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SHORTER ARTICLES

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Faded, damaged and largely illegible, the thirteenth-century *mappamundi* now preserved in Vercelli, Italy, has attracted less attention in recent scholarly work on medieval maps than it merits because of its poor state and the almost total illegibility of substantial parts of it (Plate 13). In 2014, however, with a view to extracting more of the names and features originally shown, the Lazarus Project imaged the map multispectrally.[1] In this article, I describe the process of multispectral imaging (MSI) and statistical image processing in the recovery of the map. I illustrate the promise that these technologies hold while warning that they are effective only when properly understood. Inadequate processing, sub-optimal capture technologies and methods, and incomplete digital surrogates are liable to result in poor-quality images that obscure more than they clarify—a situation we refer to as digital palimpsesting. In this short article, I am reporting on my work on the Vercelli map of the world to show how state-of-the-art multispectral imaging can reveal faded or illegible material and enhance the understanding of medieval maps.

The Vercelli Map

Few of the large world maps displayed in medieval times in churches and palaces, and sometimes mentioned in written records, have survived into the present age. Our knowledge about those that we have is liable to be incomplete, especially in cases where the extant maps have not been amenable to study. Thus the badly damaged and partly illegible world map in Vercelli has been left to languish in relative obscurity since its rediscovery despite its status as an important witness to the *mappamundi* tradition; a sadder victim of the wear and tear of time than its more famous cousin in Hereford.[2]

The Vercelli map was brought to light in October 1908 by Carlo Errera.[3] At the time, although torn around the edges from having been kept rolled up, and with a couple of unrepaired holes (the largest running north–south across western Europe), it was still relatively clean and 'legible enough'.[4] It was probably more or less in this condition in about 1951 when both Youssouf Kamal and Leo Bagrow included a reproduction of it in their respective

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books (Fig. 1).[5] Whether Kamal or Bagrow was the first to have the map photographed is unclear; neither gives details about the map or acknowledges the source of their photograph. According to Carlo Capello, however, Bagrow had consulted the original map between 1948 and 1950 and had had a photographic reproduction made.[6] Comparison of the two 1951 reproductions suggests that the negative from the photography done for Kamal was simply reprinted for Bagrow.

The 1951 photograph confirms that most fading was confined to what remained of the outermost band. In 1964, however, when Marcel Destombes found the map 'marked by humidity and rendered difficult to read', he had to use the existing photograph for his *Mappemondes*, as have almost all subsequent commentators.[7] By 1976, when Capello published what remains the only full-length study of the map, the situation was disastrous, for, as he wrote despairingly, 'humidity, mildew and time have worked inexorably to destroy the lettering and render it illegible'.[8] He explained the damage as the result of having a glass plate placed over the parchment to protect it from further fading and tearing. Whatever the cause, today nearly the whole of the lower part of the document—all Europe west of the line of the Adriatic, the western Mediterranean and most of northern Africa—is undecipherable (Fig. 2).[9]

Unsurprisingly, as I am in the process of confirming, about a third of Capello's long list of transcriptions contains errors. Recourse to the nearly full-scale, double-page reproduction in Kamal's monumental *Monumenta Cartographica* would surely have greatly aided Capello's reading of names and inscriptions, but he either did not know of it or did not use it in his study, as the omission of any reference to Kamal in his essay suggests. It is uncertain, then, whether Capello was taking his transcriptions from the damaged original or the 1951 photograph (presumably Kamal's) of the undamaged map he reproduced in his monograph together with a number of close-ups of small areas.[10] Whatever the reason, the Vercelli *mappamundi* has hitherto neither featured prominently nor been fully incorporated into the canon of medieval maps, although it is frequently alluded to.[11]

The date ascribed to the Vercelli map has ranged from 'late twelfth–early thirteenth century' to 'second half of the thirteenth century', partly on the basis of the portrayal of a king of France (assumed to be one of the three Phillips reigning in that century) in Africa.[12] Its place of origin is even more disputed, with Destombes stating only that 'it is known to have been brought to Vercelli by Cardinal Guala Bicchieri.[13] It has been held that the map had come from England, but France and Spain have also been suggested.[14] The case for an English origin for the map rests on the hand (which could be English, as Capello noted), on the belief that the map could be from the Anglo-French school of *mappaemundi*, or on its association in the Vercelli cathedral archive with an Old English codex of singular importance, but the issue has by no means been resolved.[15]

The Vercelli map was drawn in black (now mostly faded to brown), red, green and sepia ink on a single piece of parchment. Errera measured it as 81 centimetres from top to bottom with the width varying, because of the deep tears along the sides, from 46 centimetres at the narrowest part to a maximum of 64 centimetres, but Capello contradicted these figures.[16] In any case, it would have been relatively small as a *mappamundi* intended for display. East is at the top, the island-packed Mediterranean runs from the Nile and Don rivers down the middle to the Atlantic at the bottom in the traditional manner of T-O *mappaemundi*, and the map contains a rich mix of biblical and contemporary places and mythological features as is characteristic of the genre.[17]

Apart from the missing pieces along the sides, the predominant problem for the modern scholar is the indecipherability, even invisibility, of outlines and lettering over extensive parts of the map. Northeastern Asia, at the top, is hard enough to read, northern Africa is nearly obliterated except for the outline of a large animal toward Libya, but it is above all western Europe that has defeated modern scholars. Fortunately, the faded nature of the damage and the importance of the document have made the Vercelli *mappamundi* a prime candidate for digital recovery of both drawing and text with the aid of multispectral imaging (MSI).[18]

