New Light on Old Illuminations

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Abstract

This article describes a unique suite of mobile equipment designed for non-invasive, non-destructive identification of the inks and pigments in medieval manuscripts. It explains the circumstances which led to the development of the equipment, outlines some of the findings that have been made with it to date, and summarises the broader questions that may be addressed and answered with future work.

Keywords: illumination, pigments, medieval manuscripts, diffuse reflectance spectroscopy, multispectral imaging, Raman spectroscopy.

The ravishing colours of illuminated manuscripts are one of the most vivid and enduring legacies of the Middle Ages. Yet discovering exactly what was used to achieve these effects is a challenging task. Although medieval recipe collections provide useful guidance about materials and techniques in general, they do not reveal what was deployed in any particular instance.[i] For this, scientific examination of manuscripts themselves is crucial; however, progress has been restrained by the wholly appropriate requirement that the procedures be non-invasive and non-destructive, while the additional condition that such work be undertaken on library premises, rather than in laboratories, has further limited the technology that can be applied.[ii] **Reliable techniques that are appropriate from a conservation point of view have been available since the 1980s;**[iii] **however, the size, weight and expense of the equipment in question**

meant that they could only be deployed in exceptional circumstances at significant cost.[iv] **Correspondingly, much of the work done to date world-wide has taken place in a handful of major institutions, examining materials in those collections themselves.**[v] To surmount these fierce challenges **in the context of the British Isles**, the present writers have developed a bespoke suite of equipment that is safe and appropriate from a conservation point of view, while being sufficiently light and compact to be easily transportable. It can, in fact, be carried on public transport: indeed, it was thus that it was brought to Wembley in 2016, when its nature and capabilities were demonstrated live at the Archives and Records Association conference held there that year. The present article summarises for those who were unable to attend that demonstration the scientific techniques in question and explains the context in which the equipment was developed; it then highlights some of the findings that have been made with the equipment, and concludes with an indication of the long-term aims and intentions of our research group.

The only interaction with early books and documents that fulfils the dual conservation requirements of no contact and that the items be opened and supported exactly as they would be for a careful reader is, in effect, shining different types of low level light on them. Accordingly, the main techniques used by our group are diffuse reflectance spectroscopy (DRS, often referred to as FORS), Raman spectroscopy, multi-spectral imaging, and time-resolved fluorescence measurement; other possible methods include X-ray fluorescence and Infrared spectroscopy. Raman spectroscopy relies upon the scattering of light by molecules, revealing the characteristic vibrational frequencies of the material under investigation. It does this by illuminating the material with a single colour or wavelength of light. Most of this light is scattered by the material with no change in wavelength; however, a tiny fraction is scattered at a different wavelength, and it is this light that we collect and analyse to reveal the Raman spectrum, and hence the identity of the pigment. Our Raman spectrometer employs a microscope accessory to enhance the precision with which the paint surface can be studied. Furthermore, the high spectral resolution afforded by our system allows not only the identification of many important types of pigment but also the detection of mixtures or impurities (for example, the presence of massicot (PbO) in red lead (Pb_3O_4)).

Raman spectroscopy permits the unequivocal identification of many pigments, but only from a small area at a time. To map a whole page, we use a combination of multi-spectral imaging and diffuse reflectance spectroscopy. DRS records how much light the materials reflect at each wavelength. As pigments tend to show broad featureless absorption bands, this is a less certain means of identifying them; nevertheless, it can provide vital clues to corroborate (or otherwise) the data provided by Raman spectroscopy. In multispectral imaging we record a sequence of images at different wavelengths, which enables us to establish a rudimentary pigment map of an entire page within a short period of time.[vi]

Normally these analytical procedures require heavy, cumbersome laboratory-based equipment which is extremely difficult to transport to libraries and archives. Correspondingly, the delicacy and vulnerability – not to mention the high insurance value – of medieval books and documents generally debar taking them to chemistry laboratories. It was first-hand experience of precisely this conundrum that led to the development of our unique, mobile suite of equipment.

