

The potential of Reflectance Transformation Imaging in Architectural Paint Research and the study of historic interiors: A case study from Stowe House, England

Rhiannon Clarricoates and Eleni Kotoula

Abstract:

Reflectance Transformation Imaging (RTI) has been increasingly used for the recording, documentation, and analysis of cultural heritage. A series of images of a static object, taken in raking light at constant exposure, is synthesized using Polynomial Texture Mapping or the Hemispherical Harmonics fitter, resulting in polynomial texture maps or RTI images. These visualisations capture colour and texture information, reveal low relief detail and emphasise surface topography. RTI has found several applications in the study of painted surfaces, yet it has not been utilised for the study of historic interiors, which are more commonly evaluated through Architectural Paint Research, a process of empirical examination of the painted finishes to an historic structure to establish its decorative history. Typically, this is achieved through a combination of archival research, paint and substrate cross section analysis, and through the careful layer-by-layer exposure of the accumulated paint stratigraphy so that the texture, sheen and colour of each paint layer can be observed.

This study evaluates the use of RTI as an alternative means for the study of historic wall paintings, with an emphasis on the revelation of overpainted designs. Considering the efficiency of RTI in recording and documentation of subtle surface variations, this research explores its use in texture comparisons between exposed, restored and covered areas of the wall painting as a diagnostic tool and for appraising condition.

Keywords: Reflectance Transformation Imaging, Architectural Paint Research, historic interiors, wall paintings, conservation, Stowe House

Introduction

Reflectance Transformation Imaging (RTI) has been largely used for the recording, documentation, and analysis of cultural heritage. [1] A series of images of a static object, taken in raking and oblique light at a constant exposure, along with one or more reflective targets, is synthesized using either Polynomial Texture Mapping (PTM) or Hemispherical Harmonics

(HSH) resulting in polynomial texture maps (PTMs) or reflectance transformation images (RTIs). [2] These visualisations capture not only colour, but also texture information, revealing low relief detail and emphasizing texture topography of surfaces. In the case of painted surfaces, RTI has found applications from the identification of manufacturing techniques, condition assessment, treatment documentation and monitoring, evaluation of conservation materials [3], examination and documentation of wall painting fragments, easel paintings [4], painted statues [5], and ceramics [6], as well as for the analysis of complex superimposed pictographs. [7] In addition, integrated RTI approaches, such as microscopic, multispectral and transmitted RTI has been proposed for the visualisation of painted surfaces. [8]

Although there is a growing interest in understanding the composition and visual appearance of historic paint and sequential decorative schemes, RTI has not been utilized for the study of historic interiors. More commonly, this would be achieved through Architectural Paint Research (APR), a process of examining the painted finishes to the interior or exterior of an historic structure to establish its decorative history. Typically, this is achieved through a combination of archival research, sampling of the paint and substrate layers that are analysed at high magnification in cross-section, and by making careful layer-by-layer exposures of the accumulated paint stratigraphy so that the texture, sheen and colour of each paint layer can be observed. The latter technique is especially important to understand if an underlying scheme is decorative or polychromatic, such as in identifying whether a stencilled or painted scheme has been used. Whilst the APR technique is very effective, the process of exposing underlying paint schemes is destructive, and a high degree of skill and dexterity is required. In some instances, the raised edges of an underlying decorative scheme can be seen in a strong, raking light, allowing the rough composition to be ascertained.

The subject of this study, the East Staircase at Stowe House in England, was chosen as the investigative fieldwork undertaken in 2016 and 2017 revealed the presence of an extensive scheme of grisaille wall paintings, dating from c1740. [9] These paintings had been completely obscured by several schemes of overpaint, and it presented an opportunity to examine the original and later decorative finishes applied in a number of traditional and not so traditional techniques.

Stowe House is scheduled as a Grade I listed building and has a complex architectural history. The Temple family acquired the estate in 1589, but it was not until the late seventeenth century that a house was built by Sir Richard Temple, to the designs of William Cleare. [10] During Viscount Cobham's tenure, the house underwent some of its most significant alterations in the 'grand style', and he engaged many of the most prominent architects, designers and artists of the time to realise his vision, including William Kent, John Vanbrugh and Vincenzo Valdrati ('Valdré'). Cobham commenced work on the gardens in 1713, and in a letter of 1719, Sir John Vanburgh noted that Cobham 'spends all he has to spare ... on the improvement of his house and gardens'. [11] Between 1720 and 1733, major alterations to the house, including the addition of the North portico, were made by Vanburgh, with Lord Percival noting in 1724 that 'within these five years (Stowe) has gained the reputation of being the finest seat in England'. [12] After Vanburgh's death in 1726 the work continued under William Kent, who was then working on a number of designs for structures and temples in the garden in the neo-Palladian style. The North, East and West sides of the house had been extensively rebuilt by 1733, and between 1731 and 1733 a new two-tier portico had been added to the South Front. The East Corridor is thought to be contemporaneous with the North Hall, dating to the 1730s, but the Western and Eastern state apartments were extended from c1740 [13], at which time the staircase was moved eastwards, and the East Staircase and Upper Landing as seen today were constructed.

The wall paintings have been tentatively attributed to the Venetian painter Francesco Sleter, and Stowe House represents his last recorded and most significant commission, having worked for Viscount Cobham between 1731 and 1747 on a number of paintings within the house and gardens. In his eighteenth-century guidebooks on Stowe, Benton Seeley describes the East Staircase - later referred to as the Grand Staircase - as being 'ornamented with ironwork', and refers to 'three paintings by Francesco Sleter, *Fame and Victory*, which survives on the ceiling above the staircase, and two others, *Constancy and Plenty* and *Justice and Peace*', although the positions of these works were not noted, and the walls were described as being 'adorned with 'war-like' pieces'. [14] The paintings cease to be referred to in the Seeley guidebooks after 1798, after which time they are likely to have been painted over, and cross-sectional analysis revealed that over the following 200 years, the paintings were indeed overpainted an additional five times.

This study evaluates the use of RTI for the study of historic wall paintings, with an emphasis on the revelation of overpainted designs. Considering the efficiency of RTI in recording and documentation of subtle surface variations, the research explores the use of texture comparisons between exposed, restored and covered areas of the wall painting as both a diagnostic tool and for appraising condition.

Materials and Methods

During earlier phases of investigation, meticulous examination of the wall surfaces with a raking light was carried out to establish the presence and extent of the painted decoration, with pencils being used to mark out the raised edges of any composition, where visible. Such outlines were evident across the walls from skirting level up to cornice height, from the upper landing, down through the staircase and terminating at the pilaster at the foot of the stairs, suggesting the presence of a series of trompe l'oeil niches, cartouches, overdoor panels, architectural pedestals and ashlar block-work, covering an area of some 400 square metres in total. Localised removal of overpaint revealed trompe l'oeil architectural details and a female figure in a fictive niche, painted in the grisaille technique (see Figs. 1 and 2). The significance of this discovery is particularly high due to the quality and extent of the scheme, and that they are completely unrecorded.

