

Mapping Henry: Synchrotron-sourced X-ray fluorescence mapping and ultra-high-definition scanning of an early Tudor portrait of Henry VIII

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Abstract A portrait of Henry VIII on oak panel c. 1535 has recently undergone technical examination to inform questions regarding authorship and the painting's relationship to a group of similar works in the collections of the National Portrait Gallery, London, and the Society of Antiquaries. Due to previous conservation treatments of the painting, the conventional transmission X-radiograph image was difficult to interpret. As a result, the painting underwent high-definition X-ray fluorescence (XRF) elemental mapping on the X-ray fluorescence microscopy beamline of the Australian Synchrotron. Scans were conducted at 12.6 and 18.5 keV, below and above the lead (Pb) L edges, respectively. Typical scan parameters were

120 µm pixel size at 7 ms dwell time, with the largest scan covering an area 545 × 287 mm² collected in 23 h (10.8 MP). XRF mapping of the panel has guided the conservation treatment of the painting and the revelation of previously obscured features. It has also provided insight into the process of making of the painting. The informative and detailed elemental maps, alongside ultra-high-definition scans of the painting undertaken before and after varnish and over-paint removal, have assisted in comparison of the finely painted details with the London paintings. The resolution offered by the combination of imaging techniques identifies pigment distribution at an extremely fine scale, enabling a new understanding of the artist's paint application.

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1 Introduction

A portrait of Henry VIII painted on oak panel dated from 1535 to 1540 was acquired in 1961 by the Art Gallery of New South Wales in Sydney (Fig. 1). In 2014, the painting was examined in the light of recent research undertaken at the National Portrait Gallery (NPG) in London on a group of early Tudor portraits that included four versions of similar composition, two of which are shown in Fig. 2. All five paintings share compositional features, although none of them is an exact copy of the other with differences in costume details, the position of the fingers and the measurements of each panel.

The Sydney Henry VIII painting had not been on display for many decades due to the poor condition of varnish and restoration paint layers. Initial investigations suggested that although some original glazing layers appeared to have been lost and there were some damages to the original paint layers, a conservation treatment would allow the work to



Fig. 1 Portrait of Henry VIII, 1535–1540, oil on oak panel, 54.5 × 38.0 cm, Art Gallery of New South Wales. Purchased 1961. Before recent conservation treatment

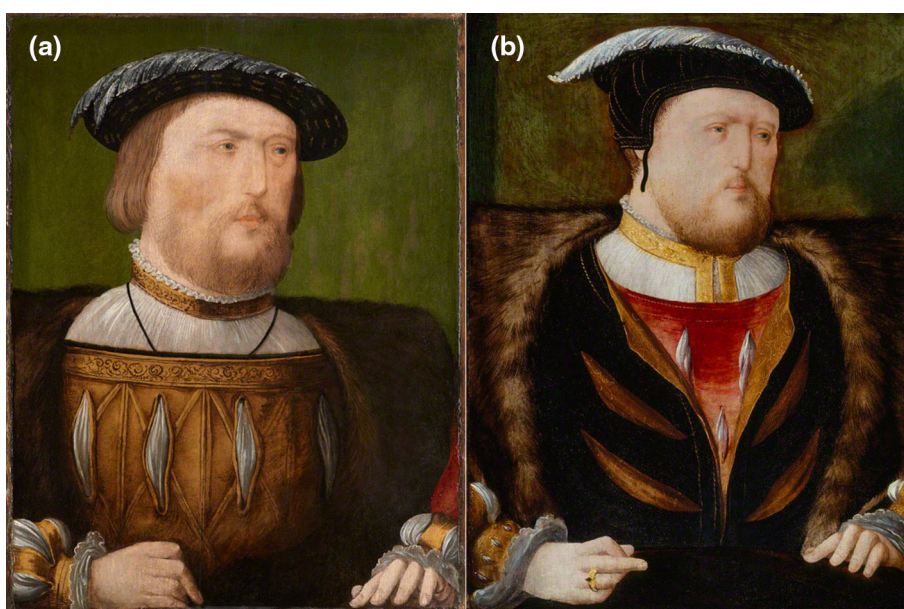
be exhibited without the obscuring and discoloured restorations that had been applied over time.

Little is known about the artisan workshops that may have been involved in the production of these early English portraits. Authorship of the Sydney painting (and the similar works in London) has been, for many decades, attributed to an anonymous Anglo-Flemish workshop. It is not clear whether the five paintings of Henry VIII derive

from a single workshop or were produced by a number of different workshops or artists. Little associated documentation on London workshops and artistic practice prior to 1540 has survived and so the paintings themselves are potentially the only source of insight into these questions. Roy Strong, Director of the National Portrait Gallery (1973–1987) writing about these paintings in 1982, noted the problem of trying to understand the source and authorship; “time and again we return to the central and imponderable issue of marrying the documentary evidence, rarely less than cryptic, to the surviving artefacts of the period” [1]. Strong further suggested that analytical studies and imaging techniques of the paintings have the best potential to provide new insight into authorship and workshop practice.

In order to assess how the Sydney painting might relate to the known group of early Tudor portraits in London, a full technical study was initiated at the Art Gallery of NSW including; infrared studies to look for underdrawing, photography in ultraviolet light to compare fluorescence of varnish and paint layers, dendrochronology of the oak panel for dating, sampling of microscopic paint samples in cross section to examine the layering of the paint and transmission X-radiography to image the elementally heavy pigments such as lead white used in ground preparation layers and white paint. The results of these analytical and imaging techniques were compared with the same techniques on the London paintings as communicated through personal correspondence, published on the *Making art in Tudor Britain* website, in the catalogue of the exhibition of the paintings and in a recent technical paper [2–4].

Fig. 2 a King Henry VIII, oil on panel, circa 1535–1540, 58.4 cm × 44.5 cm, © National Portrait Gallery, London, Gift of Sir Geoffrey Langdon Keynes, 1948 (NPG 3638). **b** Henry VIII, circa 1535–1540, oil on panel, 57.2 × 42.5 cm, © National Portrait Gallery, London. Purchased 1904 (NPG 1376)



Unfortunately for the clarity of the X-radiograph of the Sydney Henry VIII painting, the fragile and badly cracked oak panel had been supported at the back with the addition of balsa wood strips approximately 5 cm wide laid in a vertical direction. The adhesive used to attach the strips contains chalk and where it is thick between the balsa wood strips it appears as bright white vertical lines in the X-ray image (Fig. 3a). This created difficulty in the use of the X-radiograph as an aid to image the paint layers as it caused considerable visual interference.