The formation and operation of our research group (affectionately termed 'Team Pigment') began in a very specific context. The major loan exhibition 'Lindisfarne Gospels Durham: one amazing book, one incredible journey' that was held in Palace Green Library, Durham, during the summer of 2013, reunited – in some cases for the first time in over a millennium – a constellation of early medieval Northumbrian manuscripts.[vii] Thanks to generous financial support from a visionary alumnus, our team of chemists and a manuscript specialist was assembled and a large, heavy Raman spectrometer was moved from the Department of Chemistry to the basement of the building in which the exhibition was held. Then, with the permission of the lenders, various of the manuscripts were examined prior to their installation into, and immediately after their de-installation from, the cases. The incalculable value of being able to gather data from intimately related manuscripts was immediately apparent; so, too, was the impossibility of repeating the exercise with the same large-scale equipment when such items were normally scattered between different repositories the length and breadth of the country. This was the spur for developing a unique, portable version of the equipment specifically designed for the examination of books and documents *in situ* in almost any location. The result was a Raman spectrometer, a diffuse reflectance spectrometer, and multi-spectral imaging equipment which fit into two ruggedized suitcases, plus a light-weight but robust, adjustable gantry, on which the relevant parts of the equipment can be securely supported over the books and documents to be measured (see ill. 1). The entire instrumentation can be unpacked and assembled on site in about half-an-hour. Steadily refined in response to the challenges of different working conditions, the system is now sufficiently versatile that, while optimised for use with documents on a horizontal surface or books supported in a cradle, it was successfully adapted to take measurements from Hereford Cathedral's Mappa Mundi, a large, gently undulating surface, mounted vertically within a high-set wall case.

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What sort of things, then, have we been able to discover? To summarise our work to date in simple numerical terms: since 2013 we have identified the pigments of some two hundred medieval manuscripts, principally but not exclusively British, in repositories as distant from each other as Aberdeen, Cambridge, Durham, Hereford, London, Oxford, and York. Every single book and document is interesting in its own right; however, the real significance of the inks and pigments that were used therein only becomes apparent when they can be contextualised. Accordingly, wherever possible, we have focused on examples that are dated and localised, maximising our ability to perceive what is (and is not) typical for particular times and places. The inclusion in the team of a specialist in medieval manuscripts means that we have the expertise to identify optimum specimens for a particular period and to interpret their evidence within the relevant historical and cultural contexts.

The particular value of examining runs of volumes from the same milieux has been amply confirmed. The manuscripts that we studied from seventh- and eighth-century Northumbria, for instance, revealed that the dramatic effects of early Insular art were, on the whole, achieved with a strictly limited range of paints (see ill. 2).[viii] The essential palette comprised: an orange red from red lead (created by roasting white lead, which was itself made by exposing lead to vinegar); green that was either copper-based (formed by the action of vinegar on copper) or a vergaut (i.e. a mixture of blue and yellow); and yellow from the mineral orpiment (a trisulphide of arsenic). While black gallo-tannic ink was also used, 'white' was achieved simply by leaving the relevant areas of parchment bare. If other colours were added, the next would be either an indigo blue or an organic purple (obtainable from woad and lichen respectively). It is interesting that these two locally-available, easy-to-make pigments were not deployed more extensively (paradoxically, in certain manuscripts one sometimes finds indigo mixed with orpiment to create vergaut green, yet not applied as a colour in its own right), whereas the commonly-used orpiment was only available via long-distance trade. (Although the source of supply is unknown, the mineral is likely to have come from a volcanic region, such as Italy or Spain, possibly even Asia Minor.)