Whilst there had been some degree of success using the raking light technique, the texture of the plaster and the accumulation of overpaint made interpretation of some passages very difficult, and an examination of six representative areas of the wall paintings using the RTI technique were executed and analysed as part of this study. The RTI visualisations were centred on areas that had previously been investigated using the established APR technique, where it was known that the wall painting survived beneath the overpaint. Areas examined on the south wall included an area of sequential exposure of each layer of paint, three areas that had been partially exposed, and an area in the staircase where numerous horizontal and vertical lines could be seen in a raking light, but which remained fully obscured by overpaint. Lastly, an area of the north wall was examined, at the base of a fictive niche, where some sections had been fully exposed and others remained hidden. Please see Fig. 3 for locations of the RTI trials.

The selected areas of wall paintings were visualized in .rti and .ptm file formats. The data capture was carried out using the widely-recognised RTI methodology using a digital SLR camera, a tripod, a light source and reflective spheres. [15] A sequence of raking light images were captured with a static camera at a constant exposure, and the captured scene included one or two of the reflective spheres. The images were uploaded and saved for processing in the non-profit organisation *Cultural Heritage Imaging* (CHI) program, *RTIBuilder*. The sphere in an image was selected, and the program executed sphere and highlight detection. Finally, fitting of the images was completed resulting in a synthesized image, with interactive relighting visualisation of a section of the wall painting. The images were then viewable using *RTIViewer*, a CHI software program partner to *RTIBuilder*, which enables interactive manipulation of the lighting position. [16] Sections of the wall paintings visualised in .rti format could be viewed as if it were lighted from different directions, helping the viewer to better understand the surface topography. The RTI image can be further enhanced through different rendering modes such as through the application of digital imaging filters or by changing the intensity of lights. During viewing, two-dimensional images in .jpg format - as snapshots - can also be generated. In addition to *RTIViewer*, Yale University's *CHER-Ob* (CULTURAL HERITAGE-Object) software was used for the analysis of visualised wall painting areas, including the mapping of revealed overpainted designs and features using annotations. [17] *CHER-Ob* was developed for management of large scale data, analysis and evaluation, documentation and sharing, and provides a unified platform for heterogeneous documentation of historical materials, including two and three-dimensional images, computed tomography and textual information. For the purposes of the present study, *CHER-Ob*'s multilevel annotation framework for RTI images was used as it allows both general annotations for RTI files, as well as point and polygonal annotations, mainly used as pointers for features revealed during the examination of visualisations. Easy organization and retrieval of annotations are possible via the classification schema and the sort, filter and search options. The classification schema includes ten predefined categories that represent a simplified version of the Getty's *Categories for the Description of Works of Art* and also incorporates the capacity for a user-defined one. [18] In addition to the simplification of the classification system, colour coding was also introduced to further enhance interaction with the imaging data. In addition, a live-screen draw application was used as an auxiliary tool for documenting the revealed features during RTI viewing. This is the process of drawing directly

on the screen using an active pen and saving the resultant image. This is not a feature of *CHER-Ob*, as it is used to record shapes appearing on the screen, although it can be annotated in a similar way in *CHER-Ob*.

Normal map visualisations derived from RTIs were generated using the Hemispherical Harmonics fitter (HSH). The average variability of the surface normals was calculated based on data extracted from *ImageJ* software as $\text{standard deviation}/\text{mean} \times 100$, according to the method developed by Marcello Manfredi et al. for the measuring of change in cultural heritage object. [19] This strategy was originally proposed for condition monitoring purposes, but can potentially provide useful information for APR. The resulting average variability values were compared in an attempt to identify patterns of texture variation across the different decorative schemes, as well as restored and overpainted areas.

Results and discussion

RTI visualisations of areas of the paintings, either fully or partly exposed, emphasised their textural topographies and revealed information about the paint application, as well as its condition. For example, RTI views of an exposed area of wall painting on the North wall in Fig. 4 show low relief detail relevant to the condition of the wall painting, with the material loss, crack and the rough texture of the plaster substrate being emphasised. Information about the layering is clearly visible around the edges of the exposed area, as well as individual brush strokes. Additionally, areas of variation in texture, such as the detail in the upper right corner, have been emphasised. The series of visualisations in different rendering modes in *RTIViewer*, as seen in Fig. 4 B-H, were generated from a single lighting angle and demonstrate the available options for further mathematical enhancement via the interactive re-lighting of images. The default RTI visualisation, that is, without mathematical enhancement, is significantly intensified using the 'diffuse gain' and 'specular enhancement' rendering modes, particularly with regard to the perception of shape, as demonstrated by the enhanced visualisation of detail features. However, colour visualisation is not reliable as it happens in the 'normals unsharp masking' mode. Otherwise, the RTI rendering modes digitally enhance the images by applying mathematical transformations commonly used in 2D image processing software. In particular, the 'image unsharp masking' mode provides enhanced views of the texture and brush strokes, whereas the 'coefficient unsharp masking' mode emphasizes the reflectivity of surfaces.

During the 2017 investigations, guided by a photomicrograph of a cross section, a sequential exposure of each of the subsequent decorative schemes was carried out in an area on the South wall, as seen in Fig. 5. The more modern, resin-based emulsion paints (as seen in Fig. 5 schemes 5 and 6) could be removed using a cotton swab and organic solvents or, where failing, could be removed using a small spatula. Larger tracts of paint could also be removed down to scheme 2 using a gelled benzyl alcohol poultice, carefully monitored and timed. Removal of the earliest lead oil paints from the original scheme of wall painting was carried out using a scalpel under magnification, so the use of personal protective equipment was imperative. Due to the roughened texture of the original scheme (scheme 1), only a mechanical method could be employed to remove the overpaint from the peaks and troughs on the surface. Chemical methods of exposure were not able to retrieve the surface texture in the same way and, as schemes 1 and 2 share the same solubility parameters, chemical techniques of exposure risked damaging the high points and reducing surface normal variability. As demonstrated in Fig. 6, RTI provides an enhanced visualisation of these exposures when compared to 2D images, and more clearly demonstrate the differentiation between the colours and cumulative textures of each scheme.

RTI views of the overpainted areas provide useful information about the condition of the underlying paintings and previous interventions that alter the surface texture. In this instance, restored areas are much smoother, with the successive schemes of overpaint diminishing the roughened texture of the plaster substrate, and the distinctive brush strokes beneath, yet this is barely visible in any static 2D image because of the subtle texture variation. However, this is clearly differentiated in the RTI visualisations, which provide important evidence of previous restorations and repairs.

Figs. 7 and 8 allow for comparison between static 2D digital images of sections of the South and North wall with detailed RTI visualisations. Numerous hidden restorations are revealed using the RTI visualisation, such as the details shown in Fig. 7 C and Fig. 8 E-F. Through the investigations carried out to date, these restorations appear to be repairs made by decorators prior to each new phase of decoration, and relate to cracks in the plaster substrate and defunct fixtures and fittings. In most instances, the areas of damage appear to have been scraped back and then filled using various filling materials, then painted over, with or without sanding. No analysis of the filling materials has been undertaken at this stage, but they appear

to be gypsum-based. Unsurprisingly, whilst RTI can help to locate the presence of earlier, less visible phases of repair, it cannot be used to identify the type of repair. Other areas of repair were, to a certain extent, visible as they are of a smoother texture, but conventional photographic techniques alone cannot provide such an accurate record of repair as the RTI technique as shown in the examples illustrated in Figs. 7 A and 8 B-C. Where there are clearly visible features, such as the deep crack with an evident geometrical transformation, as shown in Fig. 7 B, RTI visualisation also provided an enhanced perception of shape.

