. Raman spectroscopy

This non-invasive technique reveals the chemical composition of pigments and other substances in paintings, being very valuable to technical art history. At Ghent University (Raman Spectroscopy Research Group), direct Raman analysis was performed on the Goudstikker painting using a set-up that is based on a fibre-optics Raman spectrometer (EZ-I dual Raman system, Enwave Optronics, Irvine (Ca, USA) and three orthogonally mounted motorized stages (PI Benelux, The Netherlands). The spectra were recorded using the 785 nm wavelength excitation laser and the detector was a Peltier-cooled (−50 °C) charge-coupled device (CCD) detector. The focussed laser beam had a diameter of ca. 150 µm and experiments were performed with a laser power of ca. 10 mW at the sample. A detailed description of the set-up and measuring routines is given in [22]. Spectrometer calibration was based on fitting a third order polynomial to 38 Raman band positions of 5 calibration products (Sulphur, Cyclohexane, Epsilon-Caprlactone, Polystyrene, Silicon) [23]. Data processing was performed using Matlab, including in-house programmed RamSpec Viewer and RamCal routines.

On the RCE painting, Raman spectroscopy was performed at the CCNL using the Bravo Spectrometer (Bruker). Spectra were recorded in two separate spectral ranges of 300–2200 and 1200–3200 cm-1 with a DUO Laser system (785 nm and 853 nm). The energy on the surface was approximately 45 mW with measurements performed at a distance of c. 0.5 mm and a 1 mm spot size.

4. Results

4.1. The Goudstikker painting

4.1.1. Dendrochronological dating

The Goudstikker panel is made up of two oak boards (*Quercus* sp.) placed vertically. The upper edge of the panel painting has been sawn off, leaving only the base of the arch visible. This alteration was already documented in 1864 [24], and must therefore predate that year. The transverse edge at the top of the panel seemed to be slightly polished (Fig. 3a), but to enable the correct visualisation of the tree-ring boundaries, the surface was partially