The X-ray fluorescence (XRF) technique of synchrotron-sourced scanning microscopy has the ability to provide clarity of the distribution of lead-based pigments throughout the painting without the interference created by the structural backing of the painting (Fig. 3b). In addition, synchrotron-sourced X-ray mapping offers other elemental distributions that are not possible with X-radiography.

This paper describes the unique capabilities of XRF spectroscopy mapping at the high resolution offered by the synchrotron source and the fast acquisition Maia X-ray detector used at the Australian Synchrotron. Only a small number of paintings to date have undergone full synchrotron-sourced mapping since the first major study involving van Gogh's *Patch of grass* in 2008 [5]. The field is rapidly developing, and the scanning XRF analysis of paintings and archaeological artefacts has been recently reviewed using both synchrotron [6, 7] and laboratory-based X-ray sources [8]. The Henry VIII painting provides an excellent case study of the ability of the synchrotron-sourced XRF mapping technique to provide images of high

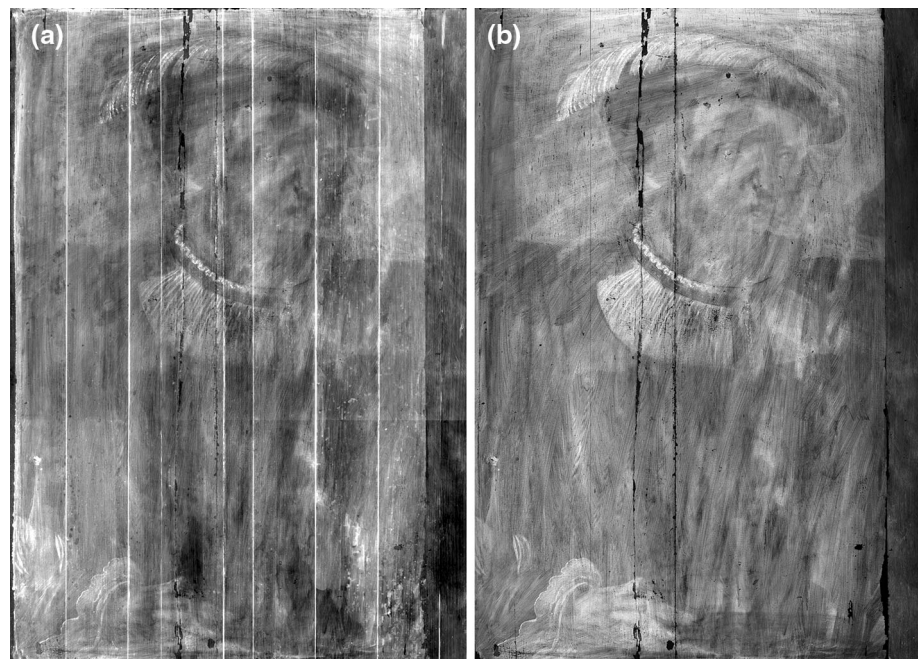
resolution to inform the understanding of the materials and techniques used in the painting.

The painting was also scanned at 1200 dpi before conservation treatment and after removal of varnish and restoration layers. These images provide highly resolved details of features of the painting for technical comparison with photomicrographs taken of the London paintings. The global nature of these scans facilitates thorough comparison with all the corresponding details on the related versions without the need for multiple individual photomicrographs.

2 Early Tudor painting and the evolution of English portraiture

The first half of the sixteenth century was a time of growing need amongst the nobility for the creation and dissemination of their embodied likenesses. This demanded artistic ability that did not exist in England at the start of the century. Henry VIII's court assembled and maintained a workshop of practitioners largely recruited from the Low Countries, Ghent and Bruges and the Court of Burgundy, which provided the model for the Tudors. These were not portrait painters but skilled artisans capable of producing sumptuously illuminated manuscripts and legal documents, portrait miniatures as well as panel paintings and a whole range of other artefacts. As far as can be ascertained, there were only a small number of foreign artists working in the city in the first half of the sixteenth century, and none of

Fig. 3 **a** X-radiograph and **b** X-ray fluorescence map of the element lead 18.5 keV



any standing prior to the mid-1520s. Surviving portraits from this period not only document the emergence of the genre of portraiture in England, but also the transition from the reliance on imported talent to the development of native practitioners.

Artists develop a certain way of working, framed by the conventions of their training and reflecting evolving aims as well as personal idiosyncrasies. These practices, the materials used and techniques deployed, shaped by the prior development of their practice and constrained by particulars of location and time, are distinctive and characteristic. In the absence of historical documentation, the forensic combination of close scrutiny and the scientific identification of materials can recognise such distinctive organisations of matter and begin to elucidate their origins. While we would expect a workshop engaged in collaborative production of artefacts to manifest some variation in method, we should also be able to recognise certain correspondences enabling us to identify relationships and classify accordingly. This is particularly so when the workshop is producing images in series.

The four London-based Henry VIII paintings have previously been seen as part of a broader group of Tudor portraits of other noble sitters, all potentially produced in the same workshop and assigned to an anonymous painter called the Cast Shadow Master, “in reference to a shadow which appears almost like a signature in all of them” [1]. The production of the Cast Shadow paintings begins in the 1530s and coincides with a period of palace decoration necessary to adorn the interiors of Whitehall and Hampton court. One question posed by the *Making art in Tudor Britain* project team was whether the Cast Shadow group were all carried out by the same hands or whether they are connected only by the formal attributes of their composition. Technical analysis demonstrated that paintings such as Edward IV (NPG 2457) and Henry VI (NPG 3542), for example, are distinctly different in technique and handling from the Henry VIII panel (NPG 3638) (Fig. 2a), based on comparative assessment of the quality of the brushwork and paint handling and would therefore seem to derive from separate workshops [3]. Due to the absence of the signature cast shadow on the Sydney Henry VIII painting when first examined, the question was whether it could even be included in the broad Cast Shadow group.