Multispectral Imaging

The process of multispectral imaging (MSI) is designed to restore texts currently invisible to the naked eye. Its value in the study of documents is in creating a digital surrogate that not only can be easily circulated and analysed but that also offers the scholar an image with damaged parts recovered and restored to legibility. The technique is essentially photographic: a series of images is taken under different wavelengths of light,

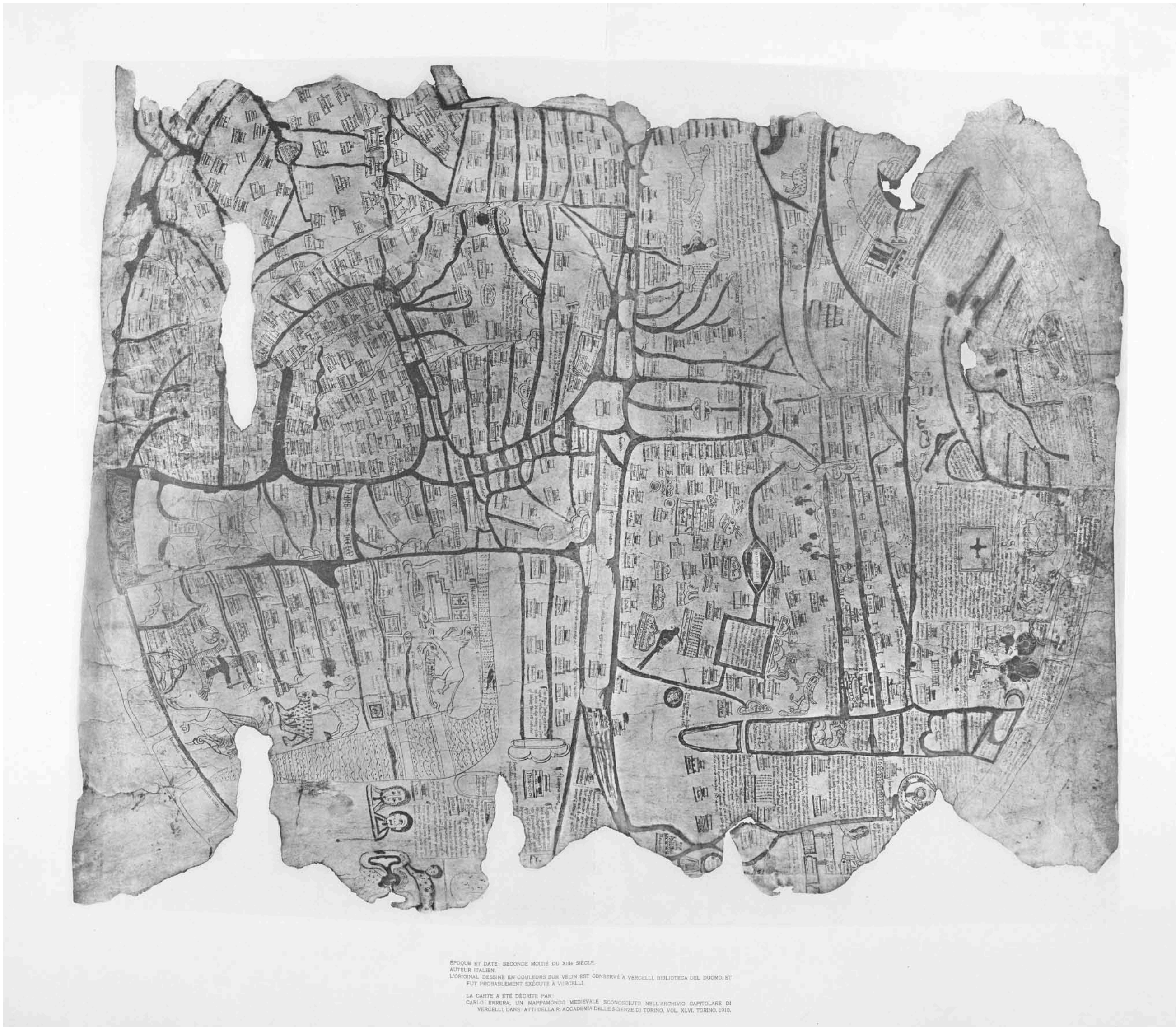

Fig. 1. The thirteenth-century Vercelli *mappamundi* as reproduced in 1951 in Youssouf Kamal, *Monumenta Cartographica Africae et Aegypti* (Cairo, 1926–1951), tome 3, fasc. 5, no. 997). 72 × 58 cm. East, at the top of the map, is on the right, Ink on a single parchment that was heavily torn along the sides, that is, at the exposed ends of the roll in which it was stored, and that had already suffered some fading, especially along the top. Dimensions of the manuscript when rediscovered were probably about 84 × 70–72 cm (see text note 16). Kamal's caption below the map notes that Carlo Errera 'described' the map in 1910 (when no reproduction was published). © The British Library Board,

Maps Ref. 156.

