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Rembrandt's *An Old Man in Military Costume*: Combining hyperspectral and MA-XRF imaging to understand how two paintings were painted on a single panel

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ABSTRACT

Over the past several decades the painting *An Old Man in Military Costume* by Rembrandt Harmensz van Rijn (ca. 1630–31; J. Paul Getty Museum, 78.PB.246) has been the subject of a number of investigations carried out in order to better visualize a second painting beneath the surface figure. The underlying image – the head and shoulders of a man wearing a cloak – is oriented 180 degrees from the upper image and appears to be fairly complete. Scanning macro x-ray fluorescence (XRF) spectroscopy reveals the face is painted with lead white and a mercury-containing pigment (likely vermilion), and the cloak is painted with a copper-containing pigment. Following the revelation and digital color reconstruction of the underlying figure, a number of questions still remained. Here, through the use of infrared reflectance imaging spectroscopy (i.e., hyperspectral imaging) and macro-XRF imaging spectroscopy, together with cross-sections taken from targeted areas, the sequence of painting in both compositions was explored. Of particular interest was the discovery of evidence of multiple attempts to situate the lower figure, and the subsequent application of a blocking-out layer over the lower figure before the artist rotated the panel and executed the upper figure. In addition, examination of the placement of the two images on the panel adds to our understanding of the subtle complexities of Rembrandt's working process.

KEYWORDS

Early Rembrandt; re-use of painting supports; infrared reflectance imaging spectroscopy; X-ray fluorescence imaging spectroscopy

RÉSUMÉ

Au cours des dernières décennies, la peinture Le vieil homme en costume militaire de Rembrandt Harmensz van Rijn (ca. 1630–31; J. Paul Getty Museum, 78.PB.246) a fait l'objet de nombreuses investigations menées dans le but de mieux visualiser une seconde peinture dissimulée sous la surface. L'image sous-jacente – la tête et les épaules d'un homme vêtu d'une cape – est orientée à 180 degrés de de l'image du vieil homme, et elle semble assez complète. La spectroscopie à macro-balayage de fluorescence X (MA-XRF) révèle que le visage est peint avec du blanc de plomb et un pigment contenant du mercure (comme le vermillon), et que la cape est peinte avec un pigment à base de cuivre. Plusieurs questions restaient en suspens suite à cette découverte et à la reconstruction numérique en couleur de l'image sous-jacente. Grâce à l'emploi de techniques d'imagerie comme la spectroscopie proche infrarouge (ex., imagerie hyperspectrale) et l'imagerie MA-XRF, combinées à l'analyse de coupes stratigraphiques prélevées à des endroits ciblés, on a pu explorer la séquence d'application des couches picturales de chacune des deux compositions. Une découverte particulièrement intéressante est la preuve que l'artiste a fait plusieurs tentatives pour positionner la figure sous-jacente puis, a ensuite appliqué une couche pour la recouvrir complètement avant de faire pivoter le panneau et peindre la figure du vieil homme. De plus, l'examen du positionnement des deux images sur le panneau ajoute à notre compréhension de la subtile complexité du processus de création de Rembrandt. Traduit par Elisabeth Forest.

RESUMO

Nas últimas décadas, a pintura Um Velho em Traje Militar, de Rembrandt Harmensz van Rijn (ca. 1630-31; J. Paul Getty Museum, 78.PB.246), foi objeto de uma série de investigações realizadas para visualizar melhor uma segunda pintura abaixo da figura aparente. A imagem subjacente - a cabeça e os ombros de um homem usando uma capa - é orientada a 180 graus da imagem superior e parece estar bastante completa. O macro mapeamento de imagem por espectroscopia de fluorescência de raios X (FRX) revela que a face é pintada com branco de chumbo e um pigmento contendo mercúrio (provavelmente vermelhão), e a capa é pintada com

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um pigmento contendo cobre. Após a descoberta e reconstrução digital da cor da figura subjacente, uma série de questões ainda permanecem. Então, através da utilização do mapeamento por imagem de espectroscopia de refletância por infravermelhos (i.e. mapeamento hiperespectral) e macro mapeamento por imagem de FRX, juntamente com cortes estratigráficos de amostras retiradas de áreas de interesse, a pintura em ambas as composições foi explorada. De particular interesse foi a descoberta de evidências de múltiplas tentativas de posicionar a figura subjacente, e a subsequente aplicação de uma camada intermediaria de separação sobre a figura inferior antes do artista girar o painel e executar a figura superior. Além disso, o exame da colocação das duas imagens no painel aumenta nossa compreensão das sutis complexidades do processo de trabalho de Rembrandt. Traduzido por Marcia Rozzi e Beatriz Haspo.

RESUMEN
A lo largo de las últimas décadas, la pintura Un anciano con traje militar de Rembrandt Harmensz van Rijn (ca. 1630–31; J. Paul Getty Museum, 78.PB.246) ha sido objeto de varias investigaciones realizadas con el fin de visualizar mejor una segunda pintura debajo de la figura de la superficie. La imagen subyacente, la cabeza y los hombros de un hombre que lleva una capa, está orientada a 180 grados de la imagen superior y parece estar bastante completa. La espectroscopia de fluorescencia de rayos X (XRF) de barrido revela que la cara está pintada con blanco de plomo y un pigmento que contiene mercurio (probablemente bermellón), y la capa está pintada con un pigmento que contiene cobre. Tras la revelación y la reconstrucción digital del color de la figura subyacente, aún quedaban algunas preguntas. Aquí, por medio del uso de la espectroscopía de imágenes de reflectancia infrarroja (es decir, imágenes hiperespectrales) e imágenes macro-XRF, junto con las secciones transversales tomadas de áreas específicas, se exploró la secuencia de pintura en ambas composiciones. De particular interés fue el descubrimiento de evidencia de múltiples intentos de situar la figura inferior, y la aplicación posterior de una capa de bloqueo sobre la figura inferior antes de que el artista rotara el panel y ejecutara la figura superior. Además, el examen de la colocación de las dos imágenes en el panel contribuye a nuestra comprensión de las sutiles complejidades del proceso de trabajo de Rembrandt. Traducción: Amparo Rueda.

1. Introduction

Dutch painter Rembrandt Harmensz van Rijn (1606–1669) reused painting supports, such as copper plates, wood panels, and canvases throughout his long career, particularly during his early years as an independent master in Leiden and Amsterdam, ca. 1626–1632 (van de Wetering 1986, 2007). Why and how compositions were painted over has not been easy to fully understand, and has been the subject of intense study and speculation in recent years (Wieseman 2010). While the upper and lower compositions often depict the same subject matter, notably *tronies* (character studies) for which Rembrandt sometimes used his own features (essentially self-portraits), subjects also diverged, with history scenes and *tronies* sometimes sharing the same support (van de Wetering 2005, 2014). Recent technological advances in non-invasive and spatially-resolved analytical techniques have allowed for the visualization of more of Rembrandt's overpainted compositions not previously identifiable using traditional x-radiographic techniques (i.e., x-radiography). The improved ability to study these obscured paintings more closely provides insight into the intricate relationship between Rembrandt's working practice and his creative process.