Computing the average percentage variability of the surface normals via the mean values and the standard deviation of 12 sample areas from the North wall - as mapped in Fig. 9 - provides quantifiable evidence for the differentiation between restored, overpainted and exposed parts of the wall painting.

And as shown in Table 1, restored or repaired areas tend to have lower average variability of surface normals, ranging between 0.5 and 0.9%, while overpainted areas have higher values from 1.1 up to 1.8%, and exposed areas have values up to 3%. Further research is required to reach safe conclusions regarding the average percentage variability of the surface normal, as the lower values of restored areas might depend on the material characteristics, the method of application and its thickness. Similarly, overpainted areas might take higher values because of the multiple designs existing underneath. The higher values of the exposed areas of the wall painting are due to the texture of the original plaster, which was recovered during the mechanical removal of the overpaint, although some subtle variations may occur depending on the thoroughness of removal and through inadvertent scalpel nicks.

RTI visualisations of the wall surface may also be helpful for the identification of completely covered-over designs, as the low relief detail of the brush marks are more readily discernible. Characteristic examples are shown in Fig. 10: in Fig. 10 A, an exposed line is distinguishable in the RTI visualisation using the 'specular enhancement' rendering mode as it continues beneath the overpaint. In the detail Fig. 10 B, three lines on the left of the exposed section and one line on the right, are clearly visible, although the interpretation of visible lines may not have been possible without the context of the exposed tracts. In Fig. 11 B, an overpainted

area to the South wall of the staircase visualised in RTI reveals numerous horizontal and vertical lines, possibly a stylised Greek key design, visible in the rendering mode.

Although these results are encouraging, the revelation and interpretation of overpainted motifs is a challenging task. The current condition of the scheme of wall paintings in the East staircase at Stowe is a result of a long and complex history, due to a series of redecoration schemes and concealed, historic repairs as evident from the paint archaeology. The RTI visualisations emphasise the textural topography of the wall painting, including the substrate, brush marks, and the raised edges of the decorative motifs, as well as areas of damage and repair. However, these can be difficult to interpret when superimposed. A characteristic example is shown in Fig. 12 A. In an attempt to assist with the interpretation of visible features, the live-screen draw application was employed. The features revealed via RTI were traced during viewing and colour grouped according to their characteristics, either as painted designs, traced in blue, or areas of repair, traced in magenta (see Fig. 12 B). The areas identified as repairs disrupt the continuity of the revealed lines of the wall painting, and as a result it is particularly difficult to interpret the composition of the painted designs.

Locating textural differentiation using the RTI visualisation is a relatively easy task and interactive relighting can successfully accentuate details, given that the appropriate software for viewing and documenting the findings has already been developed. However, in practice, identifying each individual feature is difficult and time consuming, and the results are often ambiguous. The process requires not only a familiarity with the software for handling .rti and .ptm files, such as the *RTIViewer*, but also an understanding of the deterioration of wall paintings and commonly used restoration methods, as well as some knowledge of the iconography of the period and techniques of the artist. As such, interdisciplinary collaborative research may be necessary for the successful interpretation of the data. This may be made more possible by using the *CHEROB* software, which encourages interdisciplinary communication and assists researchers in the documentation and development of projects. For example, Fig. 12 C shows the visible features mapped as surface annotations. In this case, red was the only colour used as all lines correspond to the revealed lines of the wall painting - of course it is possible to use different colours for the categorization of features according to their nature. Comments and images included in annotations can also provide necessary

justification and further explanation. Individual projects can also be merged and the annotations are searchable.

Evaluation

At the onset of this investigation it was hoped that the RTI technique could be proposed as a supplementary technique in the APR toolkit, providing a less time-consuming, non-destructive process of visualising overpainted designs by utilising readily available equipment and free-to-download software. Whilst there is some potential for this, the case study data discussed here were often too difficult to interpret accurately. The complexity of the wall paintings visualised, as well as the lack of previous research on RTI visualisation of historic interiors were contributing factors to the problems with interpretation.

The researchers suggest that at the moment the continued use of the traditional technique of manually exposing the primary scheme of wall paintings is preferable as it gives significantly more information. However, RTI could be utilised as a supplementary technique in the early stages of an APR project as a way to identify potential areas with hidden decorative schemes beneath.

Having said this the computation of the average percentage variability of surface normals and the enhanced view of planar deformations gave very useful information about previous repairs that were not readily discernible. As such, RTI could be a very useful tool to appraise the condition of paintings concealed beneath the surface, which would be especially important in determining the feasibility of any overpaint removal. It is also possible that the efficacy of the RTI technique used here may perform better where there are fewer schemes of overpaint. On the other hand, conservators would still be required to familiarise themselves with RTI data capture, processing and further analysis, and also have the capacity to store and process the large quantities of data captured.

Open access software, the well documented data capture and processing workflows, and the low-cost, readily available equipment are important parameters for the further adoption and wider use of RTI within the field of APR and the study of historic interiors. Beyond the research

benefits of RTI and its contribution to the study of subtle surface texture variations, emerging technologies relevant to online digital-based scholarship for cultural heritage, and in particular the web RTI tools such as *WebGLRTIMaker* and *WebRTIViewer*, enable online publication of high-resolution RTI images. [20] These tools provide enhanced options for public engagement and dissemination and users can explore digitised artefacts using online and interactive relighting modes. Similarly, the automatic report generation in web-based format and video generation features of the *CHER-Ob* platform facilitate easier online publication and dissemination to a wider audience.

Conclusion

This article has presented the first application of RTI technology for the study of historic interiors, using Stowe House as a case study. It has laid down the foundation of studying the potential to use RTI applications for APR and the study of historic interiors. Undoubtedly, further work is necessary regarding the limitations of the technique, but results indicate that RTI visualisations can be useful for the examination, recording, condition mapping and documentation of historic wall paintings. Furthermore, the study evaluated the potential of RTI for the revelation of overpainted motifs, which, whilst initially promising, requires some refinement, particularly in relation to interpretation, to be beneficial at this moment in time.

References/footnotes:

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[13] Bevington, *Stowe House*, 12.