Fig. 2. Detail from the bottom left of the Vercelli map, showing western Europe as recorded on Youssouf Kamal's 1951 reproduction (see Fig. 1). Compare this with the same area on Plate 13. In the box are the toponyms now transcribed as *Osiria* (?Osini), *Galice* (presumably Galicia) and *Salemarām* (presumably Salamanca), together with *Seble* (presumably Seble). The long narrow white patch is a hole in the parchment. © The British Library Board, Maps Ref. 156.

building on the familiar conservation technologies of infrared (IR) and ultraviolet (UV) photography. These, however, capture only one wavelength of light at a time, whereas MSI significantly extends this technology, first by taking images under a broad range of bands across the light spectrum and then combining the bands by statistically processing the data to produce a single image on which traces of ink and pigment that are no longer visible to the naked eye can be discerned and interpreted as lettering, lines and figures.

The key to MSI is that pigments, inks, parchment and all other components of a manuscript respond differently to individual wavelengths of light. Ultraviolet light, for example, has a short, energetic wavelength that provokes a fluorescence from the parchment, causing it to glow, unlike the pigments that do not fluoresce in the same way.[19] The camera records this contrast, bringing out or sharpening otherwise invisible or faded material and rendering it legible.

The equipment needed for multispectral imaging comprises a camera, lens, lights and a copy stand.[20] The type of light source used is important. MSI systems like the Archimedes Palimpsest Project used a broad-spectrum white light to which filters were applied to break it up into individual wavelengths until it was found that these were liable to harm the document by focusing excessive heat and light onto the parchment.[21] Accordingly, modern MSI systems use LEDs, which emit significantly less heat and are set to narrow bands of light.[22] Therefore the document is exposed to less energy, light and heat, which, in turn, prevent the document from suffering damage in these ways. A computer deploys the lights in sequence at controlled wavelengths, each of which is captured by the camera in turn.[23]

Another specification of a high-quality MSI system is the use of a monochrome sensor. In a camera with colour sensors, such as the iPhone or digital camera (DSLR), a bayer array of filters is placed between the camera lens and the image sensor. This provides a red, green and blue filter on every image. With a monochrome sensor, this filtering does not take place, effectively increasing the resolution by at least a third.[24] The computer program controls the wavelength, and thus the colour of light in each image making the monochrome sensor feasible. Instead of taking a single image in colour, as happens with an iPhone or DSLR, our program combines ten single wavelength monochrome images into one true-colour image that presents higher colour fidelity than the traditional colour photograph in which only three wavelengths are combined

Capturing the Vercelli Map

In 2013, the Lazarus Project travelled to Italy to capture the Vercelli map with an up-to-date MSI system made by MegaVision, Inc.[25] This system uses LEDs in sixteen wavelengths, a 50-megapixel monochrome camera, a lens corrected for wavelengths beyond the visible spectrum, a dual-filter wheel and a multispectral transmissive light source to illuminate the parchment from below. The two bespoke LED panels emit twelve wavelengths. These LEDs are placed next to the manuscript in a manner similar to that of traditional digitization set-ups. We imaged in reflectance and fluorescence with these lights.[26]

Alongside this method of imaging, the Lazarus Project used a single-band transmissive light on the Vercelli map. This has evolved into the current four-band transmissive protocol (cyan, amber and two infrared bands at 780 and 940 nanometres). When this four-band light shines up through the map from below, it illuminates places where the ink had eaten into the parchment, thinning it. Imaging the Vercelli map in this way, with twenty overlapping tiles, ensured high resolution over the entire document.

Thus far the outcome has been a high-resolution stitched colour facsimile of the map as seen under natural light.[27] I am now working to process this to create high-resolution multispectral images that reveal previously illegible details, thus digitally reversing the damage. At the time of writing, nineteen of the twenty image tiles have been successfully processed, but I am still experimenting with new techniques in order to recover at least something from the final tile, that of the most severely damaged fragment of the map. My ultimate aim is to publish a digital facsimile of the Vercelli *mappamundi* by 2021 from the processed images only, accompanied by a transcription of all place-names and other writing on the map.

First, however, a number of technical difficulties presented by the most damaged part of this final tile have to be overcome. While the top part of the original map suffered dramatic fading, the bottom left-hand corner, depicting Europe, seems to have suffered an extra level of damage. There is no record of a chemical reagent having been used on the map, yet something more than fading seems to have erased the content of this part of the document, and the manuscript in this corner appears mottled. Whereas the top half of the map is just frustratingly faint, this bottom section, particularly Europe, is blurred, and lines that in the rest of the map would be fairly obviously representing green waterways are here interrupted by holes. In this section, and in this section alone, the green pigment has eaten through the parchment, suggesting that something has heightened the acidity or corrosiveness of the pigment.

Furthermore, the city signs in this area are not faint and illegible as elsewhere; instead, several dark smears encourage the reader to suspect there were once lines indicating cities, as noted below. Elsewhere in Europe, large patches appear blank, but common sense and comparison with Kamal's photograph indicate that these areas were not formerly empty. Finally, some city signs in this part of the map reveal themselves inversely, meaning that whereas a mapmaker would mark a place in dark ink for it to stand out on the pale parchment, some city signs are lighter than the surrounding parchment. One might think of a dirty wall from which a framed picture has been removed; the wall behind that frame remains lighter than the surrounding wall having been protected from dirt and damage. Whatever caused this kind of damage, however, seems to have removed some of the deeper traces of ink and pigment in the parchment that MSI can normally easily recover.