In these early Northumbrian manuscripts the colours tended to be applied individually, being juxtaposed, rather than blended with each other; indeed a fine line of blank parchment was often left between them. This approach afforded maximum chromatic impact to each colour; no less important, it avoided the danger of degradation arising from contact between substances that were incompatible, as was orpiment with lead- and copper-based pigments – precisely the palette in question. The only Northumbrian manuscripts that boast a significantly broader range of pigments, the Lindisfarne Gospels and a giant Bible known as Codex Amiatinus, make more extensive use of organic substances.[ix] Deluxe copies of sacred scripture, these were the highest status volumes of their day. Yet there may be more to it than that, for Amiatinus, whose palette is the most extensive of all, is a rare case where colours were mixed and over-painted: it is an interesting question, therefore, how far its greater use of organic pigments was motivated not just by the wish for more colours but by the need to have ones that could be combined safely.

The place in England where manuscript production was most continuous from the tenth to the twelfth centuries was Canterbury: hence the books of its two scriptoria (at Saint Augustine's Abbey and Christ Church Cathedral) offer the best opportunity to evaluate continuities and contrasts in practice at a premier centre from the aftermath of the Viking invasions through to the Anglo-Norman period, and we have accordingly examined a representative cross-section of them.[x] A fine library text made at Saint Augustine's Abbey in the second quarter of the tenth century reveals the range of pigments that was then available there: red lead oranges and pinks, orpiment and organic yellows, copper-based and vergaut greens, organic and red lead-massicot browns, and lapis lazuli blues.[xi] 'White' was generally still achieved via bare parchment, though some white lead served to modulate a red that was used to highlight lettering. For the colours were not only employed to paint a series of pretty decorated initials, but were also applied in translucent bands under display script – anticipating by over 1000 years the modern highlighter-pen. It is notable that once again, although indigo was readily available in the scriptorium (being mixed with orpiment to create vergaut green), it was not exploited as a blue in its own right. What was used for blue was lapis lazuli, only obtainable at that time from Badakshan (north-east Afghanistan): scribes in Canterbury in the 930s had access to a luxury material that had travelled, albeit in stages, more than 3,500 miles.

A first change, noticeable in the second half of the tenth century is that, while red lead remained the normal pigment for red and orange lettering, organic or iron ochre reds were preferred for artwork (details within decorated initials, and line drawings alike). By the mid-eleventh century, red lead was itself being displaced by vermilion (mercuric sulfide available as the mineral cinnabar, or manufactured by roasting metallic mercury and sulphur until the vapour re-condensed as the red crystalline form of vermilion). This remained the standard 'all-purpose' red thereafter, red lead being largely reserved for making orange. Paradoxically, white lead (from which red lead was manufactured) was hardly used at Canterbury in its own right during the period when red lead was widely deployed, but then started to be utilised around the time that the latter was falling from favour. The general point highlighted here yet again is that some pigments that were certainly to hand were side-lined or ignored – presumably for aesthetic or pragmatic reasons. The paucity of gold in Canterbury books of the late tenth century was unquestionably a matter of choice, since the metal was evidently available (as its prominence in Winchester manuscripts of the late tenth century advertises); and when Christ Church's scriptorium was reformulated in the aftermath of the Viking sack of the city in 1011, gold was then embraced as part of a transformed more 'Winchester-like' aesthetic.

A decline in the use of orpiment, by contrast, may have been due to limited or intermittent availability. This beautiful yellow mineral, fundamental to early Northumbrian books (see ill. 2), seems to have been in short supply in Canterbury by the tenth century: used sparingly in the 930s and for one book in the early eleventh century,[xii] it was rare prior to the Norman Conquest; thereafter, although it appeared in more manuscripts, it only did so in small quantities. As the locations from which supplies were obtained are unknown – beyond the fact that they were certainly distant from Britain – it is impossible to judge how far broader political events and/or changing patterns of trade may have contributed to this. Certainly, acquiring pigment from the far East does not appear to have been a problem, since all the blue used in Canterbury books (even for minor initials) from the tenth to the twelfth century was lapis lazuli. As lapis regularly features in manuscripts from contemporary Normandy and elsewhere,[xiii] it seems safe to conclude that this exotic pigment from Afghanistan was more readily available in northern Europe in the tenth and eleventh centuries than was once thought.