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Figures:

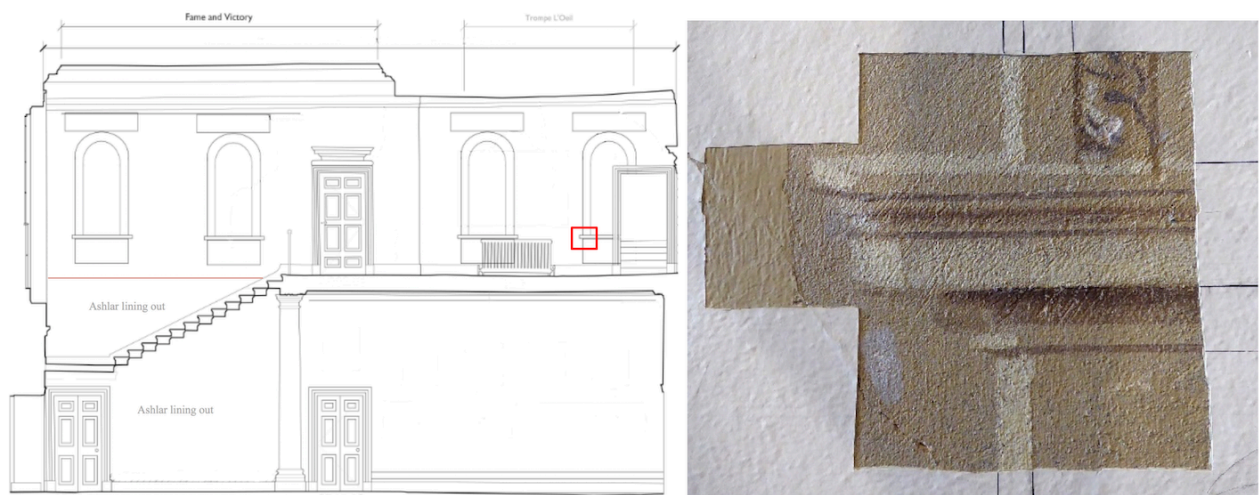


Figure 1: (above right) A section of trompe l'oeil architectural detailing uncovered on the South wall of the upper landing and (above left) an illustration showing the likely composition of paintings on the South wall, with a series of fictive niches, and a red box indicating the location of the uncovering (not to scale). Architectural drawings supplied by Purcell, architects to Stowe House Preservation Trust © Hirst Conservation Ltd

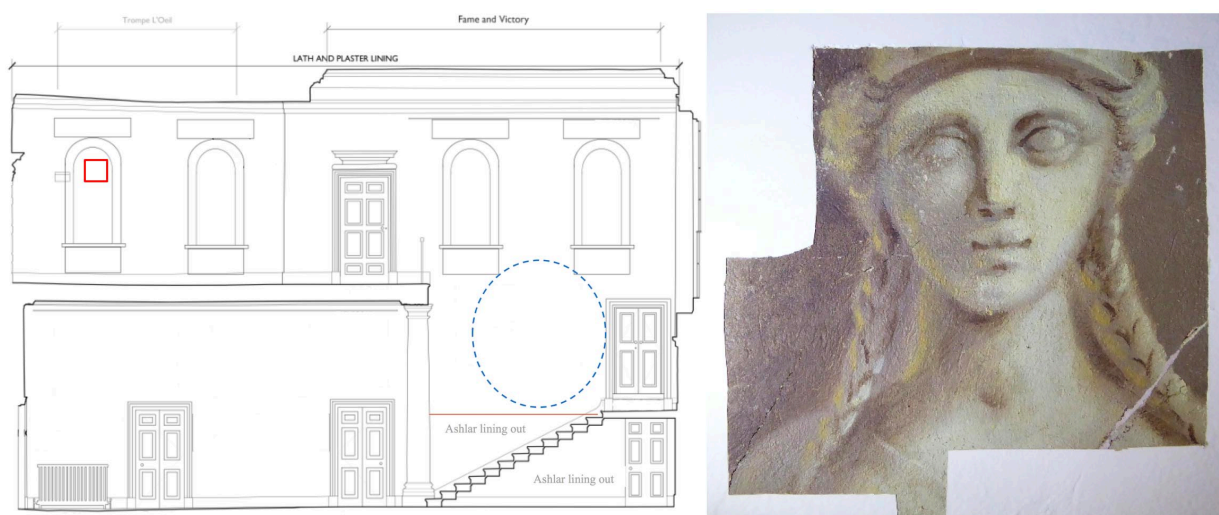


Figure 2: (above right) A section of trompe l'oeil painting within the outline of the niche, depicting a female figure, and (above left) an illustration indicating its location on the North wall of the upper landing (not to scale). Architectural drawings supplied by Purcell, architects to Stowe House Preservation Trust © Hirst Conservation Ltd



Figure 3: The locations of the RTI trials marked on the north (above left) and south wall (above right) elevations are marked with green boxes. Architectural drawings supplied by Purcell, architects to Stowe House Preservation Trust.