An Old Man in Military Costume (ca. 1630–31; J. Paul Getty Museum, 78.PB.246) (Figure 1a) is painted on one of these reused supports: a high-quality oak panel (measuring 65.7 × 51.8 cm) composed of two edge-joined vertically-grained boards. Klein's dendrochronological examination identified the wood as Baltic oak, with the boards originating from the same tree, felled by 1622 at the earliest. These results suggest an earliest possible date of use as a painting support from about 1624, based on a minimum seasoning time of two years (Klein 2000). The left board measures approximately 24 cm in width. The width of the right board measures slightly over 27 cm, resulting in the join being left-offset from the center of the panel by about 1.5 cm. The grain direction runs vertically, parallel to the longest dimension of the panel. The overall dimensions may be standard for the period, and both the grain direction and join type are typical of the oak panel supports used by Rembrandt (Bruyn 1979; van de Wetering and Retèl 2009). As will be shown below, the position of this join appears to have played an important role in Rembrandt's positioning of the figures in both the upper and lower compositions.

The reverse of the panel is beveled on all four sides and covered with a piece of canvas glued to the back, which has been painted brown. It is not clear when this canvas was applied, but the thread count corresponds to those typically found only after the mid-17th century, so it is unlikely to be original (Bruyn et al. 1982). Previous analysis identified the presence of lead

Figure 1. (a) Rembrandt Harmensz van Rijn, *An Old Man in Military Costume,* 1630–31, oil on panel, 65.7 × 51.8 cm, J. Paul Getty Museum 78.PB.246; (b) Digital estimated color reconstruction of underlying figure (image rotated 180 degrees for clarity, from Trentelman et al. 2015).

in the adhesive (Namowicz 2008), consistent with the observation that the threads of the canvas are clearly visible in the x-radiograph. The fabric interferes with reading the paint layers from the x-radiograph, however, and makes visualizing the underlying figure more challenging with this technique.

The surface painting (Figure 1a) portrays a bust-length old man wearing a polished metal collar (gorget) over a drab green-brown tunic with a deep reddish-brown cloak and a high-peaked dark beret decorated with a gold chain and tall reddish ostrich plume. Though facing forward, the man knits his brows and looks to his right as if listening intently. Rembrandt executed the figure with a close attention to detail, from the glistening eyes, fine wrinkles and wispy mustache and beard of his subject, to the reflective qualities of the polished steel collar. Rendered with the opacity characteristic of his style around 1630, under normal viewing conditions there are no indications of the existence of an initial composition below the surface of the paint. Examination by scanning macro x-ray fluorescence imaging spectroscopy (MA-XRF) along with sample-based analysis by light microscopy and elemental analysis by scanning electron microscopy with energy dispersive spectroscopy (SEM-EDS) suggest the surface composition of the old man was executed using a limited palette including lead white, diverse iron earths including umber, natural charcoal, and organic red colorants along with minor amounts of vermilion, smalt, and lead-tin yellow (Namowicz 2008; Trentelman et al. 2015).

An underlying image depicting what appears to be a young man's head, oriented 180 degrees with respect to the surface painting, was first detected with x-radiography by the Rembrandt Research Project when the painting was in a private collection (Bruyn et al. 1982). After entering the collection of the J. Paul Getty Museum in 1978, additional studies of increasing technical sophistication and specificity, including neutron activation autoradiography and more recently macro x-ray fluorescence mapping, were carried out with the goal of better visualizing both the chemical composition and figural details of the lower composition. Together, these studies culminated in the creation of a digital estimated color reconstruction (shown in Figure 1b) of the portions of the lower composition for which information was available (Trentelman et al. 2015). In contrast to the surface painting, the results by MA-XRF show Rembrandt's initial subject was a young man. He is depicted in similar fashion: bust-length wrapped in a cloak, without his hands visible. The top of his cloak is enhanced with an additional feature that is unclear, but may be a metal collar similar to that worn by the old man, a fur collar, or a silk scarf. The palette differs from that used to paint the old man in two significant ways: the face was found to contain considerably higher levels of mercury (indicating use of vermilion), and the cloak appears to have been painted using a copper-green pigment. The proper left side of the face, along with the details of the top of the head and head covering, are largely obscured in most technical images. Strong light illuminates the proper right side of his face, revealing his full lips and ear surrounded by bushy hair. The identification of the lower man, including the possibility it may be a *tronie* of the artist, will be addressed in a separate study.

The first stage of this research focused on visualizing the underlying figure. While the images depicted in

Rembrandt's overpainted compositions have been widely examined, the process by which he re-used his various supports is less well known. This paper will explore the sequence by which the two compositions were created, paying particular attention to how the different passages of the compositions were built up and what steps Rembrandt took to obscure the underlying bust before painting the surface image.

Recent advances in spatially- and spectrally-resolved imaging technologies have improved both the type and amount of chemical information that can be gathered non-invasively from paintings on diverse supports. Moreover, spectral imaging techniques sensitive in the near infrared (750–2500 nm) can help reveal painted forms present in sub-surface layers painted using carbon-based or other pigments that may not be readily visualized or identified using x-ray based imaging technologies. The precise location of a particular species of interest within the complex stratigraphy of a painting, however, may still best be determined through complementary examination of microsamples analyzed in cross-section. Here a combination of traditional broad-spectral infrared reflectography (i.e., near infrared reflectography, sensitive from about 900–1700 nm), spectrally resolved infrared reflectance imaging spectroscopy (sensitive from 967 to 1680 nm), and scanning macro x-ray fluorescence (MA-XRF) imaging spectroscopy is employed, together with the examination of targeted cross-sections by UV-fluorescence and visible light microscopy, and elemental analysis by SEM-EDS to reveal new information about Rembrandt's technique and the sequence in which he created the two images on this panel.

2. Experimental

Near infrared (NIR) reflected images were collected using an IR-modified Betterlight scan-back equipped with a Kodak trilinear CCD. Unwanted visible light was removed during imaging using a B+W Infrared 093 IR long-pass filter, which has 88% transmission at 900 nm (SchneiderOptics.com 2018) giving a spectral sensitivity from approximately 900–1000 nm. Additional broadband NIR reflectography was carried out using an OSIRIS camera (Opus Instruments), outfitted with an indium gallium arsenide (InGaAs) detector sensitive from about 900–1700 nm. Final image processing, including image mosaicking, was carried out using Adobe Photoshop.

Hyperspectral infrared reflectance images were collected using a modified NIR imaging spectrometer (SOC720 Surface Optics Corp, CA) equipped with a scan mirror. The original InGaAs area array was replaced with a more sensitive array (640HSX-1.7RT, Sensors Unlimited, NJ). The camera system has 640 pixels along the slit of the imaging spectrometer. The spectral sampling is 3.4 nm, giving 209 spectral bands from 967 to 1680 nm. The scan mirror allows the collection of images of 640 × 640 spatial pixels. A large white Spectralon panel is used to flat-field the individual image cubes, and two in-scene black and white standards are used in all cases to calibrate the image cubes to apparent reflectance. The spatial sampling at the painting was 0.275 mm. Two 125-W lamps (adjusted with a rheostat) were used to diffusely illuminate the portion of the painting imaged for each data cube acquisition. The visible light level at the painting was 900 lux. The total time required to collect each image-cube was 3 min. The image-cubes were spatially registered using a high resolution visible image (acquired with a CMOS camera) as a reference using a previously described algorithm (Conover, Delaney, and Loew 2015). The image-cube was converted to apparent reflectance by dividing the image-cube by the diffuse white standard after subtracting the dark current using the ENVI software suite (Harris Geospatial). Distribution maps were made using the spectral angle mapper algorithm (SAM) using reflectance endmember spectra obtained from regions of interest selected by eye.