It is logical to wonder whether the Norman Conquest, which had an impact on so many other aspects of English culture and society, also affected the range of pigments that were used. Arguably the most important pigment change of the eleventh century – from red lead to vermilion – occurred at Canterbury (as indeed in Normandy) a generation or so before the Conquest and was manifestly independent of it. Given that the principal source of cinnabar (mineral vermilion) was Almadén in southern Spain, its 'promotion' may conceivably reflect the increasing interaction of a resurgent Christian Iberia with the rest of Europe at precisely this time, even though the mines themselves were in the Islamic heartlands. Although, as just noted, orpiment reappeared after 1066, it did so in such a highly diluted form as to suggest that supplies of the mineral remained inadequate and unreliable. The most noticeable difference in pigment usage after 1066 was, in fact, a dramatic rise in the deployment of purple. The colorant in question was probably orchil, a cheap and readily available dye from lichen (establishing the exact identity of the substance within the current technology and operating restrictions is extremely difficult).[xiv] Hitherto employed very sparingly in books – perhaps in part because it was so mundane – such purple came into its own in a period when (owing to pressing new priorities for ecclesiastical libraries) large numbers of books for spiritual reading had to be copied and ornamented in a short period of time (see ill. 3).

Turning to consider what our work has revealed about some of the main changes in illuminators' palettes in the later middle ages, we may usefully focus first on the cases of yellow, then on that of blue. Alternative factors that may have contributed to the demise of orpiment within scriptoria (documentary records show that it was being used in other contexts in the thirteenth and fourteenth centuries[xv]) were its extreme toxicity and, above all, its incompatibility with other colours that were popular in illumination. Whatever the full picture, British scriptoria then found themselves without a satisfactory yellow: organic and ochre yellows lacked depth of colour and opacity, and illuminators commonly worked instead with orange or gold which could, in the right context, could give richer yellow-like effects. By the late thirteenth century, 'mosaic gold' (a yellow metallic-looking powder made from roasting tin with sulphur) had been added to this repertoire; and then around 1400 another versatile yellow – strong, opaque, stable, and ideal for combining with other colours – became current in northern European books. This was lead-tin yellow, a substance manufactured by heating lead and tin oxides together with silica, the hue varying according to the temperature at which it was prepared. Present not only in various high-status Parisian works at the turn of the fourteenth to the fifteenth centuries but also in a modest Bruges Book of Hours dated to 1409,[xvi] this new arrival appeared in English scriptoria during the course of the fifteenth century, enlarging the range of yellows and what could be done with them. Thus in the Abingdon Missal of 1461-2, to take one example, gold ink was used to portray the 'starburst' of spiritual light, mosaic gold was deployed for shimmering yellow foliage, while lead-tin yellow was utilised to modulate green and for over-painting on foliage rendered in other colours (see ill. 4).[xvii]

As for blue, the main difference in the late medieval palette was the rise to predominance of the copper carbonate mineral, azurite. In addition to offering an attractive and rich colour, this had the advantages over lapis lazuli that it was mined in Europe (France, Germany and, above all, Hungary) and was simpler to process, meaning that supply-chains were shorter and the end-result cheaper. Although used in Germany as early as the tenth century,[xviii] and deployed by one southern English illuminator in the eleventh,[xix] it only appears to have been readily available in Britain by the thirteenth century, whereafter it supplanted lapis as the 'general purpose' blue. Thus in the late-fourteenth-century Bergavenny Missal, for example, azurite was used for the many blue letters within the text, for all the decorated borders, and for parts of the figural scenes in the historiated initials, whereas lapis appears only in small areas of certain historiations.[xx]