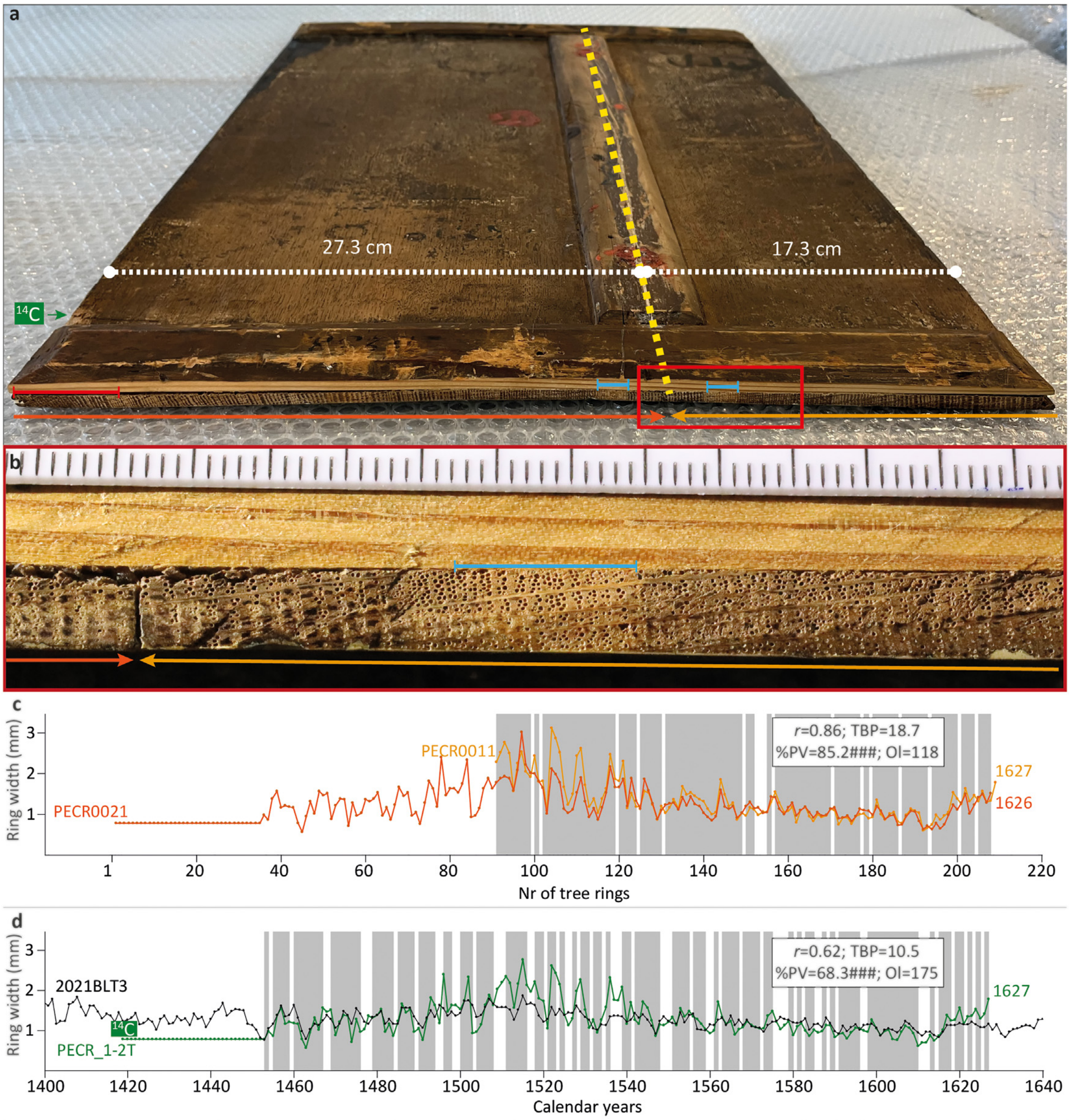

Fig. 3. Panel description and dendrochronological examination of the Goudstikker painting. **a)** Top side of the support, the arrows indicate the tree-growth direction in the boards, the dash line runs along the joint; the first rings on the left of the wide board have not been measured; sapwood inclusions are marked with green brackets, and the place where the sample for ^{14}C was collected is also indicated. **b)** Close up of the right board towards the joint, where the preparation with scalpel blades and the sapwood inclusion can be clearly observed. **c)** Visual and statistical match between the two tree-ring series obtained from the boards of this panel. **d)** Visual and statistical match between the mean tree-ring series from the boards (green) and the reference chronology 2021BLT3 (black); r: Pearson's correlation coefficient; TBP: Student's t calculated after applying the Baillie-Pilcher algorithm[16]; %PV: percentage of parallel variation[17], and its associated significance level (### represents $p < 0.001$). The shaded area is a visual representation of the %PV. OI: overlap. See Methods for a more detailed description of statistical tests.

cleaned with scalpel blades (Fig. 3b). Then it was possible to determine that the boards were joined along the edge corresponding to the outer part of the tree. Sapwood inclusions (i.e. groups of consecutive tree rings that lack tannins and retain the light colour of sapwood) were observed on both boards (Figs. 3a,b), suggesting *a priori* that they may originate from the same tree. True sapwood was absent in both boards.

Tree-ring series of 119 and 208 years were obtained from the narrower (PECR0011) and wider (PECR0021) boards, respectively. On the outer edge of the wide board, c. 34 additional rings were visible but not measured due to poor clarity. Comparison of both series shows a strong visual and statistical match (Fig. 3c), confirming that the boards derive from the same tree. The series were therefore combined into a mean curve (PECR_1–2T) spanning 175 measured rings. Cross-dating with reference chronologies dated the outermost ring to 1627, matching oaks from southeastern Lithuania (2021BLT3) [25] (Fig. 3d). As no sapwood is preserved, only a terminus post quem for felling can be estimated. Based on Sohar et al. [26], eastern Baltic oaks typically have 6–19 sapwood rings, indicating the tree was likely felled after 1633. Additional time must be allowed for transport and seasoning; evidence from signed panel paintings suggests 6–10 years for the 95% confidence interval in the 17th century [27], resulting in an *earliest possible production* date between 1639 and 1643. The Lithuanian origin of the timber provides a terminus ante quem in the 1650s, when Baltic oak exports to western markets ceased [25].

4.1.2. Radiocarbon dating results

According to the dendrochronological analysis, the part where the sample was collected corresponds to the growth ring from 1418 and several subsequent years (sampling spot indicated in Fig. 3a). The ^{14}C measurement indeed yielded a date of 517±22 BP, which translates into a calibrated range between 1395 and 1440 at a 95.4% confidence level (see Supplementary Information). By adding the 208 annual rings and a maximum of 19 sapwood rings to this result, a felling date between 1621 and 1667 is obtained. This independent dating method provides additional support for the dendrochronological results.

4.1.3. Identified pigments

The MA-XRF scans provided valuable insights into the pigments employed in the painting (Fig. 4; for the most complete results the reader is referred to the online database). While a few retouches and restorations with modern pigments were identified, the original pigments detected correspond closely with the painters' palette typical of the 15th century [28,29]. For instance, the copper scan (Fig. 4, Cu-K) clearly indicates the presence of the blue pigment azurite, a basic copper carbonate ($2CuCO_3 \cdot Cu(OH)_2$). Azurite, as a blue pigment, had largely fallen out of use after 1800 ([30], p. 25). The presence of azurite in the green areas, mixed with lead-tin yellow, highlights its application in the landscape and in the Virgin's mantle. Some azurite appears degraded, turning black in dark areas such as the floor tiles and behind Eve's figure.