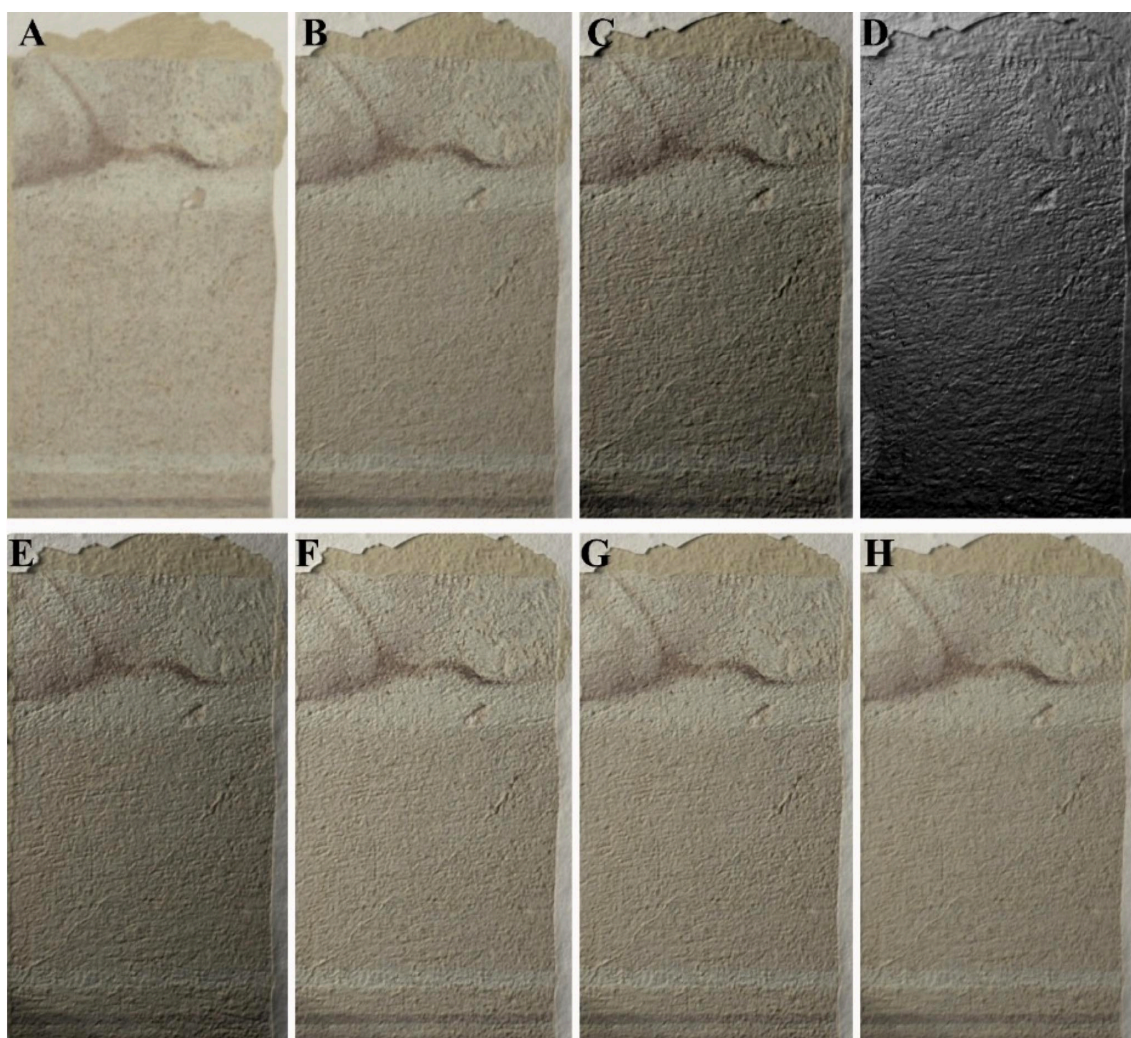


Figure 4: Detail of exposed area from the North wall in different modes: As if lighted from above (A), RTI view in default (B), diffuse gain (C), specular enhancement (D), normal (E), image (F), luminance (G) and coefficient unsharp masking rendering mode (H).

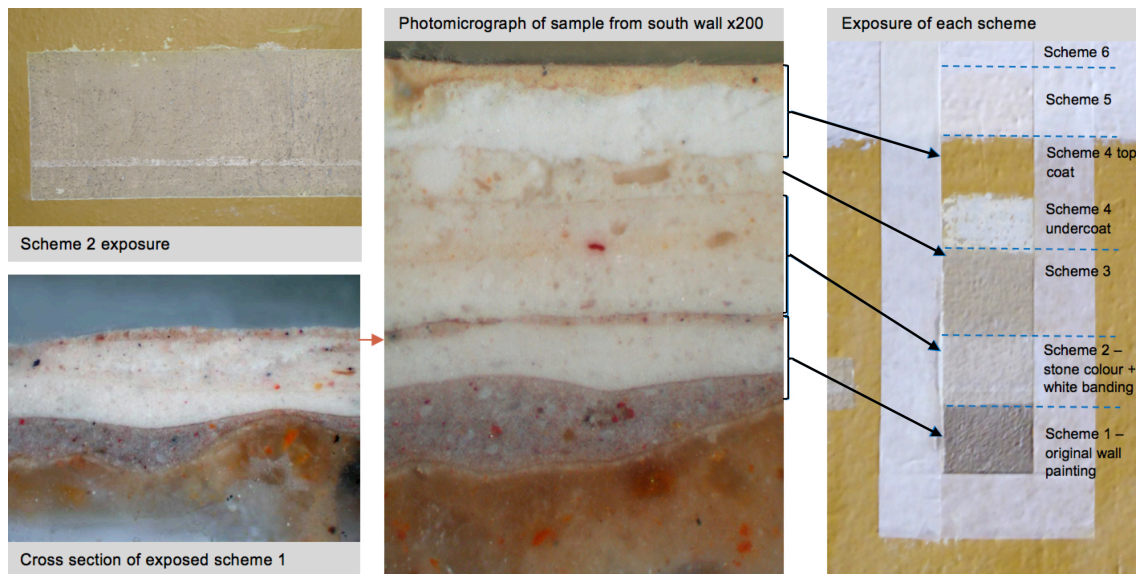


Figure 5: (above right) An exposure of each of the decorative schemes to the South wall of the upper landing, compared to a cross section of the full paint archaeology (above centre) and to a cross section from the exposed wall painting (above, lower left). A larger exposure of the second scheme showed thin white banding on a stone colour base coat, perhaps indicative of stylised, fictive ashlar block-work or rustication © Hirst Conservation Ltd

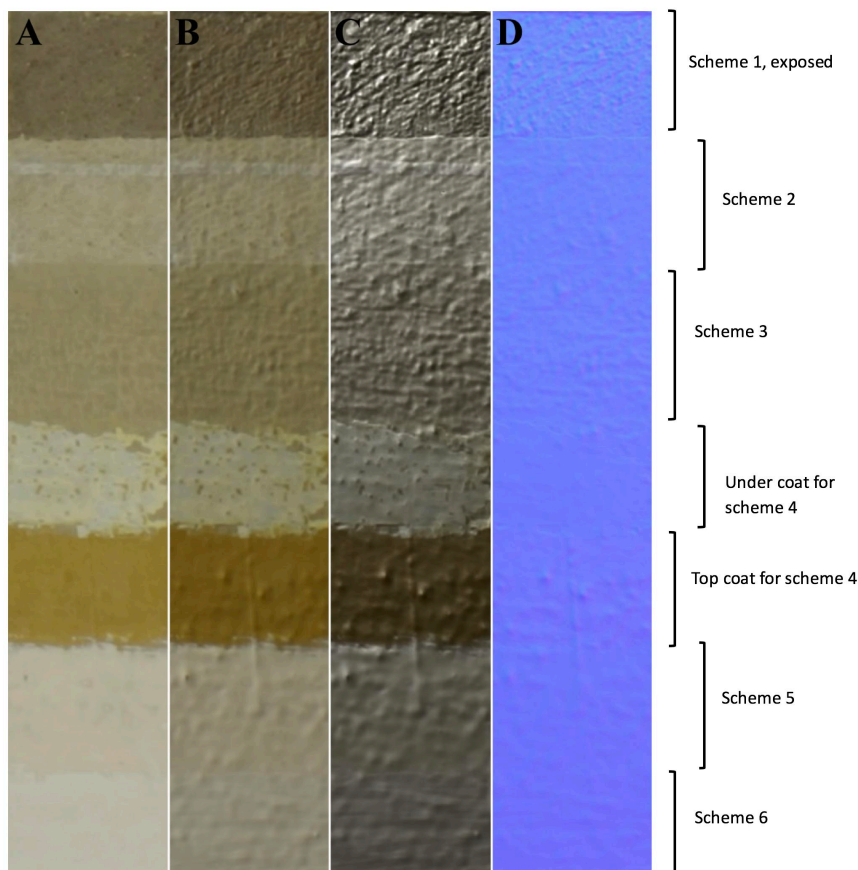


Figure 6: Detail of sequential exposures of decorative schemes on the South wall. As if lighted from above (A), RTI view in default (B), specular enhancement (C) rendering mode and normal map (D).