As this last example demonstrates, close examination of individual areas of what to the eye may appear to be one colour can provide intriguing insights into workshop practices. While most of the red in one early eighth-century Northumbrian gospel-book is pure red lead, that on two pages is red lead with massicot (a lead monoxide resulting from incomplete roasting of the lead oxides during the manufacturing process) – demonstrating that different batches of ink were used in these areas.[xxi] Similarly, in a sixth-century Italian gospel-book that was brought to England at an early date and is associated with St Augustine of Canterbury, almost all of the red is red lead except on a handful of consecutive pages, where it is vermilion.[xxii] There is no aesthetic reason for this change, which here is almost imperceptible to the human eye, but as it exactly coincides with a self-contained unit within the book, the implication is that this section was produced under slightly different circumstances from the rest. Occasionally a disjunction in material is even more localised, appearing within part of a single feature. The black outline of one initial in the late twelfth-century Bible of Hugh du Puiset, bishop of Durham, for instance, is revealed by near-infrared light to have been accomplished partly in a carbon-based ink, partly in a gallo-tannic one, indicating that this apparently unitary line was, in fact, the result of a two-stage process of draughtsmanship with a change of ink in between.[xxiii]

The blue in four manuscripts certainly or possibly associated with Canterbury, one dating from the second quarter of the tenth century, one from c. 1000, the other two from c. 1100, transpired to include, amidst their lapis lazuli, the extremely rare pigment Egyptian blue (a calcium-copper tetrasilicate, made by roasting balls formed of siliceous sand, copper, and calcium salts at temperatures of 850-1000º C) (see ill. 3).[xxiv] Widely used in Antiquity but appearing only infrequently thereafter in scattered locations, occurrences of Egyptian blue in the earlier middle ages are something of an enigma. Whether some of the isolated instances could reflect intermittent manufacturing of the pigment, as opposed to, or as well as, opportunistic recycling of antique material is currently unclear.[xxv] The way it was included in the Canterbury books (as also in a handful of late Anglo-Saxon manuscripts from other centres) suggests that their artists were unaware that these particular batches of lapis lazuli had been adulterated with a substance that was actually much rarer: the Egyptian blue had probably been added to the lapis before the supplies reached England.

If this intriguing usage of Egyptian Blue was almost certainly unwitting, there are, by contrast, fascinating instances of the strategic deployment of costly blues. Azurite was the basic blue of the aforementioned Abingdon Missal, being used by itself throughout all the text and most of the decoration (see ill. 4). However, in the full-page miniature of the Crucifixion, the most important decorated page of the book, whenever azurite was applied to areas of particular significance (God's aureole, Mary's robe, two 'IHS' monograms, and the armorial of the patron), lapis was mixed into it.[xxvi] This was evidently a way of honouring the most portentous subject-matter; yet, imperceptible to the eye (as opposed to the spectrometer), it was done for symbolic and spiritual reasons rather than for any visual effect.

Pigment identification can also provide new data to set alongside what is known or suspected about individual artistic hands (generally identified on stylistic grounds). While a team of artists working on a single book might share the same palette, there are also instances where different hands display individual preferences. Three artists who, though clearly contemporary, are quite distinct in manner (not to mention talent) were responsible for the historiated initials in the aforementioned Abergavenny Missal.[xxvii] No more than three pigments (lead white and an unidentifiable pink and green) were common to all of them; red lead and azurite were used only by Artists 2 and 3; lapis lazuli was deployed only by Artists 1 and 3; while Artist 1 alone utilised vermilion and indigo. A further telling distinction is that Artist 3 reserved his lapis for high-status figures, while Artist 1 did not. The significance of these contrasts in practice are debatable; what is, however, certain is that, as further manuscripts are examined scientifically, we shall have a broader context in which to evaluate them.