Iron-based pigments, likely ochre, were used in the seating furniture and in the reddish sections of the mantle (Fig. 4, Fe-K). Potassium, detected in the red areas, suggests the presence of organic red lake pigments, likely used alongside vermilion and ochre [31]. Organic substances cannot be detected using MA-XRF; however, red lake is bound with alum, which can be visualised through the presence of potassium. Vermilion, a red mercury sulphide pigment (HgS) ([30], p. 159], was identified in the Virgin's mantle, the small figure in the background, and other red areas of the painting (Fig. 4, Hg-L). Direct Raman analysis confirmed the presence of vermilion on the red robe of the Virgin.

Iron and manganese combinations point to the use of umber, a pigment composed of iron and manganese oxides ([32], p. 383–384). Umber was applied in the shadows, including those in the flesh tones of Mary and Christ, and in the tree trunks and columns (Fig. 4, Mn-K). Interestingly, the left column contains clearly defined shadow areas painted with umber, while this pigment is absent from the right-hand column.

Lead-tin yellow (Pb_2SnO_4), identified in gilded columns, foliage, landscape, and the golden brocade carpet (Fig. 4, Pb-L, Sn-L), imparts a golden hue and is key for dating, as its use declined after 1700 and ceased by 1750 ([30], p. 86). It also appears in the pilgrim's staff and garlands, thus indicating execution before 1750. Raman analysis confirmed the presence of lead-tin yellow type I in the Adam sculpture, tapestry, and right column.

Where lead occurs without tin, the pigment is lead white ($2PbCO_3{\cdot}Pb(OH)_2$), widely used from the 15th to 17th centuries ([30], p. 67). It forms a preparatory *imprimatura* layer applied over the underlying chalk layer in preparation for the application of paint. It was a characteristic feature of 15th-century painting practice [28,29]. Lead white also occurs frequently within the paint layers themselves, mixed with azurite in the sky and with ochre, umber, and vermilion in flesh tones, following a typical 15th-century formula ([30], p. 69; [29]).

MA-XRF cannot detect pigments such as bone black or ultramarine. Traces of modern materials, such as barium sulphate ($BaSO_4$) (Fig. 4, Ba-L), and zinc (Fig. 4, Zn-K) indicate later restorations, likely from the 19th century. Zinc occurs in zinc white (ZnO) and in lithopone (containing barium sulphate and zinc sulphide). Titanium white (TiO_2) (Fig. 4, Ti-K), introduced after 1920, was also detected in the restoration areas. The spectra of barium and titanium, with their overlapping peaks (Ba-Lα 4,47 keV; Ti-Kα 4,51 keV), are not easily distinguished from one another. The elemental identification shown in Fig. 4 is based on the deconvolution of the XRF spectra performed using the Bruker M6 Jetstream software. Although the precise identification of the titanium-, zinc-, and barium-based pigments remains open to debate, it can be established that these are localised retouchings dating from the 19th or 20th century.

4.1.4. Infrared reflectography

IRR shows no carbon-based underdrawing sketches (Fig. 5, left). This could be due to them being absent, or to the presence of thick paint layers concealing them. Carbon-based under-drawings were standard practice in 15th-century panel painting [29]. For instance, in the Budapest painting, underdrawings can be observed in the archway and in Madonna's mantle (Fig. 5, right). Similarly, in other comparable works, one would expect to see an underdrawing outlining the drapery folds in the mantle([7]; pp. 44–45]. The lack of a carbon-based underdrawing on the IRR image gives it a ghostlike appearance, characteristic for later copies of 15th-century originals [4].

A distinct feature in the Goudstikker painting is a coat of arms on the left and a monogram on the right. The coat of arms depicted in the IRR image, features three black hammers (sable) on a silver (argent) field (Fig. 6a). This heraldic emblem corresponds to the De Mametz family, as documented in the official register of French coats of arms published by D'Hozier in 1696 (https://gallica.bnf.fr/ark:/12148/bpt6k110595z/f291.item). The coat of arms is adorned with a bordure company in sable and argent (black and white), surmounted by a black hat or *galero*, with decorative loops of cord and three tassels on either side. According to ecclesiastical heraldic conventions, the black hat, the number of tassels, and the pilgrim's staff behind the shield signify that the bearer is a canon who holds the office of prior. However, no documented member of the De Mametz family is known to hold this ecclesiastical rank. Therefore, the identity of the commissioner remains for now unconfirmed.