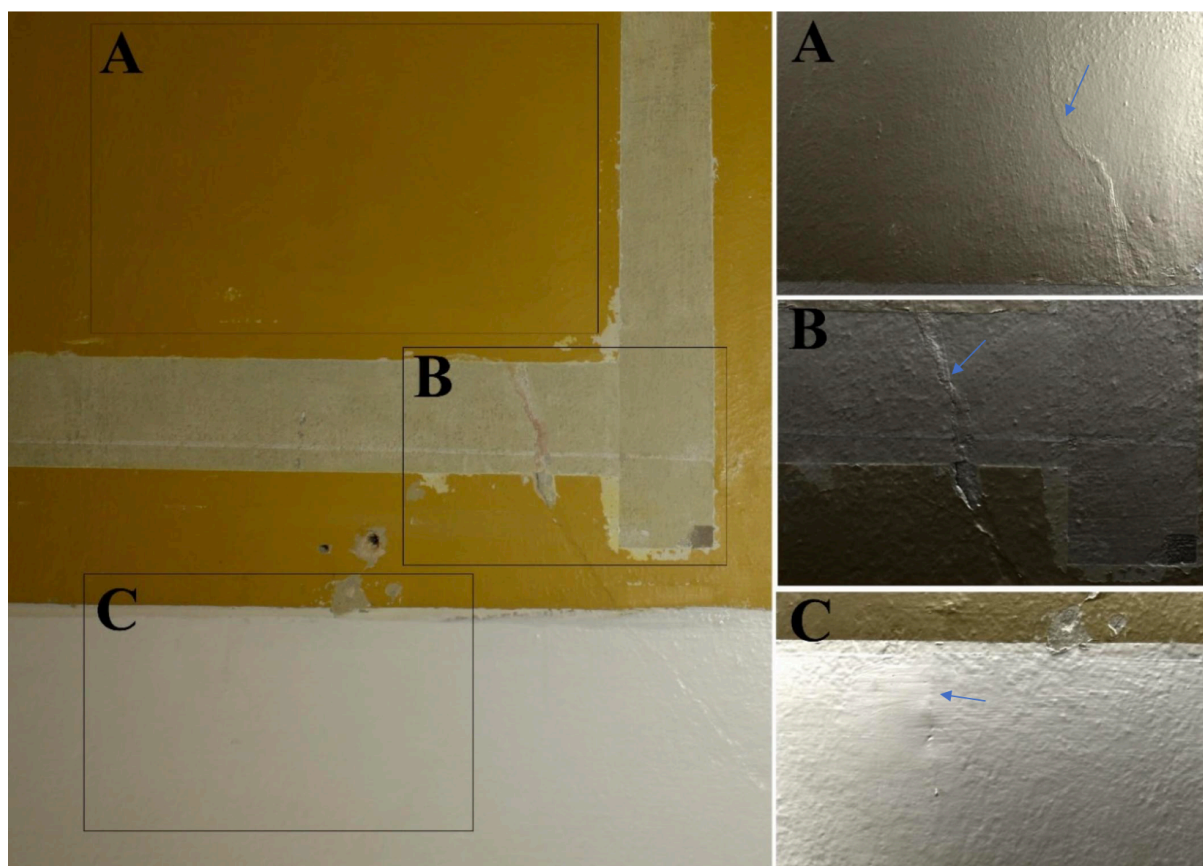


Figure 7: Detail of the South wall. Significantly more information about the surface texture of the wall can be obtained when comparing trial areas, A, B, C in the 2D image (above left) and RTI visualizations in specular enhancement rendering mode (above right). The areas of restoration disclosed in the RTI images are indicated with a blue arrow.

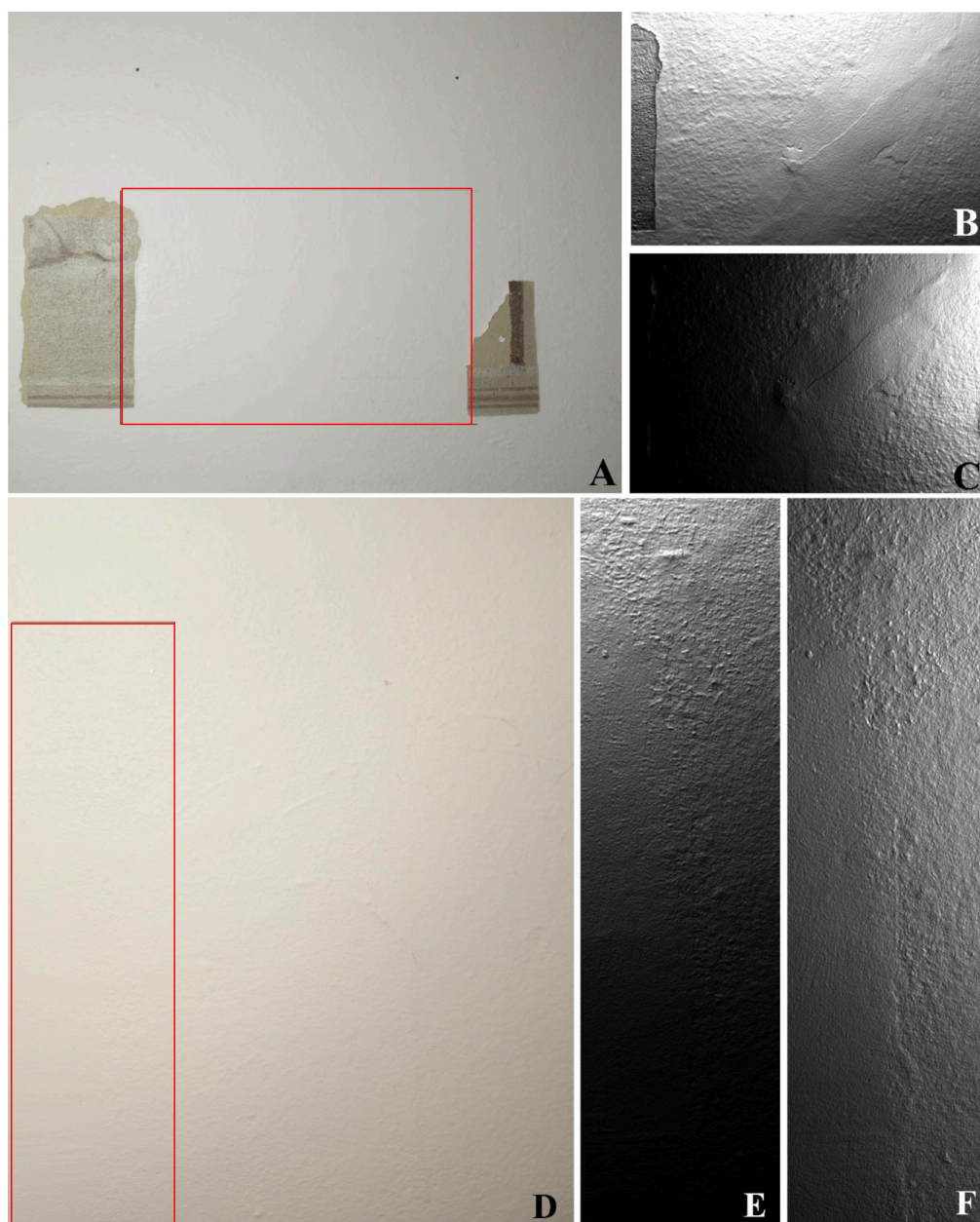


Figure 8: 2D images of sections of the North wall (A, D) and details of RTI visualizations in specular enhancement rendering mode (B, C, E and F). Details B and C are RTI visualisations of the area highlighted in a red box in image A, and details E and F relate to the area highlighted in a red box in image D.



Figure 9: Twelve sample areas of the North Wall from repaired (1, 2, 11, 12), exposed (3, 4, 5, 6) and overpainted areas (7, 8, 9, 10).