Scanning macro x-ray fluorescence imaging spectroscopy was previously carried out across the entire painting using a Bruker M6 Jetstream scanning XRF spectrometer (Trentelman et al. 2015). For this work, additional XRF scans of select detail areas were carried out using a newer version of the same instrument, utilizing smaller spot sizes and higher spatial resolution than that employed for the overall scans. The current model of the Bruker M6 Jetstream XRF spectrometer is outfitted with a 30 W Rhodium x-ray tube with polycapillary focusing optics. Detail scans were collected at a nominal spot size of 120 µm (the smallest preset spot size of the instrument), and a per-pixel dwell time of 12 ms; additional parameters specific to each scan are included in the figure captions. Data collection was carried out using the Bruker ESPRIT software. Data processing, including energy channel calibration and fundamental parameters-based spectral fitting, was carried out using PyMCA + Datamuncher (Alfeld and Janssens 2015; Cotte et al. 2007). Element distribution maps were generated for individual elements detected in the mapped areas. The maps have a resolution equal to the number of measurement points that comprise the cube. The resulting 8-bit element maps have 256 grey levels, and brighter pixels in each raster map represent higher signal from the given element within the area examined.

Since *An Old Man in Military Costume* is in excellent condition, there were no opportunities to take samples from the main part of the image. Multilayered paint samples were obtained from the edges of existing damages from eight different locations around the perimeter of the painting to investigate the stratigraphy and composition of individual paint layers. The fragments were embedded in Technovit light-curing acrylic resin LC2000 (Kulzer, GmbH) and dry polished using MicroMesh polishing cloths. The prepared cross-sectioned samples were examined and photographed under visible light using crossed polarizing filters as well as by UV-induced visible fluorescence using a Leica DM4000 microscope equipped with a Flex camera (Diagnostics Instruments).

Elemental analysis on the two cross-sectioned samples presented here (S1 and S2) was performed using scanning electron microscopy with energy-dispersive x-ray spectroscopy (SEM-EDS). Because the samples were removed in a series of sampling campaigns over the past several years, they were analyzed by different SEM-EDS systems. Sample S1 was examined using a FEI-Philips XL30 ESEM-FEG with Oxford AZTEC EDS analysis software (H_2O mode, 11 mm working distance, 20 kV accelerating voltage, and approximately 0.6 torr (80 Pa) water vapor pressure in the chamber). Sample S2 was examined using a Zeiss Gemini 300 FE-SEM with Oxford AZTEC EDS analysis software (variable pressure mode, 11.2 mm working distance, 20 kV accelerating voltage, and 25 Pa N_2 gas pressure in the chamber). In addition to single point measurements, mapping across multilayer regions of interest was also carried out to measure the elemental distribution across both samples. False-color tri-channel elemental phase maps were constructed for both samples using the Oxford INCA EDS analysis software. Additionally, backscatter electron (BSE) images of the cross sections were obtained for comparative analysis of the samples to visible light and UV-induced visible fluorescence microscopy. The greyscale BSE images provide useful information about the average atomic number of the individual species present across the entire sample surface.

3. Results/discussion

3.1. Near infrared reflectance imaging spectroscopy

In general, the NIR reflectogram (Figure 2a) captured in the spectral band from about 900–1000 nm with the Betterlight scanback shows areas having high reflectance that largely correspond to those in the visible image. There are a few exceptions, such as a few small patches visible to the left of the old man's head. However, a much larger area of higher reflectance becomes visible by extending the spectral width from 900 to about 1700 nm (i.e., broadband NIR) using the OSIRIS camera (see Figure 2b).

Previous XRF element mapping demonstrated that the underlying figure was apparently completed to a high degree of finish, with the face appearing fully realized in lead white and vermilion, and folds of the underlying figure's cloak painted with a copper-containing pigment (Trentelman et al. 2015). These details could be visualized because of the relatively high spatial resolution of the overall element maps (650 µm step size) afforded by the lead (Pb), mercury (Hg), copper (Cu), and iron (Fe) maps after fitting of the XRF image cube. Interestingly, however, no evidence of the facial details or clothing of the underlying man can be seen in the broadband (900–1700 nm) infrared reflectogram shown in Figure 2b. Rather, only a broad region of high reflectance (appearing bright in the image), roughly corresponding to the shape of the underlying figure identified by the XRF mapping is visible. This was an unexpected and interesting result considering that, in other paintings examined using similar techniques at these wavelengths, extant details from the overpainted paint layers are often discernible (Favero et al. 2017; Jackall, Delaney, and Swicklik 2015). In the case of *An Old Man in Military Costume*, however, only minor intensity modulations can be seen, ascribable to the non-uniform thickness of the carbon-containing grey surface paint layer, which was applied directly over the infrared reflective layer. It is therefore hypothesized that this NIR-reflecting, homogenous, and anthropomorphic shape roughly following the outline of the underlying figure corresponds to an infrared-opaque blocking-out intermediate layer, which was applied by the artist in order to obscure the underlying bust before painting his second composition.

This characteristic shape was not evident with any clarity in any of the earlier XRF element distribution maps. Some stippled brushstrokes, which appear similar to those visible in the NIR reflectogram, are visible in the Ca-K map near the bottom of the lower figure (in an area corresponding to lower levels of Pb) after histogram stretching to enhance the contrast of the greyscale image (not shown). Since the emitted x-ray photons characteristic of Ca-Kα transitions (Ca Kα = 3.69 keV) would be largely absorbed by any superficial layers containing lead, and given the ubiquitous presence of lead across the painting, in both surface and subsurface layers, it is perhaps not surprising that a clear image of this intermediate blocking-out layer is not detected in any of the XRF element maps.

In traditional broadband infrared reflectography the acquired image is the sum of the all the light emerging from the paint layers following absorption and scattering by pigment particles that have unique wavelength dependence in the NIR. Infrared reflectance imaging

Figure 2. Broadband near infrared reflectograms: (a) approx. 900–1000 nm; (b) approx. 900–1700 nm. Image orientation rotated 180 degrees to emphasize underlying figure.

spectroscopy, by contrast, offers the potential to separate these regions into hundreds of narrow spectral bands that can increase contrast between such paint layers (Delaney et al. 2016). Utilizing this technique thus provided an opportunity to look for evidence for pigmented layers, and in particular the hypothesized intermediate blocking-out layer suggested by the broadband reflectogram but not evident in any of the earlier XRF mapping results. By calibrating the image-cube to apparent reflectance it is possible to map disparate areas across the painting that have the same reflectance spectra. Due to the high spectral resolution of the imaging spectrometer, characteristic features in these spectra can be related to artist materials with characteristic features in this region, and thus provide information that broadband IRR alone cannot.