IRR also allowed for a clearer visualisation of the inscription on the right side of the painting, which reads "I.P.C." This could plausibly be interpreted as *invenit Petrus Cristi*, a suggestion proposed by Van Asperen de Boer [11] (Fig. 6b,c). The use of the terms invenit or inventor emerged around the mid-16th century within the context of art-theoretical debates in Antwerp as a convention to distinguish between the original creator of a design/composition, and the artist who executed or reproduced it [26]. It was in use until the second half of the 17th century [33,34]. Therefore, this inscription provides an ante quem production period for the Goudstikker painting and confirms that it was intended as a legitimate copy.

4.2. The RCE painting

4.2.1. Dendrochronological dating

The RCE panel (57.5 × 32 cm) closely matches the dimensions of the Budapest original (55.5 × 31.5 cm) and is made of a single oak board placed vertically. It has an average thickness of 3.5 mm and represents a radial section from the stem. Another oak panel is glued to the back, which is reinforced by a cradle (Fig. 7a). The pith is absent in the wood, but five sapwood rings are present. The transverse section of the wood was accessible for dendrochronological research at the bottom of the panel. Since dendrochronological research had already been carried out by Klein in the 1990s, the transverse edge at the bottom of the board was already cleaned by him with blades, and no additional intervention was required.

A series of 199 tree rings was obtained from the original board. Cross-dating with central and northern European reference chronologies dated the outermost ring to 1632 with Polish chronologies (2021BLT2 [25]). The presence of five sapwood rings

Fig. 4. MA-XRF scans of the Goudstikker painting (for selected elements).

Fig. 5. Infrared reflectogram (upto 1700 nm) of the Goudstikker painting (left) and the Budapest original (right).