Two of the Henry VIII paintings in the National Portrait Gallery (Fig. 2) and a third painting at the Society of Antiquaries share techniques so similar that it has been suggested in the light of the *Making Art in Tudor Britain* investigation, that they are likely to have been produced by the same workshop or person. The shared features of these paintings are similarities in paint application as seen through comparative photo-micrograph studies. The question for the technical study of the Sydney painting was

whether the painting shares the features which link the other three London paintings together. If so then through comparative analysis we might be able to characterise the group of related panels and begin to identify them with the output of a workshop, operating in London in the 1530s and 1540s at a time when we know very little about their activities.

3 Experiment

The X-radiograph of the portrait of Henry VIII was undertaken at the Art Gallery of NSW using a General Electric Inspection Technologies Eresco MF4 X-ray unit and AGFA CR Tower cassette NOPD. The exposure was at 40 kV 5.0 Ma for 30 s.

The scanning XRF mapping of the painting was performed at the X-ray fluorescence microscopy (XFM) beamline of the Australian Synchrotron [9]. Scans were conducted with a monochromatic incident beam ($\Delta E/E = 10^{-4}$) produced by a Si(111) double-crystal monochromator at 12.6 and 18.5 keV, corresponding to energies below and above the lead (Pb) L edges, respectively. The beam was focussed with a Kirkpatrick–Baez (KB) mirror pair to a spot size of approximately $10 \times 10 \mu\text{m}^2$ horizontal \times vertical ($h \times v$). The beam intensity was measured with a nitrogen supplied ion chamber upstream of the KB mirrors.

As lead (Pb), in the form of the pigment lead white, is one of the major elements present in the painting, the fluorescence signal from the lead L edge excitation can dominate the detector counts at higher keV at the expense of sensitivity to other elements. Thus, the painting was scanned twice using two excitation energies: 12.6 and 18.5 keV. The 12.6 keV scan, which is 435 eV below the Pb L3 edge, avoids Pb L fluorescence and provides better sensitivity to the lighter elements present such as calcium (Ca). The 18.5 keV incident energy scan, which is approximately 2.6 keV above the Pb L1 edge, provides Pb maps and accesses to other elements with excitation energies between 12.6 and 18.5 keV, such as strontium (Sr).

The X-ray fluorescence was collected with the Maia 384A detector, which consists of an array of $384 \times 1 \text{ mm}^2$ silicon detectors axially oriented in backscatter (180° to the incident beam) geometry and is specified to function 10 mm from the sample [10]. The painting is slightly bowed, and it was placed approximately an extra 2 mm farther from the Maia detector as a precaution. The Maia detection system acquires data via continuous fly scanning with zero readout overhead. The painting was raster-scanned at 16.4 mm s^{-1} , yielding a dwell time of approximately 7 ms per $120 \times 120 \mu\text{m}^2$ pixel. The largest scan covering an area $545 \times 287 \text{ mm}^2$ was collected in 23 h (10.8 MP).

The painting was mounted in a landscape orientation for scanning (Fig. 4). In this orientation, the vertical scan range of the apparatus was less than the dimension of the painting, thus precluding a single scan of the complete painting. After completion of the scans at 12.6 and 18.5 keV, the painting was rotated 180° in the sample mount to examine the remaining area. Several millimetres of overlap between scans were obtained for stitching together the elemental maps with imaging software.

The photon flux was controlled in part by adjustment of a set of slits to optimise the count rate on the Maia detector (approximately 10^6 counts s^{-1}). The photon flux incident on the painting was 2×10^9 photons s^{-1} at 12.6 keV and 2×10^8 photons s^{-1} at 18.5 keV.

Radiation damage is of concern when using high-intensity X-radiation with artworks. The risk of radiation damage is very low with the Maia detector because the actual time any part of the artwork is in the X-ray beam is on the order of milliseconds. Tests on radiation damage of cultural materials have shown that thousands of times more X-ray dose than used in this experiment is necessary to impart radiation damage [11]. The deconvolution of the full-spectral XRF data into elemental maps and elastic and inelastic scatter maps was performed using a matrix transform method called dynamic analysis [12] implemented in the GeoPIXE software suite [13]. Further details regarding the scanning of paintings at the XFM beamline can be found in previous work [14].

The painting was also scanned at two stages of its conservation treatment in ultra-high resolution by LuxLab, a joint project between the Laboratory for Innovation in Galleries, Libraries, Archives and Museums (iGLAM) at the National Institute for Experimental Arts, University of

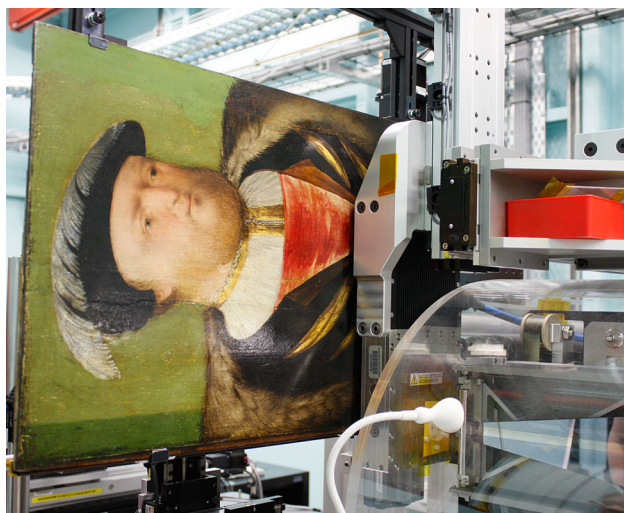


Fig. 4 Painting mounted at the XFM beamline. The Maia detector is directly in front of the painting

NSW, and the Advanced Imaging Laboratory at Kyoto University. It will be scanned a third time at the completion of its treatment. The LuxLab system incorporates a trichromatic CCD camera, macro lens and scanner controller modules developed by the Advanced Imaging Laboratory. It allows for single- and multiple-pass scanning at 1200 dpi, permitting analysis at the scale of 20 μm per pixel.