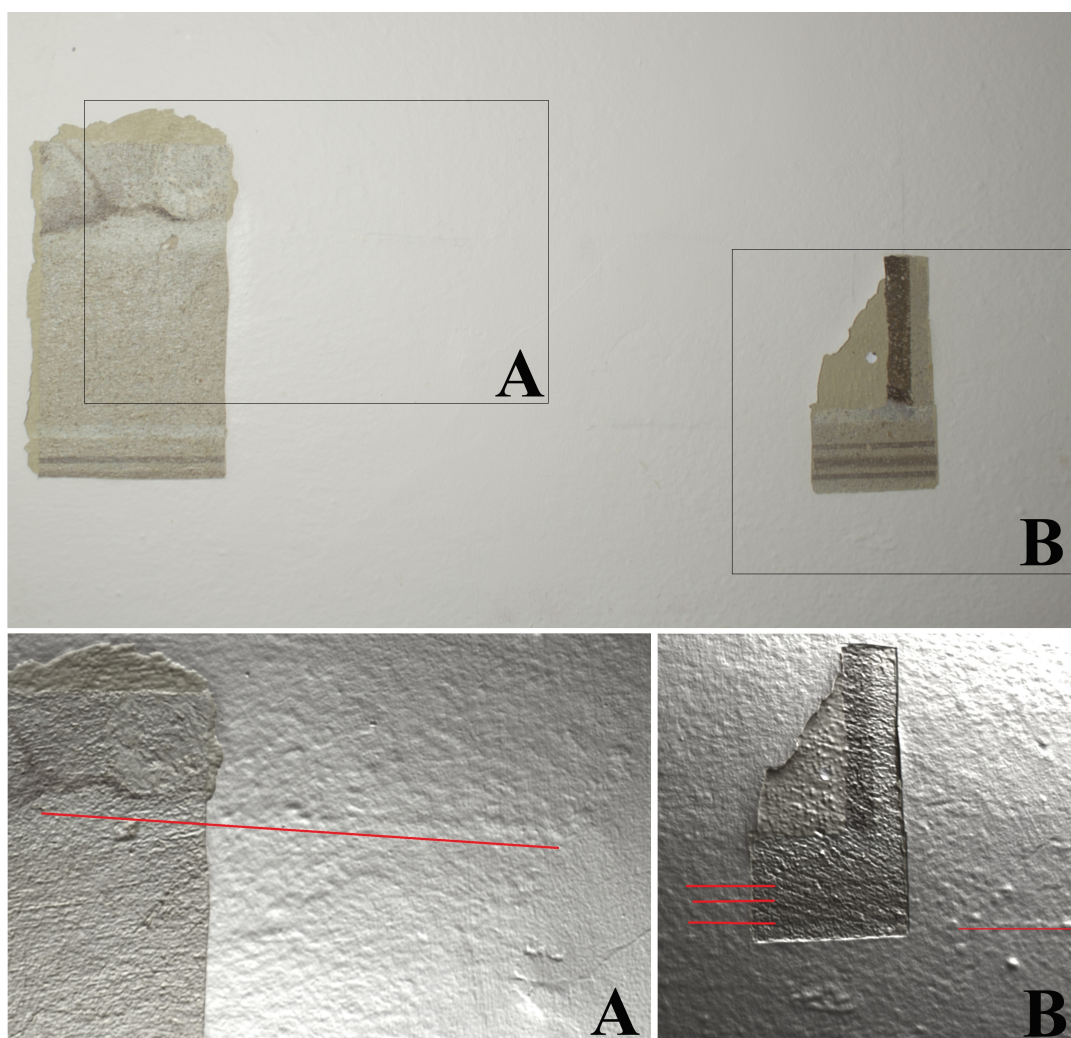


Figure 10: A 2D image (above, top) of a detail of the North wall and detail RTI visualizations (A, B) in specular enhancement rendering mode. Note the visibility of the compositional lines as they continue beneath the over paint.

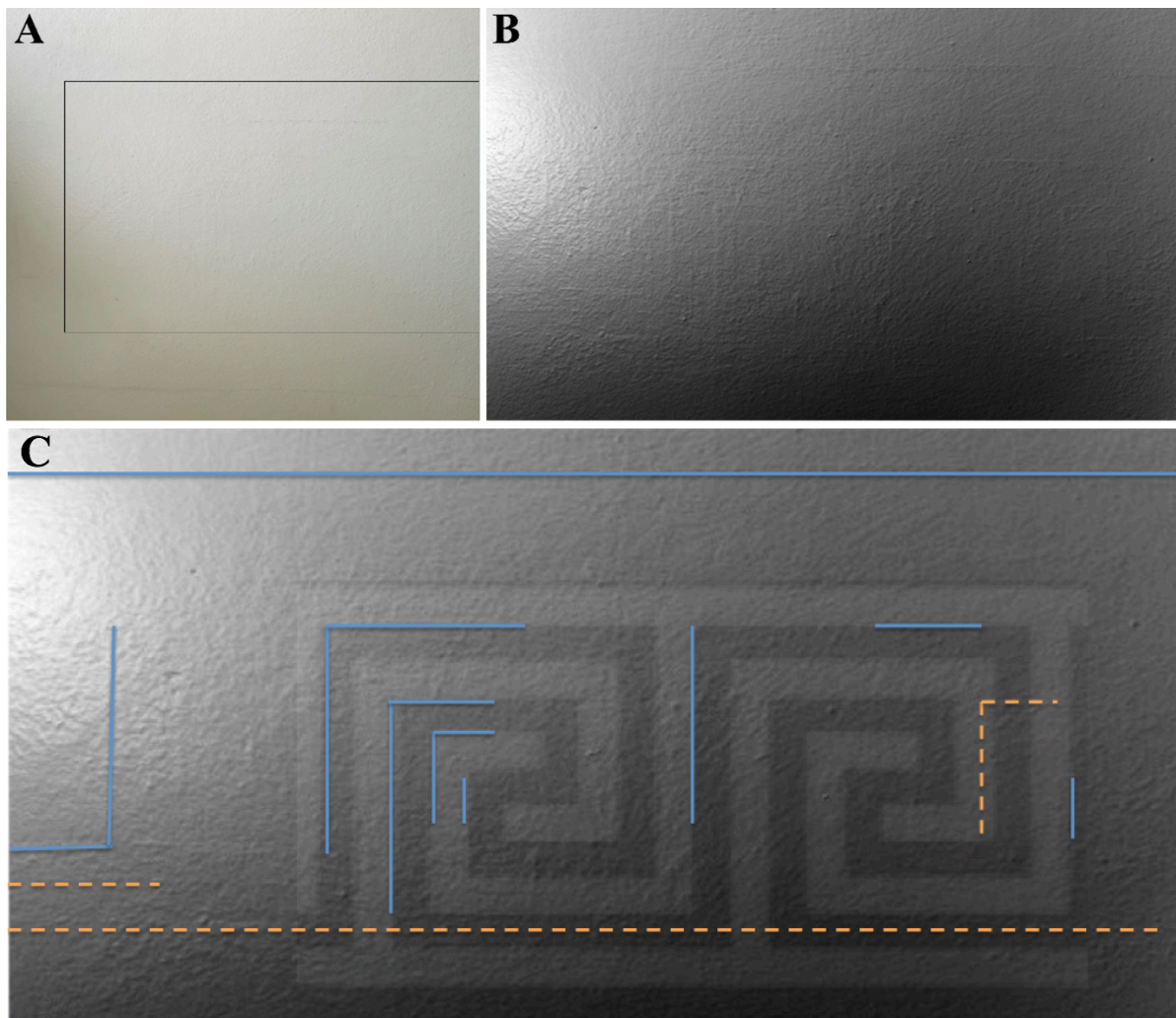


Figure 11: Detail of the South wall of staircase. 2D image (A) and RTI visualization in specular enhancement rendering mode (B). A series of vertical and horizontal lines can be clearly seen, and appear to suggest the presence of a Greek key design. Image C highlights some of the lines visible (in blue) and a graphic overlay of a Greek key design shows how many of the lines correlate. The dashed orange lines are lines that are visible but which do not correlate with the design.