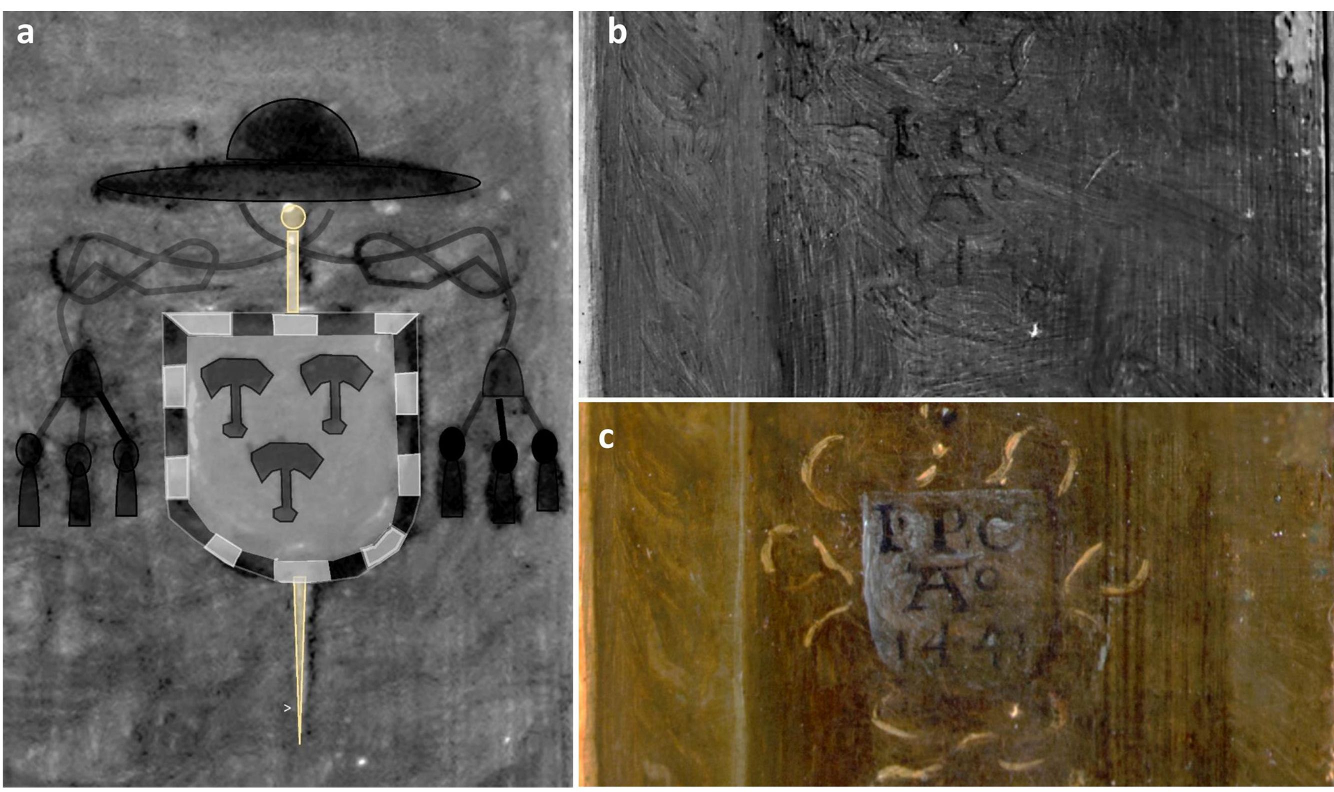

Fig. 6. Results IRR and high-resolution photographs. **a)** Coat of arms on the Goudstikker painting, visible through graphically enhanced infrared image. **b, c)** monogram and date on the Goudstikker painting: (b) Infrared reflectography (1400–1700 nm) and (c) digital photo with enhanced contrast.

enables the estimation of the felling date. Based on Wazny's observations (reported by [35]) that Polish oaks typically have 9–24 sapwood rings (90% confidence interval), it can be estimated that the tree was cut between 1636 and 1651 (Fig. 7b). Allowing for transport and seasoning (1–7 years for Polish wood according to [27]), the panel was most likely manufactured between 1637 and 1658. As with the Goudstikker panel, the Baltic origin of the wood sets a *terminus ante quem* in the 1650s.

4.2.2. Identified pigments in the RCE painting

The MA-XRF analysis of this panel largely matches the Goudstikker painting (Fig. 8), with only minor retouching in modern

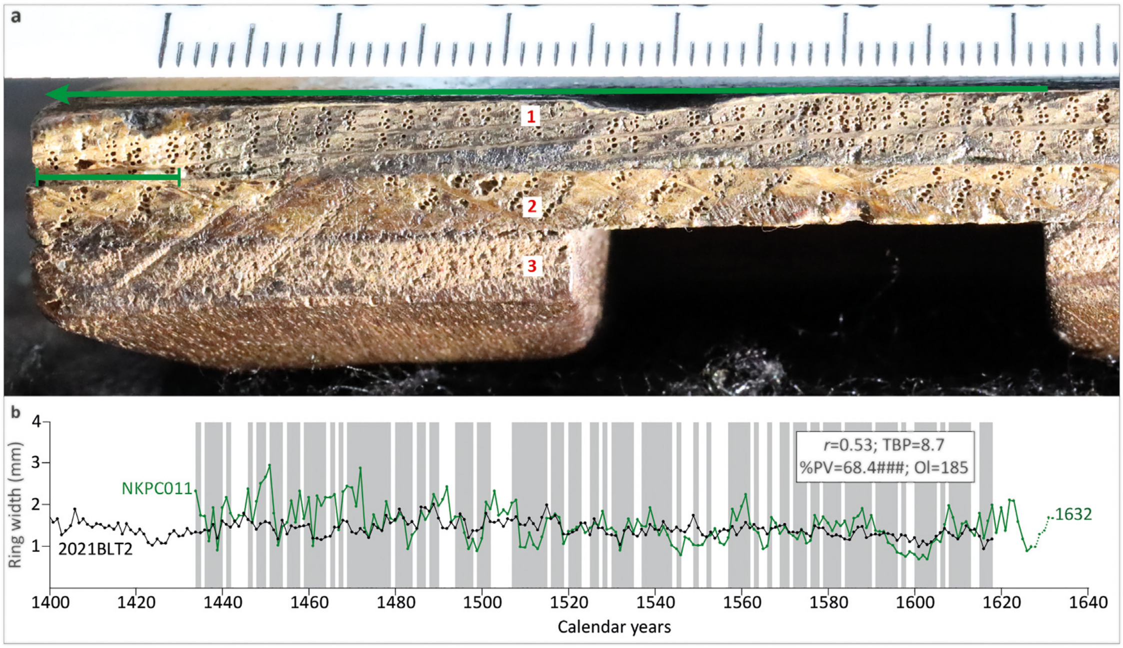

Fig. 7. Description of the RCE panel and dendrochronological results. **a)** Transverse section of the underside of the support, with (1) the original oak board, (2) the additional one, and (3) the cradle. Five sapwood rings are indicated on the left. **b)** Visual and statistical match between the tree-ring series obtained from the board (green) and the reference chronology 2021BLT2 (black). The shaded area shows the percentage of parallel variation (%PV). Statistical tests described in Fig. 3 and in Methods.