Plate 14 shows what can be seen of this western part of Europe with the naked eye: namely, virtually nothing, apart from the outlines of a river with three branches, a couple of additional linear features, the ghosts of a group of short lines on the left and a scatter of rectangles towards the centre.

A comparison of this area on Kamal's photograph of the undamaged map identifies these markings as rivers with a dense array of named city signs filling the interfluves (see Fig 2).Traditional technologies, such as UV and IR photography, would not be sufficiently discriminating to bring out anything like the potential wealth of data hinted at in the false colours of the multispectral image (Plate 15), and even a further stage of intensive statistical image manipulation is necessary before the MSI data can be rendered fully legible and useful to scholars (Plate 16).

Although MSI teams around the world have been using a variety of image processing software to enhance their data, no program was designed solely for rendering cultural-heritage artefacts. Some employ ImageJ, an open-source, Java-based application developed by the American National Institutes of Health, others turn to the computer programs MATLAB (Matrix Laboratory) or ENVI (Environment for Visualizing Images, developed by Harris Geospatial Solutions). The Lazarus Project tends to use ENVI for statistical image processing, and this is the application I have used for the Vercelli map. Although quite simple processing was sufficient to recover large parts of Asia, the most severely damaged areas at the bottom of the map, described above, demanded more extensive statistical processing. In my own attempts to emphasize the contrast between the ink and the surface of the parchment, I have found Principal Component Analysis (PCA) a particularly valuable tool. PCA works by grouping all variables in the MSI data set into a progressively smaller number of main classes (the principal components), thereby significantly enhancing the legibility of the map.

The results can be gratifying, as we see by comparing Plates 14 and 15. In Plate 15, the strange colouration, known as false or pseudo-colour, is the result of combining the processed red, green and blue image bands and inserting additional wavelengths (bands) into those channels.[28] The new combination creates the pseudo-colours. Bewildering as these might seem at first, the colours can be useful in helping to read newly recovered text. The contrast, although weird, helps the reader to see new material and to start systematically checking Capello's transcriptions.

Best of all for the humanities scholar is the final data-processing stage shown in Plate 16. Here we see what can be achieved by combining processing techniques, as Nicole Polglaze, a 2017 summer intern at the Rochester Institute of Technology, has done. She started by creating a base image by breaking up reflectance and fluorescence wavelengths into separate groups and processing them independently. Then she performed extensive statistical image processing, including PCA, on each of those sub-groups. I then combined this highly processed image with the first natural light image (see Plate 14). By changing the colour space to LAB (a standardized colour space) in Photoshop, I was able to insert the processed image into the luminance channel to create a semblance of the original manuscript that included the newly processed data (Fig. 3).[29]

Fig. 3. Detail illustrating the improvement of legibility after intensive manipulation of the MSI data along the bottom of the Vercelli map. At the top is part of the extreme southwest of Europe as seen by the naked eye (see Plate 14). Below is the same area at the final data-processing stage revealing three towns, part of the line of the surrounding Ocean and at least one (named) island in the outer rim. MSI Tile C02R04. Processed by Helen Davies. Reproduced with permission from Archivio Capitolare di Vercelli, Rotoli figurati, 6. © Fondazione Museo del Tesoro del Duomo e Archivio Capitolare di Vercelli, Italy.

From this, new words started to emerge and corrections to the toponymy became possible. For instance, where Capello recorded a river in Asia Minor not far from Antioch as 'illegible', my processing of the multispectral imaging suggests the map had labelled it *Fluminum Agnus*. Likewise, Capello's unknown *Naddocia* is quite clearly *Laodocia*, a well-documented Hellenistic city in Asia Minor. At the same time, Capello's transcription of a Biblical city in the Holy Land as *Sichar* could conceivably have been informed by his familiarity with the New Testament for, although the processed images seem to reveal an *i* as the final letter, making the name *Sichai*, an unknown place, Sichar was a Samaritan city described in the New Testament as situated near Jacob's well (John 4:5). Spelling variations of this nature are not unknown on the Vercelli map as on any medieval map—for example, Gog and Magog are inscribed as Goz and Magoz. On principle, however, it is important to represent what the map actually says rather than what we might feel it should say.

Recovering the Vercelli Map

Although in Errara's and Kamal's day, the map was mostly legible, neither of them published a transcription of the names and texts they could have read. The first attempt at a comprehensive listing was compiled by Capello when the map was already damaged and only partly legible. As noted above, though, Capello was not always reliable in his readings and identifications even where he could list the equivalent names as found on the Hereford and Ebstorf *mappaemundi*. Uncertainties will surely remain—not least when the scribes of the Vercelli map may themselves have made errors —but a new reading of the Vercelli map is long overdue and the application of MSI to the map is already proving illuminating. I conclude this brief report on current work on the map with some examples of what can be achieved.

To start at the top of the map. Little of the narrow band encompassing the world remained even in Kamal's day, but his photograph shows that it was originally filled by a series of oblong outlines representing islands containing two or three lines of descriptive text and drawings of strange beasts and plants (see Fig. 1). Capello transcribed the text on one of these islands as 'hic est insula caos; hic non regnat ventus, arbores istius terre semper habent folia' (Fig. 4 and Plate 17). From the newly recovered image, however, we can sharpen the reading to 'hic est insula tilos.