4 Results and discussion

The Sydney Henry VIII painting is an excellent case study for XRF mapping as it utilises a small number of pigments: copper-based green, mercury-based vermilion, iron- and manganese-based oxide browns, calcium-based ivory black, gold, lead white and chalk. Thus, the distribution of almost all the paint layers can be examined by their elemental fingerprint. The red lake pigment (principally organic) on the tunic is the only pigment identified on the work that is not imaged with this technique. A red lake pigment made from madder, with similar bright fluorescence under ultraviolet light to the lake pigment on the Sydney painting, has been mapped by portable XRF on a painting by Rembrandt dated 1669, by the presence of potassium in the dye [15], but potassium does not correlate with the deep red pigment on the tunic of the Henry VIII painting. This may be explained by different types of dye processing through time and across countries.

4.1 Lead map (18.5 keV)

Several new discoveries about the making of the painting are disclosed by the XRF map of the distribution of lead-based pigments (Fig. 3b). The lead white priming layer that lies over the chalk ground and under the coloured paint layers is clearly imaged in the lead map. The brush strokes used to apply the priming radiate diagonally across the panel from a starting point at the upper right and describe a brush width of approximately 2.5 cm (1"). Similar diagonal brush strokes in the lead white priming layer are described as texturally visible ridges on parts of the Henry VIII painting at the National Portrait Gallery, London (Fig. 2b), but are not seen in their full distribution across the panel [16]. A comparison of techniques of applying the lead white ground layer in a diagonal pattern may be an important clue to a shared workshop practice if the ground application on the London painting was to be similarly imaged. The detail of a hidden slashed sleeve of the right proper arm is also revealed in the XRF lead map of the Sydney painting, despite being obscured by a broad area of brown restoration paint (Fig. 5a). These two features bring the Sydney painting closer to the London works in the

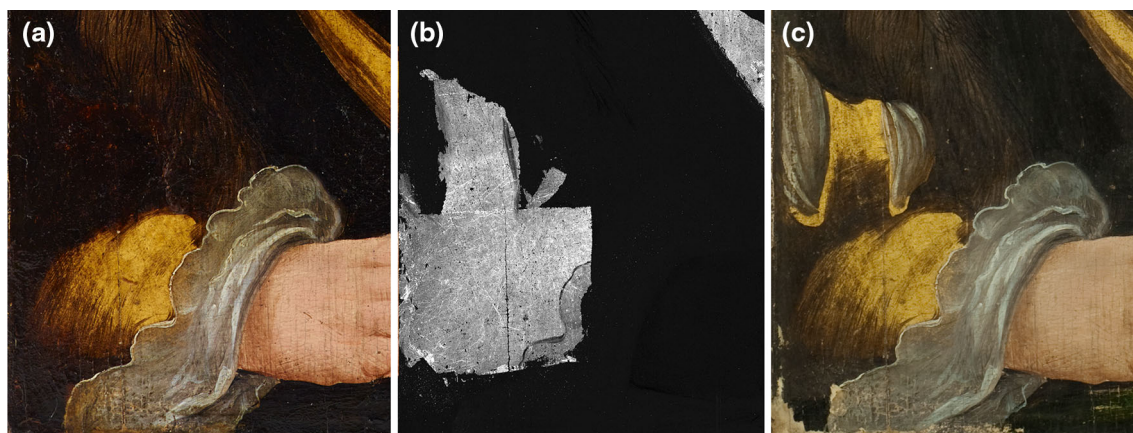


Fig. 5 **a** Lower *left* sleeve detail before treatment, **b** gold XRF map (12.6 keV) of lower *left* sleeve showing use of gold leaf and **c** original *slashed* and gold leaf sleeve revealed after removal of restoration paint

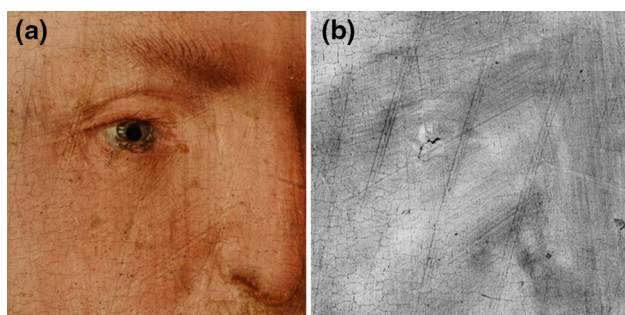


Fig. 6 **a** Right proper eye detail and **b** same area in lead XRF map (18.5 keV) showing *diagonal* patterns made by blade used to scrape lead *white* priming layer prior to applying *coloured* paint layers

comparison of priming application and compositional similarities.

An unusual feature of the Sydney painting is also disclosed by the lead XRF map. Distinctive marks were noted on the painting as depressions in the paint film throughout the area of the face (Fig. 6a). These are clearly indicated in the lead map as three parallel dark lines at set spacing of 2 and 1.5 mm (Fig. 6b). The channels in the lead priming are likely caused by a sharp scraping instrument used to smooth the priming layer after its application. Either small burrs or particles caught on the blade have dug these consistently distanced channels in the lead white priming layer. It is possible that scraping of the priming layer on the Sydney painting was conceived as a solution to reduce the textural effect of a roughly brushed priming layer.

4.2 Copper map (12.6 keV)

The narrow vertical passage of green paint extending down the right edge of the panel from top to Henry's proper left shoulder (Fig. 7a) was shown by XRF mapping to be principally a chromium-based green pigment. As the metal

chromium was not known until its discovery in 1797 and did not appear in pigments on artist's palette until the nineteenth century [17], this cannot be original. The chrome green paint is also covering a triangular passage of paint. The copper XRF map shows that the obscured area was painted originally in copper-based paint of a slightly higher concentration, that is a copper-rich green (Fig. 7b). Subsequent removal of the chrome paint during conservation treatment revealed a partial shadow of the hat cast on the background as a deep green (Fig. 7c). Examination of the wood support had demonstrated that the entire vertical strip along the right edge was a later addition, and the difference in the paint composition between this addition and the rest of the painting is visible in the chrome (12.6 keV), copper (12.6 keV) and lead (18.5 keV) XRF maps. Another painting on panel was the source for the additional oak strip along the right side, as a finely painted sheaf of wheat on a brown background was revealed under the chrome green paint, suggesting that a source for the replacement wood might be from a Netherlandish genre painting. The loss of a significant part of the original painting along the right edge accounts for the lack of a full cast shadow and left proper arm, and this realisation places the Sydney painting of Henry VIII more firmly with the four London-based paintings.