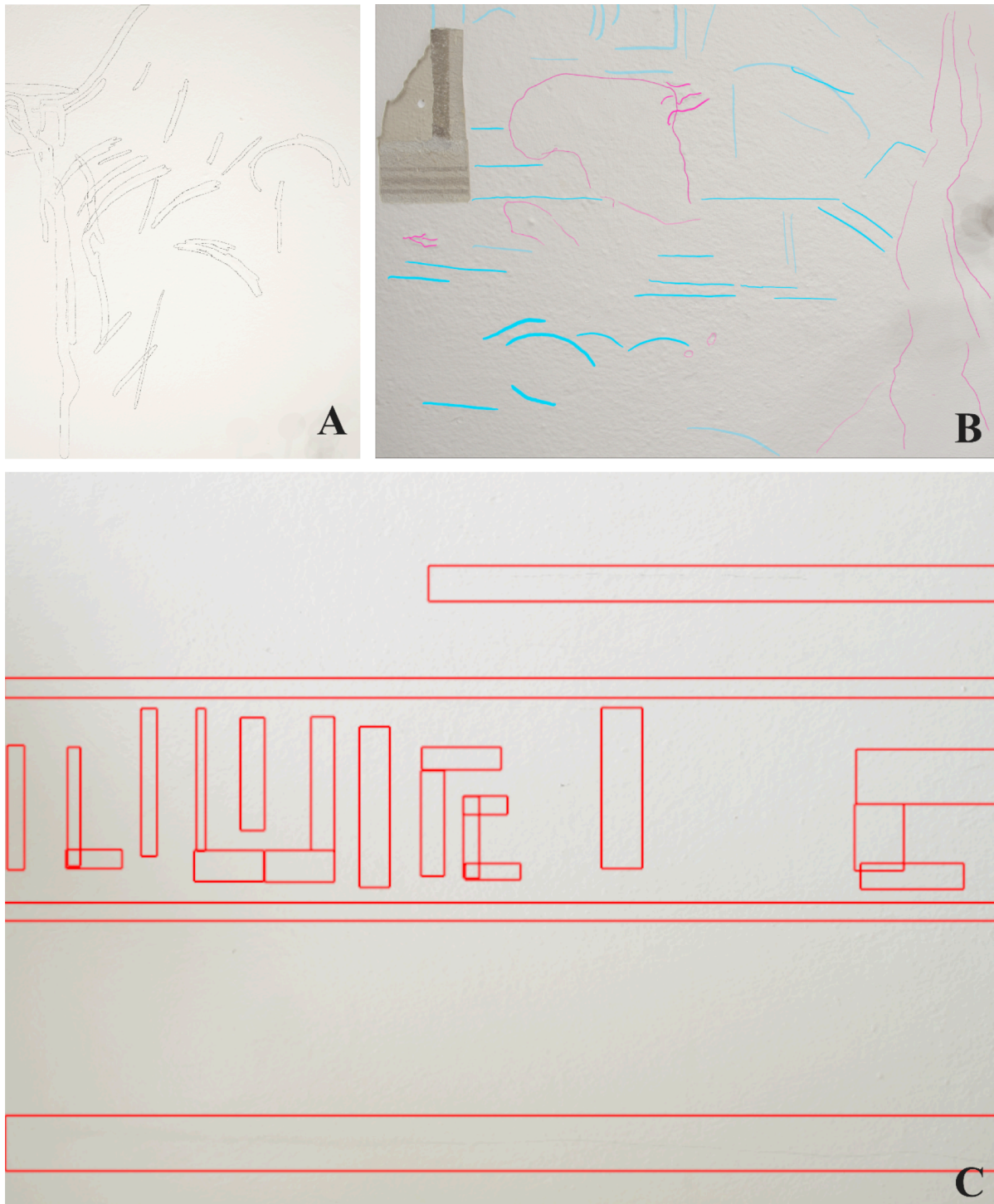


Figure 12: An illustration showing different styles of annotation. (A) Lines revealed on an area of the north wall during RTI virtual visual analysis have been traced to record their position. (B) Lines revealed in another section of the north wall traced using live draw apps and colour coded to indicate a certain characteristic e.g. magenta = restoration areas, blue = concealed original designs such as figurative painting or stencilling. (C) Screenshot of a detail of the South stairway in CHER-Ob. Surface annotations were used as means to indicate the position of lines revealed during RTI viewing.

Sample area		Values exported from ImageJ		Average variability of surface normals (%)
Label	Description	Mean	StdDev	
1	Restored area	178.64	0.916	0.512763099
2	Restored area	176.755	1.028	0.581595994
12	Restored area	165.728	1.191	0.718647422
11	Restored area	162.534	1.475	0.90750243
7	Overpainted area	156.367	1.79	1.144742817
9	Overpainted area	169.355	1.94	1.145522719
8	Overpainted area	160.136	1.932	1.206474497
10	Overpainted area	166.027	2.136	1.286537732
6	Exposed area	150.397	2.816	1.872377773
5	Exposed area	156.403	3.566	2.280007417
4	Exposed area	174.397	4.51	2.586053659
3	Exposed area	177.272	5.412	3.052935602

Table 1: Average variability of the surface normals from 12 sample areas of the North Wall.

Authors:

Rhiannon Clarricoates <http://orcid.org/0000-0003-3348-4745>

Rhiannon Clarricoates MA BA (Hons) ACR is an accredited paintings conservator and senior research fellow at the University of Lincoln. Rhiannon specializes in the conservation and research of paintings, decorative surfaces and polychromy, and has received several research grants to conduct research into a newly discovered scheme of grisaille paintings at Stowe House, dating from c1740, which is also the topic of her PhD. She has spoken at a number of conferences on the subject, and has contributed to a book about the conservation of Stowe House. Rhiannon is an active member of the conservation community, striving to promote best practice through her work with the Institute of Conservation Paintings Group, as an assessor for the Victoria & Albert Museum and Institute of Conservation's Care of Collection and Conservation Technician's Diploma (level 4), and as an associate lecturer for the University of Lincoln's conservation department. rclarricoates@lincoln.ac.uk

Dr Eleni Kotoula <http://orcid.org/0000-0003-1606-5039>

At the time of writing this article, Eleni Kotoula PhD was a fixed-term research fellow

specialising in digital heritage at the University of Lincoln. She is currently affiliated to the University of Edinburgh's Digital Research Services department. eleni.kotoula@ed.ac.uk