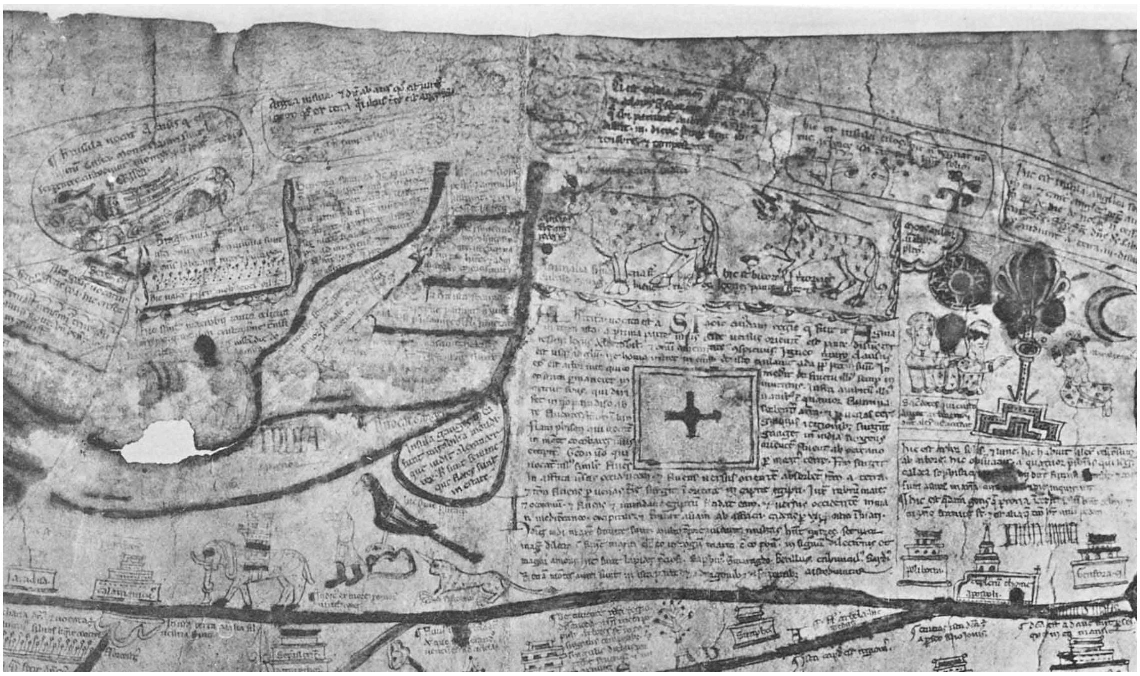

Fig. 4. Detail from the outer band at the top of the Vercelli map as recorded in Youssouf Kamal's 1951 reproduction showing the island of *Tilos*, which Carlo Capello transcribed from the damaged original as *caos* (see Fig. 1 and Plate 17).

hic non regnat ue(n)tus. arbores. iustus t(er)re semper h(abe)nt folia', meaning 'this is the island *tilos* [Tilos, in the Indian Ocean]. Here there is no wind, the trees of this land always have leaves'.[30] Not far below this island, in India and close to an elephant bearing what appears to be a howdah on