4.3 Mercury map (12.6 keV)

The synchrotron-sourced XRF maps are well resolved and sharply defined using a pixel size of 120 μm . This is crucial in the use of the XRF mapping images to locate the extent and edges of losses and damages on paintings. The XRF mapping of the Henry VIII painting also makes visible the variety of brush sizes and various techniques of paint application by the artist. The map for mercury for example describes a red vermilion pigment (mercuric sulphide) that

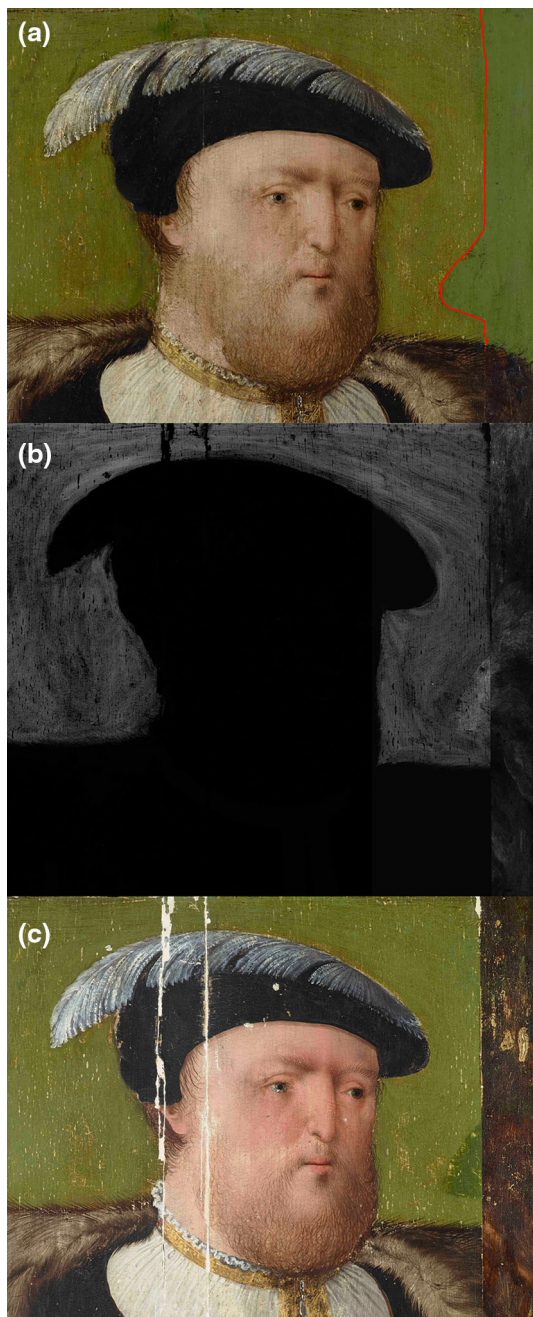


Fig. 7 **a** Detail before treatment indicating chrome green over-paint to right of red line, **b** XRF copper map (12.6 keV) and **c** same area after removal of over-paint showing remnant of shadow of hat and added panel along right side

has been used to model the flesh tones in the face (Fig. 8). The famous red beard of the sitter is painted with brush strokes less than 0.5 mm wide. The depiction of the subject's fur cloak utilises similarly fine brush strokes, but vermilion is apparent only in the fur at the shoulder where the light is depicted penetrating through the hairs and appears redder in comparison with the fur throughout the remainder of the cloak.

While XRF mapping has provided useful information regarding elements of the painting both hidden under paint layers and visibly lost through abrasion, the identification of original from non-original paint layers can be difficult if both were painted with pigments containing the same element. The hand of the sitter at the lower left and the cushion across the foreground of the painting both demonstrate these enhancements and limitations in the XRF mapping technique. For example, the map for mercury reveals a hidden finger on the right proper hand (Fig. 9b). The modification of this finger into a straight orientation is also visible in the mercury image along with area of damage and paint loss. There is some difficulty in deciding which is the original finger and whether this is the artist's own modification to straighten the smallest finger, or a later restoration. In this determination regarding non-original paint layers on the cushion and hand, which were painted with similar pigments to the original paint layers, other examination techniques that demonstrated the presence of paint which flowed over cracks in the aged paint film were used to assess the originality of paint layers. In both the curled finger and copper-based green cushion, it was assessed that the overlying paint layers were non-original, thus informing the decision to remove them (Fig. 9c).

4.4 Gold map (12.6 keV)

Gold leaf has been used by the artist around the neck and in the slashed vest and sleeves, but is not imaged in the conventional X-radiograph of the painting (Fig. 4a). Because of a heavy atomic mass, the leaf form of gold is extremely thin and does not significantly prevent X-ray penetration. Synchrotron-sourced XRF mapping has demonstrated a unique capability to detect and locate extremely small amounts of gold including, for example, in leaves from eucalyptus trees growing over gold deposits [18]. XRF mapping of gold on the painting of Henry VIII reveals the straight cut edges of the applied gold leaf sheets even though they are hidden under paint layers later applied by the artist (Fig. 5b). They appear to have been applied with a mordant technique (laid on oil or glue size) due to the minimal overlap seen between sheets of gold laid side by side. Crease and fold lines created during the gilding process are visible as sharp fine lines, but visible too are the more diffuse variations in the gold thickness, called lamellae, created during the beating of the gold into thin leaves [19]. This information seen in the XRF gold map of the painting provides an extraordinary documentation of gold leaf technology of the period. Although gold leaf has previously been imaged on a painting with terahertz radiation, the detail seen in the synchrotron-sourced XRF map of Henry VIII is unparalleled [20].