Figure 3a shows a tri-channel false color composite extracted from the hyperspectral reflectance image cube. This false color image is the combination of three spectral channels (1650 nm = red, 1325 nm = green and 1000 nm = blue) and while it shows more contrast variation than the broadband IRR it also suggests reflectance spectral information of interest. Examination of false color images over narrower spectral ranges (data not shown) reveals some features closer to that of the XRF maps. Namely, high reflectance areas having an absorbing feature at 1449 nm characteristic of the hydroxyl group of lead white are evident in the areas of the ear and temple of the underlying figure. Areas of low reflectance generally correspond to regions of the hair. These features support the notion that the original composition was somewhat thinly painted as expected for this artist. However, the most intriguing aspect is the blocking-out layer.

The presumed intermediate blocking-out layer is characterized by a high reflectance throughout the region

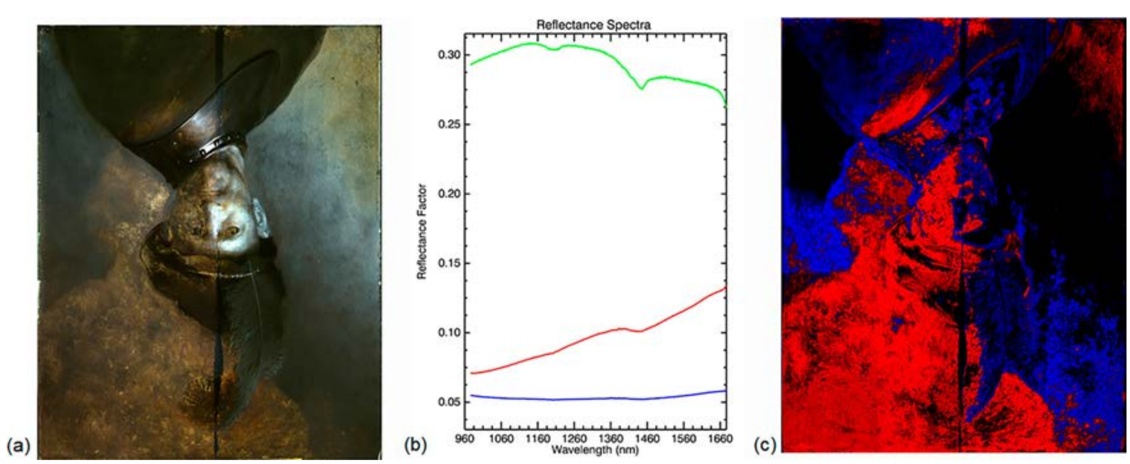

Figure 3. Hyperspectral infrared reflectance imaging spectroscopy: (a) tri-channel false color composite (red = 1650 nm, green = 1325 nm, blue = 1000 nm); (b) relevant endmember spectra; (c) spectral angle map of red and blue end member spectra.

from ~1000 to 1650 nm. The relatively loose, flowing brushwork assigned to the dark green-grey paint of the surface layer is also visible in the false color composite due to the contrast against the high reflectivity of the blocking-out layer below. In fact, the overall extent of this blocking-out layer is quite easily visualized in the false color composite due to its high reflectivity in contrast to nearly all the other paints that comprise the upper composition, which include infrared absorbing materials. Some of the painted elements of the final composition are also visible in the false color composite, especially those painted with NIR absorbing pigments, such as carbon blacks and umbers in the robe and gorget worn by the old man.

Information about the materials present, and their distribution across the painting, was obtained by additional processing of the hyperspectral image cube. Three relevant spectral endmembers, shown in Figure 3b, were found. The first endmember spectrum (green trace in Figure 3b) is characterized by high reflectance and a narrow, sharp absorption band near 1446 nm, assigned to hydroxyl (OH) stretching, which is characteristic of basic lead white ($2PbCO_3{\cdot}Pb(OH)_2$) (Delaney et al. 2010; Hunt 1970). The distribution map of this endmember (not shown) corresponds to where lead white is seen on highlights and the lit-painted face of the old man of the surface composition, and some areas, as noted above, that relate to the temple and right ear of the underlying figure.

The second endmember spectrum (red trace in Figure 3b) shows rising reflectance with increasing wavelength throughout the region 967–1680 nm, with a broad absorption band centered around 1443 nm. The map of this spectral endmember (red area in Figure 3c) shows a distribution concomitant with the intermediate blocking-out layer as revealed by diffuse reflectance imaging spectroscopy (c.f. Figure 2b). The red endmember clearly correlates to the subsurface blocking-out layer and supports the hypothesis that this layer is relatively homogenous in composition across the entire layer. The general increase in reflectance with increasing wavelength can occur from decreased absorption due to the presence of a copper-green pigment (inferred from the earlier XRF mapping) or from decreased scattering from a coarse chalk and lead white layer. While the absorption band near 1443 nm and shoulder at 1571 nm could be interpreted as having some contribution from the hydroxyl group of lead white, the observed broadening and spectral shift plus shoulder feature is more similar to that observed from a wood panel (Li et al. 2015). In fact, the wood structure of the support panel can be seen in a number of places throughout the infrared reflectance composite. Most importantly, the false color infrared composite image (Figure 3a) together with the red endmember map (Figure 3c) suggests that the blocking-out layer extends vertically far above the sitter's face (an outline of the area described by the blocking-out layer is shown in Figure 7a and Figure 8a). These images offer the first convincing evidence that the lower figure was wearing some kind of hat or other form of peaked headgear.

The third endmember spectrum (blue trace in Figure 3b) is characterized by its low and near constant apparent reflectance in the region 967–1680 nm. This endmember spectrum is attributed to the presence of a dark, carbon-containing pigment or other highly IR absorbing pigment(s) such as umber. The map of this endmember (shown in blue in Figure 3c) corresponds to the dark robe and collar of the surface figure, and the background of both figures. It is interesting to note that the background areas directly adjacent to the edges of the underlying bust were strongly delineated using a carbon-containing pigment, most notably around the neck, back of head and to the right of the robe (proper left of underlying figure). In the upper painting, adjustments to the area adjacent to the neck and along the shoulder (see Figure 1a) serve to refine the relationship of the figure to the background and clarify the position of the figure in space. Characteristic of Rembrandt's working method, these amendments likely occurred in the final stages of painting.

3.2. Detail images

Figure 4a-d are element distribution maps obtained from a high-resolution XRF scan over a small region of interest at the tip of the old man's feather (yellow box in Figure 4a). In this area Rembrandt appears to have incised a number of lines directly into the fresh paint of the surface composition using a rigid tool, such as the end of a paintbrush, in order to achieve an optical effect. From an analytical viewpoint, these scratched lines function as small "windows" into the subsurface layers. With respect to the underlying composition, the tip of the feather lies directly over the lower figure's drapery, which is painted in a copper-containing pigment. In the Pb-L element distribution map (Figure 4b) the incised lines are clearly visible as dark lines, due to the low concentration of lead detected in these areas. In contrast, the same lines appear as areas of high signal in the Ca-K distribution map (see Figure 4c). Figure 4d shows the distribution of the Cu-K signal in this same region of interest. Interestingly, while all of the incised lines appear enriched in calcium, only a small subset of these lines are also rich in copper. Visual examination revealed that the lines which show elevated signal in the Cu-K map are shallower in depth, suggesting these incised lines only extend into the Cu- and Ca-rich layer that describes