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The ultimate aim of our team and its work is to provide a reliable guide to the use of pigments in British manuscripts and documents from the seventh century to the fifteenth. As the inks and pigments of more volumes are securely identified, we shall be able to map with ever greater precision the materials that were current in a particular place at a given time, to see how they were used there and in what sort of combinations. Correspondingly, it will be possible to recognise exceptions and anomalies for what they are. A case in point is our discovery that the red used to highlight some of the contours within the drawing of Lady Philosophy that prefaces a tenth-century Canterbury copy of Boethius was vermilion, a pigment that only became current there during the course of the eleventh century; every other red throughout the book was – consonant with its date – red lead and/or red ochre.[xxviii] This strongly suggests that the red highlights on the frontispiece were, in fact, later additions made during a subsequent re-touching of the image in question.

The acquisition of sound data about individual books will mean that accepted wisdom concerning their scribes and illuminators and about workshop practices in general can be re-evaluated in the light of myriad new facts. Questions such as the extent to which individual illuminators may have had their own palette, and the circumstances in which particular pigments might be used by certain members of a team but not others – questions which it was hitherto impossible to approach – may now be addressed. Equally, it becomes possible to see how the palette of illuminators compares with those of contemporary mural painters and panel painters (about which far more is already known owing to the scientific examination of actual samples detached during conservation work),[xxix] as with those used by the scribes and draughtsmen responsible for colouring coeval documents and maps. Such investigation of British medieval maps as we have undertaken suggests that they were coloured using a restricted selection of the pigments that were current in contemporary illumination. Where data are, or become, available from comparable research on continental manuscripts – the situation is currently patchy but certain areas at particular times, such as **the milieu of Charlemagne**, Germany in the tenth and eleventh centuries, Paris c. 1400, and northern Italy in the fourteenth and fifteenth centuries, are reasonably well documented **owing to pioneering work by a handful of colleagues based in Cologne, Paris-Orléans, and at the Fitzwilliam Museum, Cambridge**[xxx] – it will be possible to compare and contrast British pigment use with that of practitioners across the Channel. Based **on** such analyses as have been published to date, it would appear that around 1400 southern English illuminators lagged a little behind their Parisian counterparts in terms of the range of their palette. However, whether this was really the case – as opposed to being a distortion resulting from imbalances in the small sample that has been studied so far – will only become clear once more British books from this period have been examined scientifically.

It will also be interesting to discover to how far, and in what ways, our medieval and renaissance practitioners may have responded to the technical limitations of their materials. How did they deal with known problems such as the circumstance that some colour stuffs are fugitive, others aggressive to parchment, while certain combinations of pigments could lead to discoloration? On occasions we have observed blank areas of parchment or glazes being used to isolate substances that were chemically incompatible yet whose vibrant hues made juxtaposing them irresistible for the illuminator. Was there any response to the toxicity of particular pigments, notably those based on arsenic, mercury or lead? As noted above, deployment of orpiment (the arsenic sulfide yellow that was ubiquitous in the early Middle Ages) dwindled from the tenth century; however, whether this was on account of its known threat to health or rather because of problems of supply is currently unclear.

Whatever the answers to these and similar questions about the contexts and motives for changing patterns of pigment use across time, the identification of the colour stuffs themselves is likely to be relevant to modern conservators. Knowing the exact nature of the materials within the manuscripts and documents in their care is potentially of great value. For example, reds that have darkened in whole or part and which display a metallic sheen and have typically been diagnosed 'by eye' as red lead; however, our instrumentation reveals that they are often, in fact, vermilion. Equally, we have observed instances where red lead has been placed directly onto orpiment (or vice versa) and, contrary to what one would expect, there has been no obvious adverse reaction: the physical circumstances that have permitted this felicitous result deserve further investigation. On a more sobering note, conservators should be aware that some commercially available spectrometers that are purportedly suitable for **use in** libraries and archives employ power densities that, our preparatory work on test samples made in the laboratory clearly shows, could cause damage to historic books and documents. Thus it is our recommendation that, before spectroscopic analyses are made on a manuscript with any such device, a full and informed assessment be undertaken of the measurement conditions, in particular the levels of light (power density).