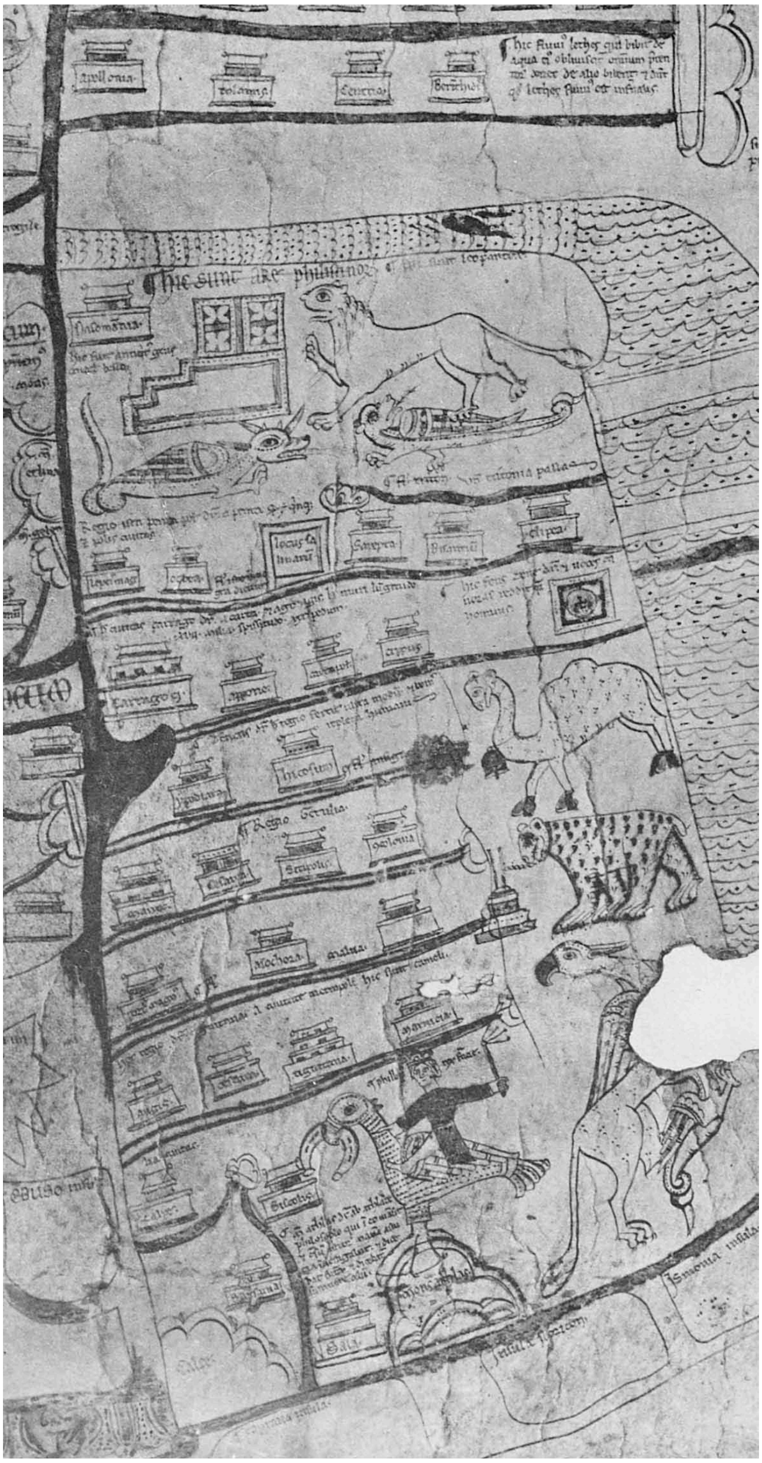

Fig. 5. Detail showing northern Africa on Youssouf Kamal's 1951 photograph of the Vercelli map (see Fig. 1). New transcriptions include *Asochora* and *aagris* (which could be the classical site *Agris*, location unknown). © The British Library Board, Maps Ref. 156.

its back, we find a city labelled *Calamanicus*. Capello recorded this place as *Calaniqui cy* although he could not offer an equivalent from either the Hereford or the Ebstorf maps.

In the southwestern quarter of map, the depiction of northern Africa seems to have passed through the centuries relatively unscathed to judge from Kamal's photograph, only to be badly damaged in the twentieth century (Fig. 5). Now little of the text in this part of the original map can be made out with the naked eye. With the aid of the MSI images, though, it is possible to resolve Capello's indecision about the identity of a city he listed as 'Asochora or Morchora', which can now be identified unambiguously as *Asochora*. For another place in this region, for which Capello could evidently make out no more than ' –gie', the processed images show it clearly to be *aagris*.

Thus encouraged, we can turn to the most damaged part of the map where almost nothing of western Europe can be discerned in natural light on the original manuscript. Here the full potential of MSI begins to be appreciated. Spain, for instance, nestling between the Mediterranean and the edge of the world, is at last coming into focus. Whereas Capello could make out little from the ghostly markings of former city signs (preserved from the dirt that dimmed the surrounding parchment by the ink lines until the pigment itself mouldered away), we can now correct or confirm his suggestions with some confidence. The city he transcribed as *Sebie*, for instance, we can now see was originally written *Seble*, his *Glides* was inscribed *Galice* (the middle letter clearly has no ascender to make a 'd'); and a place Capello failed to read at all is revealed to be *Salemarām* (with a contraction over the second 'a') (see Fig. 2).

Improving the legibility of just one or two letter forms can make all the difference when it comes to identifying the place. Thus, where Capello had *Osbia*, close examination of the most intensively processed MSI images shows this cannot be right. Again there is no ascender and at present the most likely reading has to be *Osiria*. I cannot say conclusively what this toponym represents today, but the website Pelagios suggests Osini, Italy, as one possibility. Whereas, however, we may allow ourselves to be encouraged by such successes in Iberia, it is still a major struggle to recover any place in France, the single most badly damaged part of the parchment. Here, each recovered name becomes a huge victory, like my reading *Limogus* in the appropriate location for Limoges, instead of Capello's *Almogum*.

In such manner, slowly and one by one, the overall distribution pattern of the cities marked on the map is emerging. Eventually the scholar can take over and explain the selection and the thinking behind the composition of the Vercelli *mappamundi.*

As has been made clear throughout this article, the image processing that is leading towards the unveiling of the original Vercelli *mappamundi* is still in progress. As I process each bit of data, I am looking forward to uncovering something new—a toponymical secret that will need to be unlocked—and to highlighting another historical challenge. Eventually, with the full digital facsimile created with *Digital Mappa* to hand, I hope the Vercelli map will attract renewed attention and be restored to its rightful place in the corpus of early maps of the world.[31] What I have been able to demonstrate in this interim article is that, while the new digital techniques can 'work wonders' in coaxing distressed medieval maps to reveal writing and drawings thitherto assumed lost forever, it is no less apparent that the historian and the scientist have to work closely together if the former is to have confidence in the latter when something unexpected emerges.