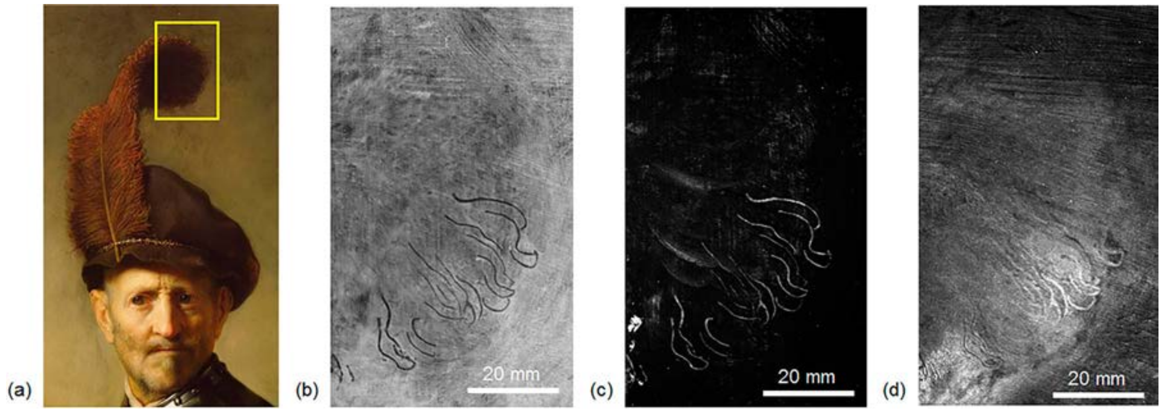

Figure 4. Detail macro-XRF element maps over area of scratches in feather: (a) location of scan (yellow box); (b) Pb-L; (c) Ca-K; (d) Cu-K (Scanning parameters: spot size 120 μm, step size 95 μm, dwell time 12 ms/pixel).

the underlying figure's robe. The other, deeper, lines appear to extend further into the paint stratigraphy, and the predominance of Ca suggests they may be extending to the ground.

These incised lines are also important to better understand how Rembrandt approached the repainting of the underlying figure. Significantly, all of the incised lines have rounded edge profiles, which supports a hypothesis that Rembrandt added these incisions when the paint layers belonging to both the upper and lower compositions were both still relatively soft. While it is impossible to recreate an exact timeline based on the hardness of oil paint, the smoothness of the incised lines suggests that relatively little time had elapsed between the abandonment of the original composition and the application of both the intermediate blocking-out layer and final paint layers belonging to the old man.

The center of the panel, including the area where the two faces overlap one another, was a region of particular interest in determining how Rembrandt approached the repainting of the panel. Results from high-resolution XRF scanning and hyperspectral imaging over this region are shown in Figure 5a–e. The smaller spot size and higher sampling of the detail XRF maps more clearly reveals compositional details than the overall MA-XRF scans from our previous study. Significantly, the results reveal multiple attempts to place the eyes of the lower figure. The positions of these eyes are indicated by arrows in the individual data images. However, due to the visual congestion of these images, a simplified schematic that outlines the shapes and positions of the eyes is also presented in Figure 5e.

At least two sets of (proper right) eyes belonging to different painting phases of the underlying figure are visible in the Pb-L map (indicated with yellow and blue arrows; see Figure 5b). Surprisingly, both eyes appear to be painted to a high level of finish, indicated by the clarity to which both the overall shape of the eye as well as the iris and the surrounding sclera are visible. The eye indicated by the blue arrow in Figure 5b (and shown in blue in the schematic in Figure 5e) appears to be the final position. This interpretation is supported by the close agreement with the rest of the painted face of the underlying figure, as is visible in the Pb-L map. The other painted eye, positioned just below and to the viewer's left of the final eye (indicated by a yellow arrow in Figure 5b and drawn in yellow in the schematic in Figure 5e), is therefore understood to have belonged to an earlier phase of painting.

Infrared reflectance imaging spectroscopy helped reveal evidence for yet another pair of eyes, positioned to the viewer's right respective the final location of the eyes of the underlying figure. These eyes do not appear to have been painted to the same level of finish as those discussed above. They are visible in the false color composite (Figure 5d) as dark (i.e., infrared absorbing) outlines, which describe the oval shape of an eye (indicated by red arrows in Figure 5d and the schematic in Figure 5e). The same outline shape, belonging to the proper right eye, is also visible in the Fe-K element map (red arrow in Figure 5c), suggesting that these outlines were created using an iron earth pigment, such as umber, perhaps mixed with charcoal or another carbon-based black. Such a composition would account for outline's dark (absorbing) appearance in the infrared composite and bright appearance in the Fe-K map (indicating relatively high concentration). A close examination of the Pb-L map in Figure 5b also reveals the outline of this eye (indicated by a red arrow), which appears dark due to a lack of lead content. Strikingly, Rembrandt appears to have approached this important physiognomic feature more directly in the upper figure, deftly painting the eyes rather than using a preparatory guide, as in the lower man.

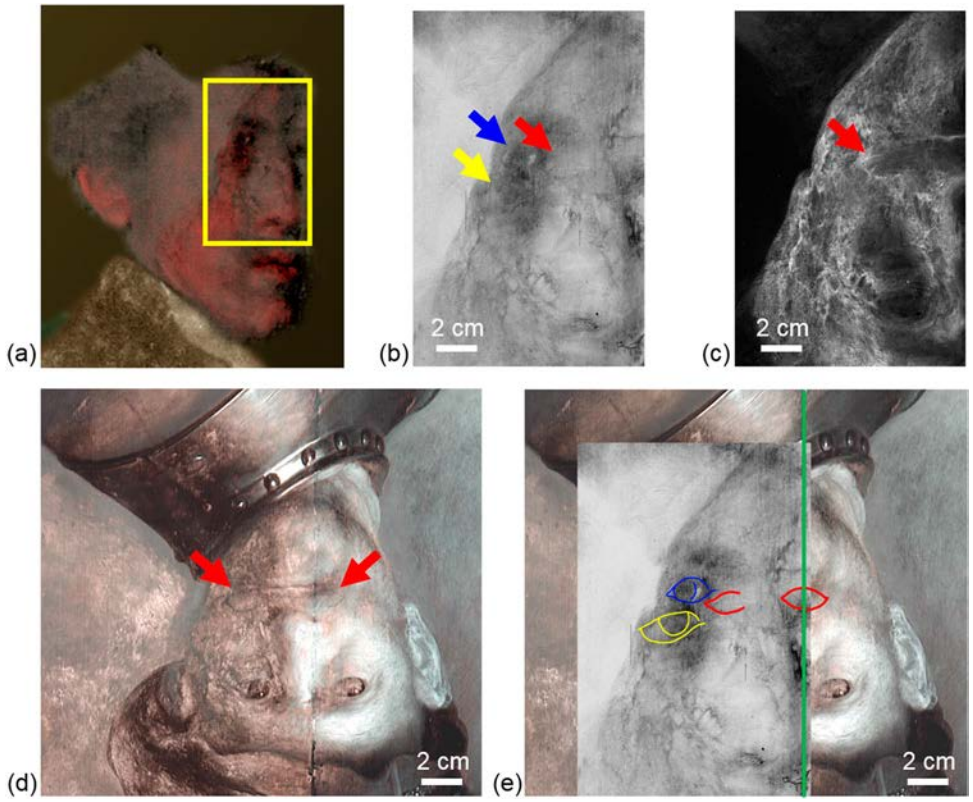

Figure 5. Detail XRF and NIR scans of face of underlying figure: (a) color digital reconstruction of face of underlying figure showing location of XRF scans (yellow box); (b) Pb-L element map; yellow arrow points to a presumed abandoned eye, positioned below and slightly left of the placement of the final eye (indicated by a blue arrow). Red arrows points to a third set of eyes, sketched in an iron-containing medium as seen in (c) Fe-K element map; and (d) infrared false color composite (red = 1650 nm, green = 1443 nm, blue = 1300 nm); (e) schematic showing the outlines and shapes of the different eyes (colored to match arrows) belonging to the underlying figure, board join is outlined in green (XRF scan parameters: spot size 120 μm, step size 100 μm, dwell time 12 ms/pixel).