To sum up: the capability to transport appropriate technology to the manuscripts and documents themselves promises to revolutionise knowledge of the pigments in **medieval** British books **and documents** and, by extension, of **the** scribes **and** illuminators **responsible for them. Correspondingly, the integration of our data with the findings of the handful of other groups in Europe and in the USA who do similar work, focusing on continental manuscripts, will enlarge understanding of artistic relations between Britain and the Continent, and of** early book culture more generally. Moreover, it is quite clear from the work to date that, as previously insoluble questions are answered, new ones, hitherto unimaginable (such as the sources and significance of Egyptian blue in England during the tenth and eleventh centuries), will emerge. Few fields can promise so rich a harvest of new discoveries – and pertinent new questions – in the near future.

Biographical Notes

Andrew Beeby is a professor of chemistry at Durham University, specialising in optical absorption, emission and scattering spectroscopies. His expertise in engineering and the development of spectrometers underpins the continuing upgrading of the team's portable equipment.

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Catherine Nicholson is a lecturer and Programme Leader in Applied Sciences at Northumbria University. She has turned a decade of working with spectroscopic analysis of polymorphic compounds and nanocrystals to the new field of non-destructive pigment analysis.

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Captions

1.Mobile Raman spectroscopy: the kit. Reproduced by kind permission of Cambridge University Library.

2. Durham Cathedral Library, MS A.II.17, fol. 69r, detail (gospel-book; ?Lindisfarne; *s.* vii[ex]). Reproduced by kind permission of the Dean and Chapter of Durham Cathedral.

3. Durham Cathedral Library, MS B.II.16, fol. 65v, detail (Augustine; Canterbury, Saint Augustine's Abbey; *s.* xi/xii). Reproduced by kind permission of the Dean and Chapter of Durham Cathedral.

4. Oxford, Trinity College, MS 75, fol. 224r (Missal; ?Oxford; 1461-2). Reproduced by kind permission of the President and Fellows of Trinity College, Oxford.

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i Overview: Clark, *Art of All Colours*. Two model editions of such texts are Neven (ed.), *Strasbourg Manuscript* and Clarke (ed.), *Medieval Painters' Materials*. **Most,** however, remain unpublished.

ii The fundamental guide to what has, and can be achieved in the field as a whole is now Panayotova (ed.), *Colour*, which is based around manuscripts (of all countries) in the collection of the Fitzwilliam Museum. The Raman spectroscopy there reported was accomplished by the present team.

iii **Guineau, "Analyse non destructive" and Vezin, "Microsonde Raman Laser" were early reports concerning the application of the technology to pigment identification.**

[iv] **The first such major initiative in Britain, focusing on the Lindisfarne Gospels, is described by Brown, Brown and Jacobs, "Analysis of the Pigments"; the scale of the equipment can be appreciated from their figs. 2 and 3.**

[v] **A pioneer in the Anglophone world was Nancy Turner at the Getty Conservation Institute, Los Angeles (see, e.g., her "Manuscript Painting Technique"). The most significant workers to have undertaken scientific investigations of British manuscripts to modern standards are Robin Clark (e.g. Brown and Clark, "Analysis of Key Anglo-Saxon Manuscripts", "Lindisfarne Gospels", "Three English Manuscripts"), Mark Clarke ("Anglo-Saxon Manuscript Pigments"), Stella Panayotova and Paola Ricciardi (various entries in Panayotova (ed.), *Colour*), Cheryl Porter (e.g. "Meaning of Colour"), and Nancy Turner (in Collins, Kidd and Turner, *St Albans Psalter*, pp. 73-7).**

[vi] For the technical specifications of the equipment used in our different campaigns see Beeby, Duckworth, Gameson and Nicholson, "Earliest Northumbrian Manuscripts", pp. 50-52; and Beeby, Gameson and Nicholson, "Lancastrian England", pp. 144-5 with note 1. Further on the various techniques in general see Panayotova (ed.), *Colour*, pp. 376-379.