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NOTES AND REFERENCES

1. The Lazarus Project is directed by Gregory Heyworth, formerly associate professor of English at the University of Mississippi and now associate professor of English at the University of Rochester, New York.
2. Vercelli, Archivio Capitolare di Vercelli, Rotoli figurati, 6 [Mappamondo]. For an introduction to the Hereford map, see P. D. A. Harvey, *Mappa Mundi. The Hereford World Map* (London, The British Library, 1996); for the inscriptions, see Scott D. Westrem, *The Hereford Map: A Transcription and Translation of the Legends with Commentary* (Turnhout, Brepols, 2001). For the Ebstorf map, see Hartmut Kugler, *Die Ebstorfer Weltkarte. Kommentierte Neuausgabe in zwei Bänden* (Berlin, Akademie Verlag, 2007).
3. Carlo Errera, 'Un mappamondo medievale scnosciuto nell'Archivo Capitolare de Vercelli', *Atti della R. Academia delle Scienze di Torino* 46 (1910): 8–11;

[idem], 'Un mappamondo medioevale ritrovato a Vercelli', *Rivista Geografica Italiana* 46 (1911): 107. Neither note includes an illustration.

4. ' … e ancora basta visibile': Errera, 'Un mappamondo medievale scnosciuto' (see note 3), 8.

5. Youssouf Kamal, *Monumenta Cartographica Africae et Aegypti*, 5 vols. in 16 parts (Cairo, 1926–1951), tome 3, fasicule 5, no. 997; Leo Bagrow, *Die Geschichte der Kartographie* (Berlin, Safari-Verlag, 1951), plate 21. See also Leo Bagrow, *History of Cartography*, revised and expanded by R. A. Skelton (Cambridge, Harvard University Press, 1964; enlarged and reprinted Chicago, Precedent Publishing, 1985), plates XXX and XXV respectively.

6. Carlo F. Capello, *Il mappamondo medioevale di Vercelli (1191–1218?)* (Turin, Stabilimento Tipografico C. Fanton & C., 1976; vol. 10 in the Università di Torino, 'Memorie e Studi Geografica' series), 6.

7. ' … avec des traces d'humidité qui rendent sa lecture très difficile': Marcel Destombes, ed., *Mappemondes A.D. 1200–1500*, for the Commission des Cartes Anciennes de l'Union Géographique Internationale (Amsterdam, N. Israel, 1964), no. 52/1, pp. 193–94, and plate XXIII; quotation on 193. Destombes's gives different dimensions (84 × 70–72 cm) compared with Errara's (81 × 64 max or 46 cm min), which Capello, *Il mappamondo medioevale di Vercelli* (see note 6), 15, made a point of correcting to 84 ×70–72 cm. Among those who derived their illustration from the 1951 photograph is David Woodward, 'Medieval mappaemundi', in *The History of Cartography*, vol. 1: *Cartography in Medieval Europe and the Mediterranean*, ed. David Woodward and Brian Harley (Chicago, Chicago University Press, 1987), fig. 18.17 at 308.

8. ' … l'umido, le muffe ed il tempo lavoravano inesorabilmente a distruggerlo ed a renderne illeggibile le scritture': Capello, *Il mappamondo medioevale di Vercelli* (see note 6), 6. The damage is well illustrated in Capello's numerous plates.

9. In one of the few modern attempts to study the map, Anna-Dorothee von den Brincken reported it as 'in very bad condition, a fragment, faded by damp and partly illegible': Anna-Dorothee von den Brincken, 'Monumental legends on medieval manuscript maps: notes on designed capital letters on maps of large size (demonstrated from the problem of dating the Vercelli map, thirteenth century)', *Imago Mundi* 42 (1990): 9–25, quote on 9. Leonid S. Chekin, 'Northern Eurasia in medieval cartography: inventory, text, translation, and commentary', *Terrarum Orbis*, vol. 4 (Turnhout, Brepols, 2006), also reproduced the 1951 photograph.

10. All reproductions of the whole map are small compared with Kamal's (70 cm in height). Capello's folded illustration measures 37 cm in height, and Bagrow's and Destombes's are each about 20 cm.

11. Neither Kamal nor Bagrow has anything to say about the Vercelli map. See, however, P. D. A. Harvey *Medieval Maps of the Holy Land* (London, The British Library, 2012), 14, 25, 28 and figs. 17 and 39; Peter Barber, 'Mappa Mundi di Vercelli', in *Segni e Sognia della Terra. Il disegno del mondo dal mito di Atlante alla geografia delle reti* (Milan, de Agostini, 2001), catalogue for the exhibition held in the Palazzo reale Milan in 2001, 67; and Asa Simon Mittman, 'The Vercelli map (*c.*1217)', in *A Critical Companion to English Mappae Mundi of the Twelfth and Thirteenth Centuries*, ed. Dan Terkla and Nick Millea (Woodbridge, Suffolk, Boydell & Brewer, 2019), 127–46. Mittman's description of the recovered content of the map is based, however, on high-resolution scans taken by the Lazarus Project at the same time as the MSI images discussed in the present article.

12. Capello, *Il mappamondo medioevale di Vercelli* (see note 6), 21, opted for a date between 1191 and 1218. Harvey, *Medieval Maps* (see note 11), 25, places it in the early 13th century, as do Barber, 'Mappa Mundi di Vercelli' (see note 11), 67, and von den Brinken, 'Monumental legends on medieval manuscript maps' (see note 9), 15. Mittman, 'The Vercelli map' (see note 11), has *c.*1217. Those favouring a date later in the thirteenth century include Errera, *Un mappamono* (see note 3), 9, and Kamal, *Monumenta Cartographica* (see note 5), 997. According to Mordechay Lewy, who has revisited the reputation of the last of the three King Philips of France, the date lies between 1270 and 1285 (forthcoming in this journal).