Fig. 8 **a** Detail of head before treatment and **b** detail of mercury XRF map (12.6 keV) of head and shoulder area

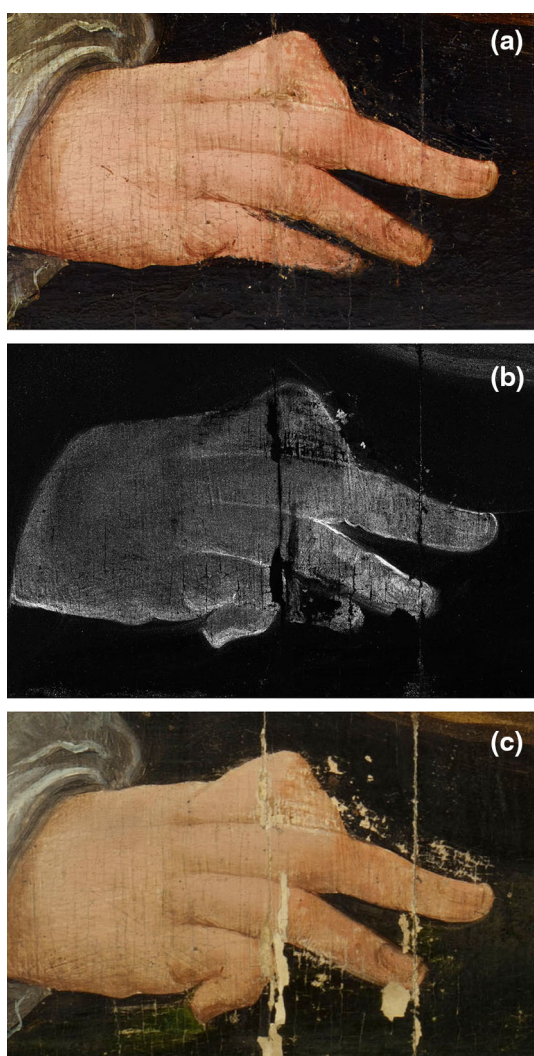
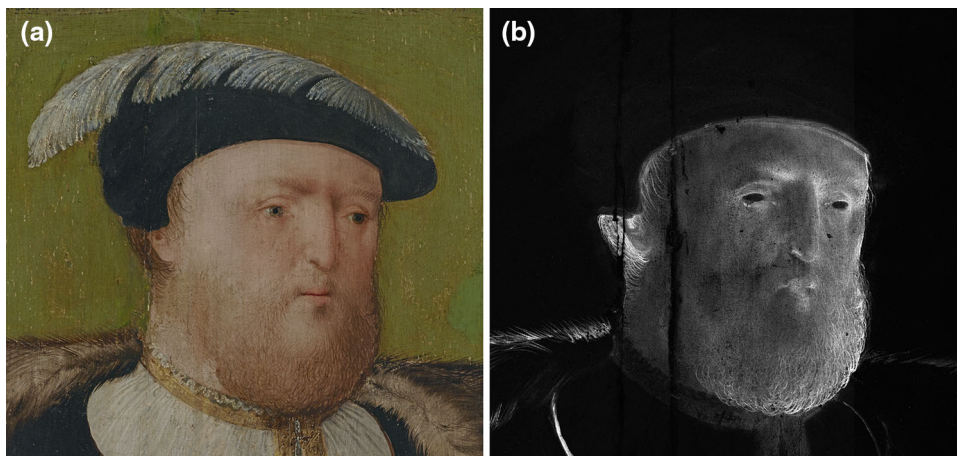


Fig. 9 **a** Right proper hand detail before treatment, **b** mercury XRF elemental map (12.6 keV) and **c** after removal of over-paint

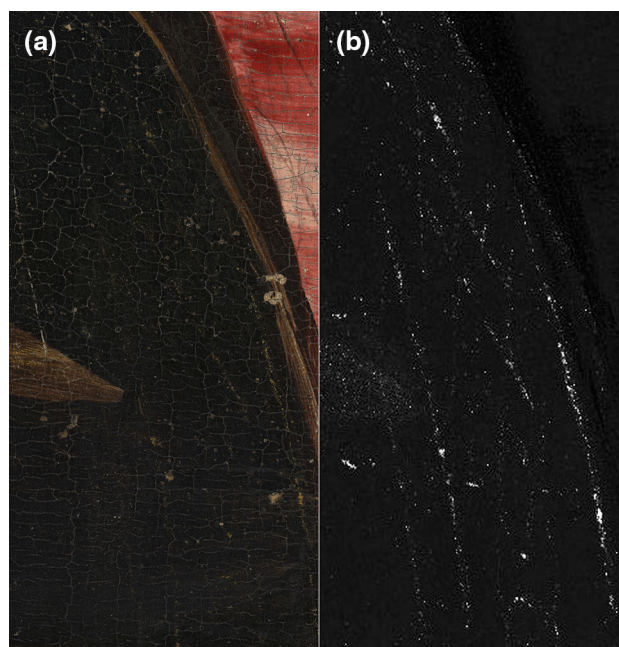
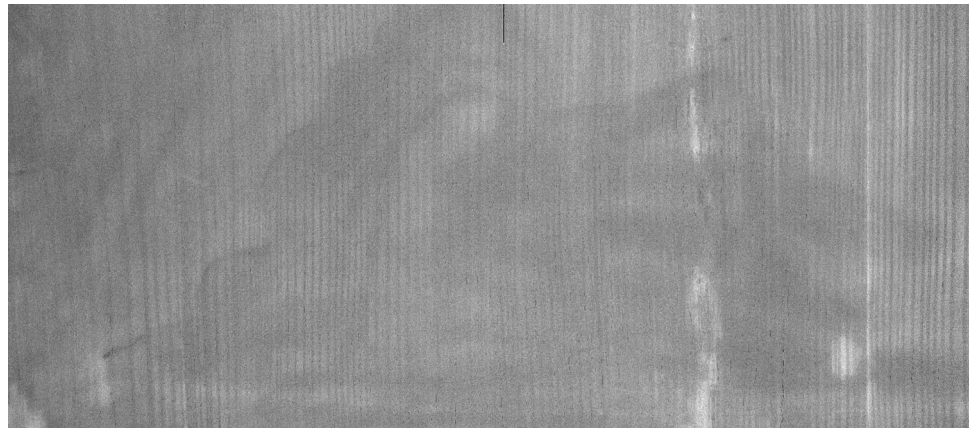