These draft outlines likely represent the artist's initial placement of the eyes, which were followed by the painted ones, which he also repositioned. The numerous trial positioning of the eyes, an unusual feature not found thus far in other works by Rembrandt, suggests the artist was seeking a different solution for the position of the figure, perhaps to distinguish it from similar *tronies*. Given the relatively low position of the old man on the panel, which permitted or perhaps necessitated the height of the showy plume, similar expectations of the size of the lower figure's hat may have been a factor in seeking the appropriate placement of a key feature such as the eyes. The varied placement of the proper right eyes also may reflect a concern for the best positioning of the head vis-à-vis the panel join (highlighted in green in Figure 5e). It is possible that Rembrandt purposely aligned the two faces, as they share a common shadow line down the center of the face, which also follows the join of the two boards that make up the panel. However, situating the illuminated cheek and nose to the side of the join pushed the head to the left side of the field, an arrangement Rembrandt may not have felt to be ideal, leading him to abandon the lower *tronie* and reuse the panel in a different orientation.

Along with revealing evidence of initial positioning, close inspection of the area around the proper right eye of the surface figure in the false color infrared reflectance image (Figure 5d) reveals visual evidence of the wood grain of the panel support, highlighting an important feature of the underlying bust: the lighting. Because most of the pigments used by Rembrandt to paint the upper composition, including vermilion, ochers, and thin layers of lead white, become transparent in the NIR, the wood grain is visible in these regions. In contrast, the wood grain is, in general, obscured to a greater degree by the blocking-out layer, consistent with the impact of increased scattering of the chalk and lead white contained in this layer (see cross-sections, below). The blocking-out layer, which is highly reflecting in the infrared and tan in color in the false color infrared composite, extends across the proper left side of the old man's face terminating in an almost vertical line parallel and adjacent to the panel join.

The relative transparency seen in this area implies that the strongly IR absorbing background, which was painted around much of the underlying figure (see blue endmember spectral map component in Figure 3c) was not painted up to the proper left side of the figure's face in this area. This suggests the proper right side of the face of the underlying man was strongly illuminated, while the proper left side was in shadow. Such treatment is in keeping with Rembrandt's interests in the late 1620s and early 1630s, when he explored the fall of light across his own features, leaving his eyes in shadow and proper right cheek exposed, as in *Study in the Mirror (human skin)* (ca. 1627/28, Indianapolis Museum of Art) and in *Self-Portrait, Age 23* (ca. 1629; Isabella Stewart Gardner Museum), and in more symmetrical bifurcation, as in the underlying figure in the Getty panel, and *Self-Portrait with a Gorget*, (1629, Nuremberg, Germanisches National Museum) and *Self-Portrait in Oriental Attire*, (1631, Paris, Petit Palais) (Figure 6).

3.3. Sample-based analysis

Results from the study of two multilayered samples, S1 and S2, which are understood to contain a complete stratigraphy of the extracted location in the painting from within and without the blocking-out layer, are shown in Figures 7 and 8. Both reveal a similar preparatory buildup. The first layer is composed of a calcium-containing ground, identified by FTIR spectroscopy as chalk, which was applied over the entire oak panel (only a small portion of this layer is contained in S1, localized at the lower right side of the sample). The backscatter electron images reveal a closely-packed particle matrix, with individual particles measuring only about 1–2 µm. A thin (averaging from <10 to about 20 µm in the samples examined), and lightly pigmented layer containing a mixture of lead white, iron earths, umber, calcitic species, and charcoal was applied over the calcium-containing ground (layer 2). This pigmented layer – consistent with what has typically been called primuersel (Bomford et al. 2006) – also appears to have been medium-rich, evidence by the increased saturation of the upper half of the chalk ground when viewed under crossed polarizing filters. The presence of umber in the primuersel has been previously described in other contemporary paintings by Rembrandt, where, apart from imparting a tonal effect, it would speed the drying of the medium-rich preparatory layer (Bomford et al. 2006). It is after these first two layers that the sample stratigraphy in the two samples diverge.

Sample S1 was removed from the proper upper right edge of the panel, corresponding to the area containing the copper-rich cloak belonging to the underlying bust and the blocking-out layer (see Figure 7a). Visible light and UV-induced visible fluorescence images are shown in Figure 7b–c, and a backscatter electron (BSE) image and a tri-channel elemental phase map, in which iron (Fe) = red, calcium (Ca) = green, and copper (Cu) = blue are shown in Figure 7d–e, respectively. Layer 3 is applied directly atop the primuersel (layer 2) and appears dark brown under crossed polarizing filters. The BSE image indicates this layer has an overall lower average atomic number (Z) compared to the other paint layers in the sample and SEM-EDS analysis suggests it is composed mostly of a calcitic species (chalk), mixed with iron earth, lead white, and clay minerals. This layer is notable in that it contains Cu-containing particles (colored blue in the phase map, see Figure 7e), and thus is part of the overall copper-containing layer identified by MA-XRF as corresponding to the underlying figure's cloak.

Layer 4, which has a warm, creamy tone under crossed polarizing filters, is interpreted to be the blocking-out intermediate layer applied by Rembrandt to mask the lower composition. The overall elemental composition of the blocking-out layer appears qualitatively similar to that of the primuersel, containing lead white, a calcitic species (green channel in Figure 7e), with iron earth

Figure 6. (a) Rembrandt van Rijn, *Self-Portrait, Age 23*, 1629, oil on panel, 89.7 × 73.5 cm, Boston, Isabella Stewart Gardner Museum; (b) Rembrandt van Rijn, *Self-Portrait with a Gorget*, ca. 1629, oil on panel, 38.2 × 31 cm, Nuremberg, Germanisches Nationalmuseum; (c) Rembrandt van Rijn, *Self-Portrait in Oriental Attire*, 1631, oil on panel, 65.5 × 52 cm, Paris, Musée du Petit Palais.