pigments. Copper indicates the presence of the blue pigment azurite in the blue-green areas of the landscape, sky, and robe (Fig. 8, Cu-K) In the blue areas of the landscape and sky, the pigments ultramarine, lead white, and chalk (likely from the ground layer) were identified by Raman analysis. Ultramarine was also confirmed in the Virgin's tunic. The pigment azurite, however, is difficult to distinguish by non-invasive Raman analysis, and its presence could not be confirmed. Vermilion (Fig. 8, Hg-L) appears in the mantle, column, carpet border, and in the lips (far more intense than in the Goudstikker version). Ochre (Fig. 8, Fe-K) occurs in the bench, mantle, columns, Mary's hair, and uniquely in the left tree (this tree was depicted without ochre in the Goudstikker painting). Umber (Fig. 8, Mn-K) is present in shadows, tree trunks, and architecture. Lead-tin yellow (Pb_2SnO_4; Sn-L), confirmed as type I by Raman, appears in columns, landscape, carpet, mantle lining, hair, and diadem.

In terms of lead white, several parallels with the Goudstikker painting can be observed. Lead white forms part of the flesh tones and the depiction of the sky (Fig. 8, Pb-L). The lead scan reveals clear vertical striations from the preparatory layer, which were not applied with consistent precision, similar to the other painting in our study.

The restoration histories of the two panels also differ. In the RCE panel, the presence of zinc (zinc white or lithopone), barium sulphate and/or titanium white was detected in several isolated retouched areas: in the sky, a large area of overpainting at the lower left section of the mantle, and the floor tiles beneath (Fig. 8, Zn-K, Ti-K/Ba-L). The deconvolution software used by RCE did not allow to make a distinction between the occurrence of titanium or barium but in both cases these Ti/Ba occurrences indicate a modern retouching. A small restoration was also identified on the right-hand side of the bench's backrest. In the retouched areas within the red and brown zones, ochre was used, but no vermilion was detected. Evidence of the loss of original lead white (and vermilion) is apparent in the restored sections. The presence of titanium white suggests that the retouching on this panel occurred after 1920.

4.2.3. Stylistic analysis on both paintings

Both paintings have undergone restorations, including some in the 20th century, though these are highly localized. Despite their fidelity to the original, the copies exhibit subtle differences in pigment application and stylistic variations. For example, the castle in the background on the right is depicted identically in both paintings, with matching rooftops, chimneys, and battlements. However, the surrounding landscape reveals differences: the RCE panel features monochrome clusters of stippled trees, while the Goudstikker panel shows greater colour variation and a more distinct contrast of light and shadow. One landscape appears hazy, while the other is more sharply defined (Fig. 9). A similar contrast is visible in the depiction of the statue of Adam. The RCE panel shows a gradual transition between shaded and illuminated areas of the brass sculpture, whereas the Goudstikker copy has a sharper contrast, with highlights applied as small dots instead of linear strokes. These differences in handling light and shadow are also apparent in the Madonna's face. A closer look at the folds of Mary's garment reveals that the artist of the RCE copy had less understanding of drapery structure compared to the Goudstikker copyist, who demonstrated a clearer grasp of the folds' form. These stylistic variations strongly suggest that the paintings were created by different artists. However, their faithful reproduction of minute details indicates that the copyists likely had direct access to the original, as previously proposed by Urbach [9].

5. Discussion

The combined technical and art historical evidence identifies both paintings as intentional copies produced around the mid-17th century. Their provenance history discards them as 20th century forgeries, as both can be traced back to the late 19th century, and the presence of lead-tin yellow indicates an execution predating the disappearance of this pigment from artists' palettes after 1750 CE [30]. More importantly, dendrochronology pins the production of both panels around the mid-17th century, with the outermost

Fig. 8. MA-XRF scans of the RCE painting (for selected elements).