[vii] Exhibition guide: Biddlecombe-Brown, *Lindisfarne Gospels Durham*. Exhibition companion: Gameson, *From Holy Island to Durham*.

[viii] See further Beeby, Duckworth, Gameson and Nicholson, "Earliest Northumbrian Manuscripts".

[ix] Respectively London, British Library, MS Cotton Nero D.iv (pigments identified by Brown and Clark, "Lindisfarne Gospels"), and Florence, Biblioteca Medicea-Laurenziana, MS Amiatino 1 (pigments identified by Bicchieri *et al.*, "Bibbia Amiatina").

[x] Some of this material was presented at the conference, "Manuscripts in the Making: art and science", Cambridge, Department of Chemistry, 8-10 December 2016, and a fuller version will be published in its proceedings, edited by Stella Panayotova and Paola Ricciardi.

[xi] Cambridge, Trinity College, MS B.11.2 (Amalarius). For colour images see Morgan and Panayotova, *Catalogue ... British Isles*, no. 11.

[xii] Respectively Cambridge, Trinity College, MS B.11.2, and York Minster, MS Add. 1.

[xiii] Coupry, "Pigments"; Oltrogge and Fuchs, *Maltechnik*, pp. 153-165.

[xiv] On the problem of identifying purples non-destructively see, e.g., Oltrogge and Fuchs, *Maltechnik*, pp. 155-159.

[xv] Howard, *Pigments*, pp. 153-4.

[xvi] For the former see Villela-Petit, "Palettes comparées". The pigments of the latter (Durham, Ushaw College, MS 10: Kelly (ed.), *Ushaw*, pp. 58-61) were identified by the present writers.

[xvii] Oxford, Bodleian Library, MS Digby 227 + Oxford, Trinity College, MS 75: see Beeby, Gameson and Nicholson, "Lancastrian", pp. 153-158.

[xviii] Oltrogge and Fuchs, *Maltechnik*, p. 163.

[xix] London, British Library, MS Harley 603 (Artist F).

[xx] Oxford, Trinity College, MS 8: Beeby, Gameson and Nicholson, "Lancastrian", pp. 145-151.

[xxi] Cambridge, Corpus Christi College, MS 197B, fols. 2r and 10r. The former is reproduced in colour: Gameson, *Holy Island to Durham*, p. 55, ill. 31.

[xxii] Cambridge, Corpus Christi College, MS 286.

[xxiii] Durham Cathedral Library, MS A.II.1: Mynors, *Durham Cathedral Manuscripts*, no. 146; Gameson, *Manuscript Treasures*, no. 18

[xxiv] Respectively: Cambridge, Trinity College, MS B.11.2; Cambridge, Corpus Christi College, MS 411; Cambridge, Trinity College, MS B.3.9; and Durham Cathedral Library, B.II.16. For a summary of the equivocal evidence for associating Corpus 411 with Canterbury see Morgan and Panayotova, *Catalogue ... British Isles*, no. 25.

[xxv] On the manufacturing of the material in Antiquity see Kakouli, *Greek Painting Techniques*, pp. 61-66.

[xxvi] Oxford, Bodleian Library, MS Digby 227, fol. 113v: Marks and Morgan, *Golden Age*, pl. 40; Browne, Davies and Michael (ed.), *Embroidery*, no. 76.

[xxvii] Oxford, Trinity College, MS 8: see note 20 above.

[xxviii] Cambridge, Trinity College, MS O.3.7: Morgan and Panayotova, *Catalogue ... British Isles*, no. 15.

[xxix] Overview: Howard, *Pigments*.

[xxx] **Roger, "Étude des couleurs"; Roger-Puyo, "Les pigments"; Oltrogge and Fuchs, *Maltechnik*; Panayotova (ed.), *Colour*.**