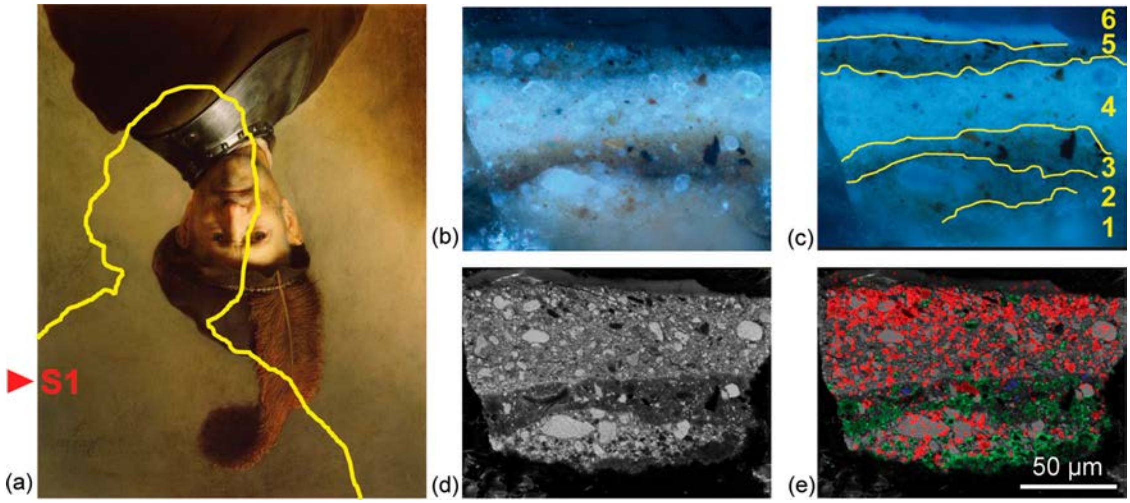

Figure 7. (a) Location of sample S1. Yellow outline shows area covered by blocking-out layer. Microscopy results from sample S1 are shown in 7b-7e; (b) visible light (crossed polarizing filters); (c) UV-induced visible fluorescence; (d) backscatter electron image; (e) elemental phase map for Fe (red channel), Ca (green channel), Cu (blue channel) overlaid onto backscatter electron image.

(red channel), and charcoal. Examination of the particle morphology and distribution, however, suggest that the particles are more finely ground in the blocking-out layer compared to the primuersel, which is characterized by a relatively large, jagged particle matrix.

The blocking-out layer appears relatively thick in sample S1, with an average thickness of approximately 20–30 µm throughout the sample. Examination across other samples obtained from different locations in the panel suggests the thickness of the blocking-out layer is highly variable, with an overall average thickness measuring between less than 10 and up to 30 µm. As discussed above, this is consistent with the results of spatially resolved infrared reflectance imaging spectroscopy in which the transparency of this layer appears to modulate across its distribution over the underlying figure. In particular, the wood grain of the panel support, which was generally obscured by the presence of the highly scattering blocking-out layer, was in fact visible in isolated areas where the blocking-out layer was presumed to be present in a layer thin enough to more fully penetrate in the region from 967 to 1680 nm. While the reason for the variability of the thickness of this layer is not fully understood, it may be due to the manner in which Rembrandt applied the layer, perhaps daubing on material using his hands, or perhaps to the requirement of more or less material to effectively mask the diversely colored passages of the lower composition.

The next, and topmost, layer in the stratigraphy (layer 5) in this sample corresponds to the surface paint layer, again containing a mixture of lead white and calcitic species tinted by iron earth pigments but with more charcoal, giving it an overall grey color under crossed polarizing filters.

Sample S2 was obtained from the opposite end of the panel (see Figure 8a), and corresponds to an area understood to belong to the background during the painting of both the upper and lower compositions; i.e., it is not in an area containing the blocking-out layer. The results by visible light, UV, BSE, and SEM-EDS analyses are shown in Figure 8b–e. The preparatory layers match the stratigraphy previously identified in sample S1, above. Layer 3, which appears dark under crossed polarizing filters, has an overall lower average Z than the preparatory layers. This layer is interpreted as being the background that was applied around the underlying figure. Examination of both the individual particle morphology by light microscopy and elemental composition by SEM-EDS suggests the presence of natural charcoal as a major species throughout this layer. The presence of charcoal, a carbonaceous material, relates this paint layer to the blue endmember distribution map in Figure 3c (Aceto et al. 2014). The endmember distribution map reveals an accumulation of this layer around the outlines of the underlying bust, tapering off with increasing distance from the figure. Layers 4 and 5 in sample S2 belong to the build-up of the background in the upper composition around the figure of the old man, in which Rembrandt is modulating light and shadow in a manner similar to that used in the underlying bust, described above.

The interpretation of cross-sections from this painting was complicated by Rembrandt's rather restricted palette. As noted above, most of the paint layers in the samples analyzed by light microscopy and SEM-EDS were found to consist of subtly differing mixtures based on lead white, umber and other iron earths, natural charcoal, and chalk. Therefore, the results obtained by examination of the cross-

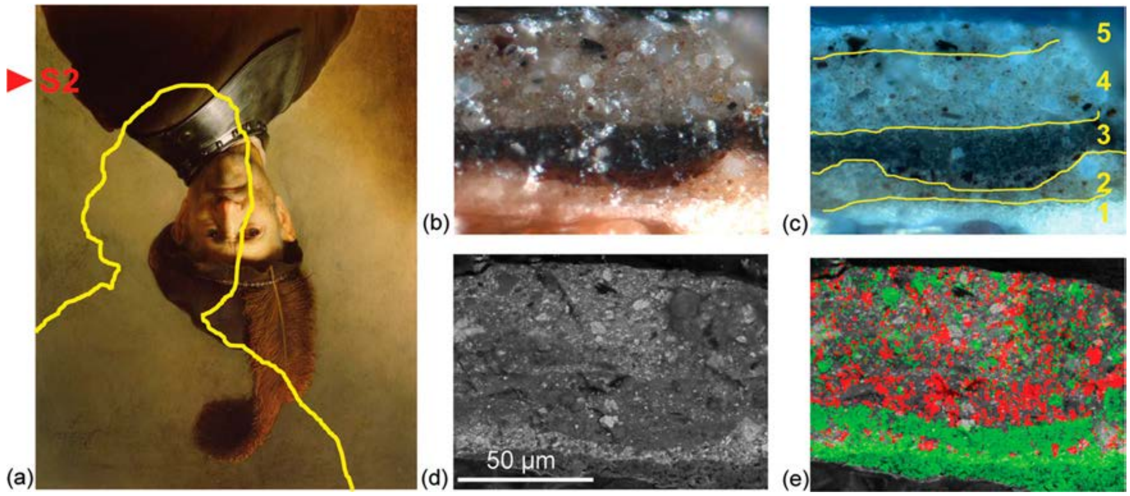

Figure 8. (a) Location of sample S2. Yellow outline shows area covered by blocking-out layer. Microscopy results from sample S2 are shown in 8b–8e; (b) visible light (crossed polarizing filters); (c) UV-induced visible fluorescence; (d) backscatter electron image; (e) elemental phase map for Fe (red channel), Ca (green channel) overlaid onto backscatter electron image.

sections must be considered in conjunction with the results obtained by the spatially-resolved infrared reflectance imaging spectroscopy and scanning macro-XRF imaging spectroscopy, which provided indispensable complementary chemical information allowing for a more confident relation of the results of microscopic analysis at the edges of the panel across the central portions of the painting.