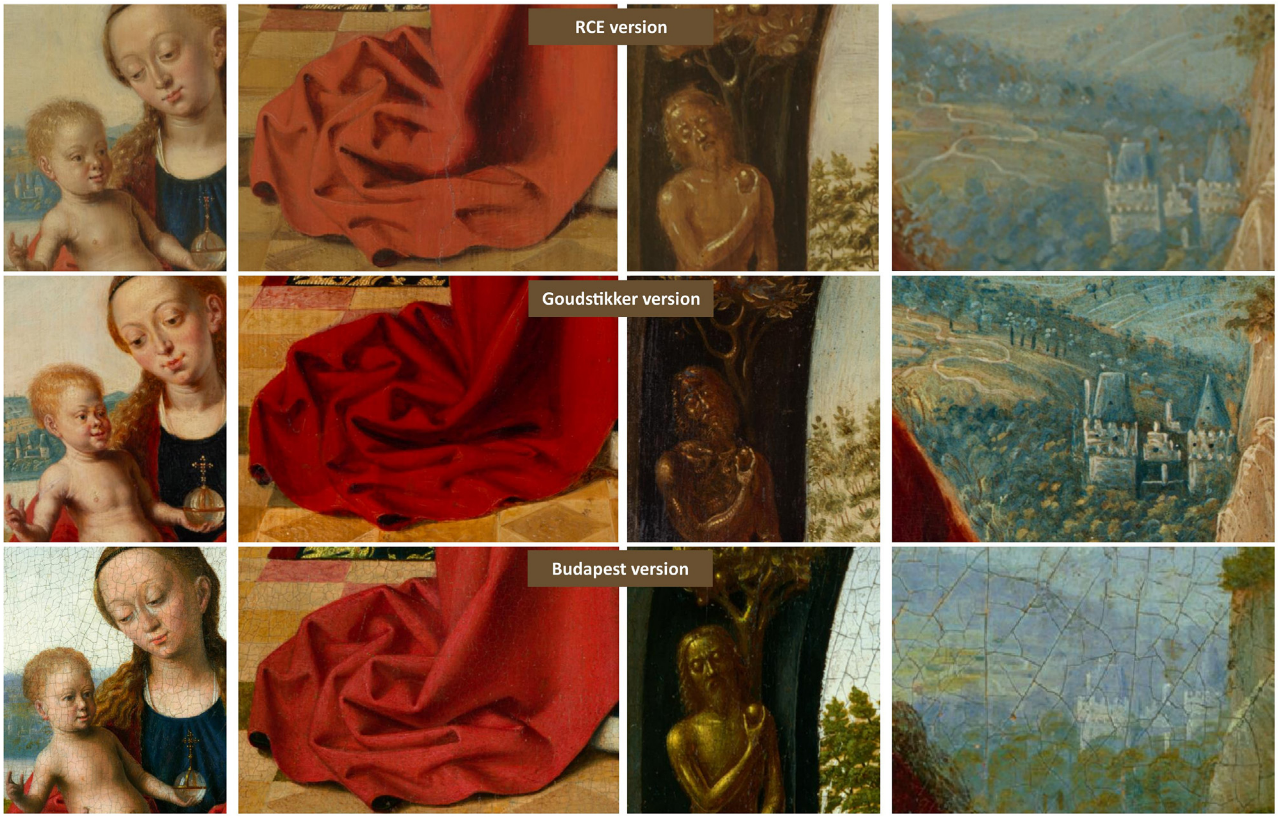

Fig. 9. Visual comparison of specific details on the three versions.

rings in the boards dating to 1627 for the Goudstikker support, and 1632 (including 5 sapwood rings) for the RCE one. The later date refutes the one reported by Klein in the 1990s. Considering sapwood estimates based on the provenance of the wood and seasoning time, the production of the panels can be estimated to have taken place between the late-1630s and the 1650s.

Dendrochronology has therefore played a crucial role in discarding a 15th century production of the copies. However, the results raise questions about the reliability of pioneer dendrochronological analyses carried out with hand-held lenses. While dendrochronology is a science founded on principles anchored in well-understood natural processes [36–38], early dating studies lacked the network of reference tree-ring chronologies currently available, as well as rigorous criteria that are becoming standard practice nowadays to accept a date. Such criteria include having high statistical scores as explained in Section 3.1. Measuring ring widths by direct observation with a hand-held lens is also a method prone to deliver faulty tree-ring series, as errors could occur in several steps of the process (from the interpretation of tree rings, the annotation, up until the manual insertion of the ring values in the computer [39]). While it is not possible to know how Klein came up with the date of the RCE panel back in 1994, when comparing the tree-ring series he obtained with the one obtained in this study, it becomes evident that the former contains multiple errors (see detailed comparison in Supplementary Information). The present method, based on digital photographs, allows repeated verification, especially where rings are very narrow. Good dendrochronological practice also requires publishing graphs and statistical results to substantiate the dating. Such graphs and statistical data are lacking in the 1990s study, making its 15th-century attribution difficult to explain. As this is not an isolated case of errors in tree-ring measurements from the 1990s ([39]) or of misdated panels ([40]), it is advisable to revisit early dendrochronological dates of panel paintings using modern techniques, as the results can be crucial for accurate attribution [41].