Fig. 10 **a** Detail from scanned LuxLab image before treatment showing opening edge of *black coloured* vest with no visible decoration and **b** gold XRF elemental map (12.6 keV) showing remnants of gold decoration in criss-crossed pattern

A second type of gold application was found on the painting with XRF mapping. Remnants of decoration on the edges of the black vest and along the top of the red tunic, all but lost probably through previous restorations and cleanings, can be seen in the XRF map for gold as faint fine lines with criss-crossed pattern (Fig. 10). These painted parts are likely made from gold leaf ground into powder and mixed with a binder (sometimes called shell gold) and applied with a brush. This type of gold painting is rarely

Fig. 11 18.5 keV elastic scatter map of lower left area of hand showing detail of wood grain in the oak panel as *vertical lines* of various density



seen on paintings of this age due to its vulnerability to loss from abrasion and wear of the surface.

4.5 Elastic scatter map (18.5 keV)

The elastic and inelastic (Compton) scatter XRF maps provide complementary information to the elemental maps. Lighter elements are good Compton scatterers, and it has been noted that Compton maps can be excellent for imaging canvas supports in paintings [14]. The wood grain of the support on Henry VIII was visible with the Compton maps at both 12.6 and 18.5 keV, but significantly masked by the covering paint layer structure. The elastic scatter map at 12.6 keV partially revealed the wood grain also, but it too was highly masked. The elastic scatter map obtained at 18.5 keV best revealed the underlying wood grain, with the changes in wood density providing a means of contrast (Fig. 11). This non-invasive data acquisition has been of assistance to the dendrochronological study of the panel, whereby the sequence of seasonal growth ring widths is studied to match the wood to a specific historical date. This is helpful because the top and bottom end edges of the panel, typically used for tree ring dating, have been difficult to precisely document due to the rough cut edge and the presence of embedded varnish and wax. The 18.5 keV elastic scatter map also reveals areas of the wood panel that have been affected by burrowing wood pests.

5 Ultra-high-definition scanning

As the three London panels and the Sydney painting appear to have been produced according to a common scheme (perhaps by a single workshop), a comparative analysis of magnified structures to identify shared materials and techniques is useful for the purposes of attribution. To this

end, the Sydney Henry VIII was scanned before and during treatment at 1200 dpi. The resulting images of $21,400 \times 29,800$ pixels allow for digital projection and magnification at many times the size of the original object. At higher levels of magnification cracks, areas of loss, brush marks and traces of paint invisible to the naked eye become apparent.

The synchrotron XRF maps in combination with the ultra-high-resolution LuxLab scans have also proved effective analytical tools. Similar examples of characteristic features identified under the microscope on the London works can easily be located in the ultra-high-resolution scans of the Sydney painting. Until the advent of large-scale analytical imaging processes, such work may have been carried out using the elemental data from a single-point analysis using a portable XRF spectrometer alongside an isolated photomicrograph image of surface details. The limitation of this process is the relatively large sampling area and the inability to image its exact positional relationship to the wider object.

The holistic comparison of the XRF maps and LuxLab scans thus reveals new insights. For example, examination of the sitter's right eye in both the scan and XRF map pinpoints the presence of a tiny stroke of copper-based blue, approximately one millimetre in length, therefore presumed to contain the pigment azurite (Fig. 12). No other use of blue pigments has been identified anywhere else on the painting. This has provided a further link to the National Portrait Gallery Henry VIII (Fig. 2b) in which azurite has also been similarly identified in the eye.

These high-resolution image archaeologies provide powerful new methods for interpreting objects. The data sets have obvious applications for heritage preservation purposes and provide new opportunities for digital reconstruction. However, the superb fidelity of the images also

allows for the creation of immersive and embodied digital encounters that possess a unique materiality that complements the experience of the original object.¹ In partnership with iGLAM, the Art Gallery of New South Wales is developing an interactive installation to be presented on a 4K system (4000 pixel resolution). The interactive, developed as both an industry tool for conservation analysis and an audience engagement device, will collate the LuxLab scans and XRF imagery in an interface that will allow the user to zoom and pan between the various forms of imaging to uncover historical, technical and compositional meaning from the painting at various stages of its conservation. The exploratory format plays on the phenomenological sympathy between the user peeling back the digital layers of the interactive and the analytical deconstruction of surfaces practised by the conservator. An additional sensory experience is offered by the ethereal nature of much of the XRF imagery, which has the potential to evoke users' memories in unexpected ways, thus providing another avenue of interpretation and experience beyond the mere didactic.

6 Conclusion

The Sydney painting presents at first sight a slightly crude depiction of King Henry VIII. Closer analysis and conservation treatment with the aid of synchrotron elemental maps and ultra-high-definition scanning have revealed a particularly fine picture, a striking image of the notorious Tudor monarch carried out with delicacy and precision. It has also enabled us to discover and unravel modifications to the composition wrought by time and by restoration and piece together a compelling idea of its original appearance before conservation treatment removed the layers of

restoration treatments. It has cast light on its relationship with similar paintings in London and given intriguing insight into the manufacture of such images at the very origin of portrait painting in England.

What we see are clustered passages of real technical excellence set amongst a more workmanlike broader scheme. Powdered and leafed gold is used, there is a minimal sketchy underdrawing, evidence of the use of magnification, extremely precise minute decorative work, and high-quality calligraphic skill. Features are delineated using very finely hatched brush lines, rather than being built up by means of modulation of the body colour, although this effect may be emphasised by the loss of coloured glazing layers through past cleaning practices. These mediaeval techniques would appear to be adapted from practices otherwise applied to the small-scale graphic work of illumination. The quality of execution and the keenly observed nuances of colour and light revealed by paint application, such as the vermillion used to redden the beard at the profile where the light is able to penetrate, suggests that this is not simply a pattern painting mechanically copied from a series but rather a crafted work with its own keenly observed qualities.