3.4. Visual analysis

The information provided by MA-XRF and infrared reflectance imaging spectroscopy were also helpful in furthering the interpretation of visual analysis of the paint surface. In *An Old Man in Military Costume*, the paint and ground layers are generally thin and the vertical grain of the wooden support is visually apparent in the surface texture of most areas. Raking light clarifies this further and also reveals very subtle evidence of the lower painting due to slight textural and thickness differences in the paint layers. However, the underlying image is mostly camouflaged by the paint covering it. The paint appears to be both smoothly and carefully applied, and close examination shows a variety of paint applications: some areas have an appearance of being dabbed on, and very small peaks of paint can be seen where a brush or other tool (possibly a finger) was lifted after the application of a fairly stiff paint. There are also a number of shallow linear incisions in the background that may be evidence of the use of a tool (other than a brush) to apply paint or preparatory layers in long sweeping strokes. It is difficult to understand the relationship of these features to the complexities of the double painting, but it is possible that some of these application methods aided the artist in his efforts to hide the composition below. The lower painting has left its mark in other ways as well. Thin white lines, running in a horizontal direction, generally alongside horizontal cracks, are evident under high magnification only in areas directly above the blocking-out layer (see Figure 9a). These are interpreted to be a degradation product, and require further analysis to properly characterize them.

As discussed above, marks were made in the feather by scratching into the paint with the handle of a brush or another implement, a well-known technique used by Rembrandt that offers a tantalizing glimpse of the hidden layers below when these “windows” are examined under the microscope. The dark green layer seen in some of the scratches (see Figure 9b) is presumably the robe of the underlying figure. Evidence that the final touches may have been applied while the painting was in a frame is found along the lower right edge, where the dark surface paint does not extend to the edge (see Figure 9c).

4. Conclusions

The wealth of information from hyperspectral reflectance imaging, XRF mapping, cross-sectional analysis by SEM-EDS combined with close visual observation helps us build a compelling hypothesis to understand Rembrandt’s sequence of work on these two intimately related paintings.

For the underlying figure, Rembrandt selected a high-quality Baltic oak panel primed with a chalk ground, which was probably prepared by an outside supplier. Before painting, a medium-rich toning layer, or primuersel, was applied, presumably in Rembrandt’s studio. Dark iron-rich and infrared absorbing painted outlines (Figure 5c–d) reveal that he began by situating the eyes of the

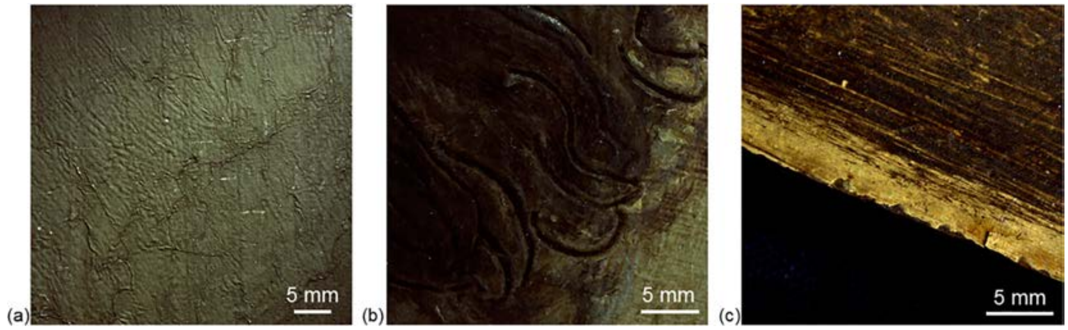

Figure 9. Details from visual analysis: (a) surface of painting showing texture of paint application and thin white lines, thought to be a degradation product; (b) incised lines in feather; (c) lower left edge of painting, showing that the dark surface paint does not extend to the edge, suggesting the painting was in a frame when this layer was applied.

underlying figure, initially choosing two off-set positions to the left and above the center of the panel, before settling on the final, slightly higher, location. He established the form of the head and rest of the underlying figure, apparently in reserve, as suggested by NIR imaging (see Figure 3a). A dark gray (carbon-containing) background was applied around the back and along the proper left shoulder of the figure, roughly along a diagonal extending from the top left to the bottom right. This step may have been completed before the figure was painted, but it does not appear that a full reserve was established for the lower bust. Following this preliminary stage, Rembrandt painted the first man, including the shock of hair around the exposed ear and moustache, and completed the soft folds of the brownish-green drapery and neck decoration. The peaked head covering, revealed during the current study (see outline in Figure 7a or Figure 8a), may be similar to the beret featured in several *tronies* of the late 1620s and early 1630s and worn by the old man in the surface image, or possibly a wrapped textile like the artist's turban in *Self-Portrait in Oriental Attire*, 1631 (see Figure 6c). He adjusted the background tonality where it meets the neck and proper left shoulder, deepening its tonality with a darker hue, and suggested the diagonal fall of light in the background with a light-colored pigment in a diagonal area between the shoulder and edge of the panel.

Despite considerable investment in the execution of the lower figure, Rembrandt abandoned the image. One of the practical reasons for his decision to reuse the support, suggested by the 2015 and current studies, may be his dissatisfaction with the position of the figure, which had been pushed to the left, possibly in order to avoid an inconvenient intervention by the panel join in the face. As perhaps one in a series of busts of young and old men in various guises, however, Rembrandt evidently was willing to sacrifice this particular iteration but not the sizable oak panel. He rotated the panel 180 degrees to utilize the expanse on the other end which had previously served as a neutral backdrop. As revealed in the current study for the first time, Rembrandt applied a variably thick, semi-opaque, blocking-out layer in a daubing action over the head and body of the figure. Confronted with a panel with a large neutralized area in the center and at the top, with darkish sides and lower region, he opted to situate the face of the new subject, an old man, over the head of the underlying figure, aligning the side of the face to be illuminated over the midline of the lower head, with the shadowed side of the lower head supplying the basis for the shaded side of the upper face. Because the first head had been placed relatively high in its field, the second figure occupies a relatively lower position on the panel. In the creation of the backdrop for the old man, the draped body of the lower figure supported the rich shadow of the plaster wall behind him. In the upper image, Rembrandt repeated the diagonal fall of light across the figure from the upper left, using it to animate the neutral background. In a late stage of painting, he also attended to final details, using a light gray paint along the proper right side of his subject's neck and proper left side of the head to separate it from the setting. Other refinements include lowlights in gray in the body of the plume and judicious gouging in the tip (see Figure 4) to enhance the texture of this ostentatious feature. The malleability of the lower paint layers suggests the two painting campaigns on this panel took place in relatively close succession. A dark reddish-brown tone was added to the lower left corner, apparently after the panel was placed in a frame (see Figure 9c).

Using the combined macroscopic analytical techniques of infrared reflectance imaging spectroscopy, scanning macro-XRF imaging spectroscopy and microscopic analyses using light microscopy and SEM-EDS, we present new information about Rembrandt's working process to reveal how the artist followed very similar procedures for both paintings when reusing a panel support. Complementary non-invasive and spatially-resolved imaging techniques are especially valuable for elucidating a process involving a limited range of materials for two similar subjects painted in close succession. Of particular significance is the clear evidence of Rembrandt's use of a blocking-out layer over the underlying figure, a procedure he employed on other occasions, but not routinely (Wieseman 2010). In the case of *An Old Man in Military Costume* and its underlying figure of a man, Rembrandt carefully related the images on the panel, but ensured the presence of the lower figure did not disrupt the meticulously rendered, intensely focused upper bust. With the knowledge gained through study and analysis, it is evident that the lower composition was influential in the distribution of light and form in the upper image. Although Rembrandt's working method varied during the busy early years as an independent master, with quicker and rougher modes, sketchiness and refinement finding expression during this period, his approach to the two paintings on this panel was thoughtful and precise.

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No potential conflict of interest was reported by the authors.

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