Furthermore, it is important to note that while dendrochronology dates the wood rather than the artwork, recent research shows that panels were used within 10 years (depending on the provenance of the wood) after the trees were cut [27]. Could then one or both paintings have been produced decades later (but before 1750), possibly by overpainting the panel of another painting, or recycling wood panels from furniture made in the 1650s? The lack of traces of an underlying painting in the MA-XRF scans rules out the former option, and for the Goudstikker painting, the *invenit* inscription eliminates the later hypothesis. In the 16th and 17th centuries, many early Netherlandish works were replicated and marked with the term *invenit*, a precursor to modern copyright [33,34]. The earliest known panel painters to adopt this convention were Maerten van Heemskerk and Frans Floris [42]. Similarly, Jan Gossaert's Christ on the Cold Stone (1527) was widely reproduced, with numerous copies bearing the inscription *Ioannes Malbodius invenit 1527* ([43], p. 152–153). Consequently, the inscription *I.P.C.* suggests that the Goudstikker painting was created as a copy after an original work by Pieter Cristus. Considering that the original painting by Pieter Cristus bears the inscription *Petrus Cristus me fecit* ("Pieter Cristus made me") on the left and right posts of the archway, it is plausible that a copyist would have used *invenit Petrus Cristi* to clarify that the conceptualization of the original composition was made by Pieter Cristus. The use of a monogrammatic signature with the *invenit* inscription was abandoned during the second half of the 17th century [33,34]. Combined with the dendrochronological date, this monogram allows the production date of the Goudstikker copy to be narrowed down to the 1650s, when the *invenit* formula was still in use.

Interestingly, the pigments closely match 15th-century practices. As in the original panel, the palette consists mainly of late medieval materials—lead white, azurite, vermilion, ochre, lead-tin yellow, and umber—and includes a lead-white imprimatura over a chalk ground. Both the palette and the imprimatura technique are usually associated with the 15th century [29,44]. However, in light of the dendrochronological results, this result illustrates that such materials and techniques remained in use well beyond the late-medieval period, as other works had previously reported [e.g. 45,46]. In line with those works, our results demonstrate that pigment composition and ground preparation alone cannot securely date a painting to the 15th century.

Our study also shows that stylistic and iconographic analysis alone is insufficient for attribution, given its subjective nature. Arguing against a 15th century attribution of the copies, Martens [13] already noted that the RCE panel displays features typical of the late 16th and early 17th centuries, including fuller anatomy, more fluid drapery, and distinct shadow treatment. Our observations further support this. Compared to the Budapest original, the copies show more defined musculature in the Christ Child, softer and rounder drapery folds, stronger chiaroscuro, and warmer, Rubensian flesh tones (Fig. 9)—all consistent with a 17th-century Baroque aesthetic [47–50].

6. Conclusions

The attribution of copies of 15th century paintings often poses a challenge to art historians. Our research has revealed that the paintings under investigation are 17th century copies from the Budapest original *Virgin and Child in an Archway* by Early Netherlandish painter Pieter Cristus, resolving a long-standing debate. While this study concerns just a single case involving two copies, it carries broader implications for the field of art historical research into copies of Early Netherlandish paintings. The production of 17th-century copies of 15th century paintings, places such copies in a significant category of art production. Their investigation through technical and art historical research should be pursued, as it will refine our understanding of workshop practices beyond the production of original works.

The apparent absence of a carbon-based underdrawing set these early modern copyists apart from 15th-century painting practices. However, thorough analyses of the paint layers and infrared reflectography of the RCE panel are lacking in our study. While stratigraphic cross-sections could have yielded additional information regarding ground preparation, paint stratigraphy, or restoration history, this study deliberately prioritized minimally-invasive methods capable of addressing the primary research question concerning chronology and purpose. Therefore, detailed stratigraphic investigation of the paint layers was beyond its scope. Similarly, the one-sided focus on elemental presence, which is inherent to MA-XRF analysis, is a limitation in this context. As such, some minor and difficult-to-detect differences in pigment use may well have remained under the radar. However, none of these analyses would have affected the chronological conclusions established by dendrochronology and the *invenit* inscription.

In line with previous technical studies, our findings highlight that pigment composition and ground preparation alone cannot provide a secure chronological attribution and should always be interpreted in conjunction with complementary evidence, such as dendrochronology. A complete technical comparison with the Budapest original would further clarify the relationship between the original composition and the two copies, particularly regarding workshop practice and copying techniques. Such an in-depth comparative study falls outside the scope of the present work but represents an important avenue for future research.

Lastly, it has become evident that the trained eye of the art historian still makes a significant and indispensable contribution to multidisciplinary research. Authors such as Urbach and Martens had already noted in the previous century that the 17th-century character of these two panels was readily apparent. Therefore, combining art historical observations with available technological analyses is strongly advised to resolve debates about the chronology and history of works of art.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.culher.2026.08.001.

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