To address the questions posed in this paper regarding comparison of materials and techniques amongst the group of works discussed, the XRF mapping technique needs to be applied across the group and also more broadly to establish connection to the output of an identifiable practitioner's oeuvre. However, this case study demonstrates the useful information that could be obtained from such a comparative study. Features disclosed such as techniques for applying the gold leaf and painted gold ornaments, the idiosyncratic methods for applying the lead white ground which were then scraped smooth with a sharp blade, the variability in brush widths, modification to the composition, hidden sequences of execution, as well as imaging the range of pigments in their distribution across the painting are all features uniquely uncovered by XRF mapping. In addition, the assistance given by the elemental mapping technology to the decisions regarding removal of non-original restoration layers is unprecedented in a conservation treatment.

The XRF mapping technique provides detailed structural evidence of the material composition of the painting in its entirety and not just confined to limited discrete locations. It is these aspects to the data, global and comprehensive in character, and revealing of otherwise hidden structures which gives the technique its power as an exploratory and explanatory tool. Furthermore, the synchrotron data in high-definition form enable it to be presented in a layered format in conjunction with ultra-high-definition scans. This facilitates the direct comparison of the maps with a similarly detailed visual image of the

¹ These emerging techniques of digital exploration of objects have profound implications for museological interpretive strategies, offering a shift from formal didactic methodologies to affective, sensory, dialogic and self-driven visitor experiences. See Witcomb [21]. Examples of the successful development of interpretive narratives from ultra-high-resolution scanning can be seen in two interactive systems produced by the Applied Laboratory for Interactive Visualization and Embodiment (ALiVE), City University of Hong Kong, from the scanning of one of the treasures from the collection of the Hong Kong Maritime Museum, *Pacifying the South China Sea*, an eighteen-metre-long nineteenth-century silk scroll. The first system immersed the viewer in a 360° environment, 10 m across 4.5 m high. As the scroll rotates around the screen, 55 animations reconstruct the narratives in an unfurling sequence. The second featured a 42-in. 4K scrolling screen that allows users to pan and zoom the image in great depth, where part of the screen displays historical texts related to the painting, dynamically revealed as the user zooms in and around the image. An important consideration was that the approaches taken respected the mode of viewing originally intended of the object. See Kenderdine [22].

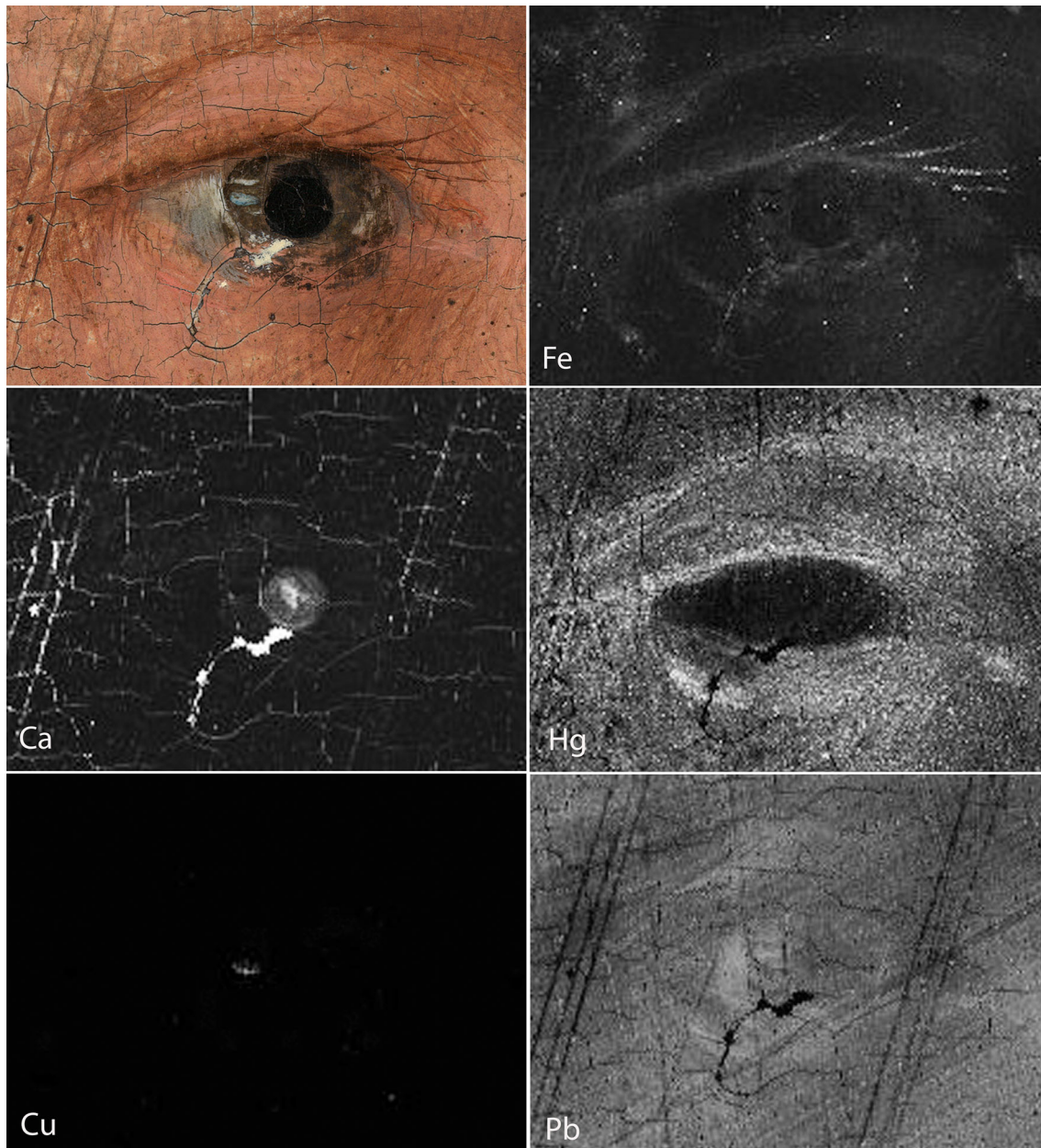


Fig. 12 Detail of LuxLab scan of sitter's right eye after varnish removal alongside XRF maps of same area

paintings surface, producing a very effective investigative, analytical and presentational tool.

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