13. 'L'on sait que la carte a été apportée à Vercelli par le Cardinal Guala Bicchieri lequel, vers 1220, fonda un college pour étudiants (Scola Santi Eusebii)'. Bicchieri's college became the initial nucleus of the 'Studium Generale Vercellense' recognized by the commune in 1228. Destombes, *Mappemondes* (see note 7), 194. I am doubtful about Destombes's statement.

14. The following support an English origin of the map: Woodward, 'Medieval mappaemundi' (see note 7); Harvey, *Medieval Maps of the Holy Land* (see note 11); Barber, 'Mappa Mundi di Vercelli' (see note 11); and Mittman, 'The Vercelli map' (see note 11). Capello followed Errera in noting the density of Spanish and Italian places on the map, although Errera also pointed to some errors in the original place-names; Capello, *Il mappamondo medioevale di Vercelli* (see note 6), 11. According to von den Brincken, 'Monumental legends on medieval manuscript maps' (see note 9), 11, Anna Maria Brizio thought the drawings looked Spanish: Anna Marie Brizio, *Catalogo delle cose d'arte e di anitchita d'Italia*, vol. *Vercelli* (Rome, 1935), 109–10.

15. Capello, *Il mappamondo medioevale* (see note 6), 11. The enduring England–Vercelli association owed much to the Italian city's location on the pilgrim route to Rome. For scholarly relations between France and England in the context of the early *mappaemundi*, see Dan Terkla, 'Hugh of Saint Victor (1096–1141) and Anglo-French Cartography', *Imago Mundi* 65:2 (2013): 161–79, esp. 171.

16. Capello, *Il mappamondo medioevale di Vercelli* (see note 6), saying that Errera was wrong, gave the dimensions as 84 × 70–72 cm, the figure adopted by Destombes in 1951 and von den Brinken in 1990. Kamal gave no dimensions, and his photograph (printed at 70 cm in height and 57.5 cm wide at most) is somewhat reduced. The Lazarus Project's measurements agree with Capello's.

17. Mittman, 'The Vercelli map' (see note 11), 138–49. See also the gazetteer in Capello, *Il mappamondo medioevale di Vercelli* (see note 6), 20–115. The frayed parchment is now a rough-edged rectangle; Destombes, *Mappemondes* (see note 7), 193, described it as oval, and Mittman, 'The Vercelli map' (see note 11), 131, conjectures that it was circular. His essay contains a detailed interpretation of the topographical content of the map.

18. Multispectral imaging works best when the ink has sunk into the substrate over time, thus allowing the imaging technology to pick up traces no longer on the surface of the manuscript and invisible to the naked eye.

Therefore damage like that affecting the Vercelli map, made after centuries of the ink sitting on a thick and absorbent substrate, responds well to recovery efforts using this type of technology.

19. My colleague at the University of Rochester, Alexander J. Zawacki, describes the effect evocatively: 'Anyone who has worn a white shirt under a black light will be familiar with this phenomenon. There, the fabric of shirt is absorbing the invisible ultraviolet light and re-emitting it down-spectrum as visible blue light'. Helen Davies and Alexander J. Zawacki, 'Making light work: manuscripts and multispectral imaging', *Journal of the Early Book Society* 22 (2019): 179–96.

20. The stand, or cradle, holding the document being scanned resembles the stands used in traditional digitization, although a number of MSI teams have made specific modifications to their copy stands. For example, Michael Phelps and EMEL (Early Manuscripts Electronic Library) in collaboration with Stokes Imaging have developed a computer-controlled book cradle that rotates the spine of the manuscript as the pages are turned. For more information see 'Technologies', Sinai Palimpsests Project, http://sinaipalimpsests.org/technologies (accessed 16 July 2018).

21. For a full description of the Archimedes Palimpsest Project, see Reviel Netz and William Noel, *The Archimedes Codex: How a Medieval Prayer Book Is Revealing the True Genius of Antiquity's Greatest Scientist* (Boston, Da Capo Press, 2007).

22. For a detailed description, see Greg Bearman, Ken Boydston and William A. Christens-Barry, 'Measuring the illumination exposure of LED illuminants in a multispectral imaging system', MegaVision, Inc., http://www.mega-vision.com/news/pdfs/LED_exposure_of_EV_System_at_IAA.pdf (accessed 21 January 2020), 1–6 at 6.

23. For a more detailed description of an MSI system see William Christens-Barry et al., 'Camera system for multispectral imaging of documents', *Proceedings of SPIE —The International Society for Optical Engineering* 7249, Sensors, Cameras, and Systems for Industrial/Scientific Applications X, 724908 (2009). MegaVision, Inc. systems use Photoshoot for image capture, calibration and export (see http://www.mega-vision.com), and PhaseOne cameras may use Capture One for both camera control and image editing (see https://www.phaseone.com).

24. The ideal camera also has lenses designed to capture sharp images across the UV and IR bands as well as visible light; standard lenses tend to blur images in wavelengths beyond the visible since they are not calibrated specifically to each band.

25. The Project's team, led by Gregory Heyworth (see note 1), included Ken Boydston (Chief Executive Officer at MegaVision), Roger Easton (Center for Imaging Science at Rochester Institute of Technology), Michael Phelps (Executive Director of the Early Manuscripts Electronic Library, http://emel-library.org/), and students from Sally Barksdale Honors College (University of Mississippi). They spent two months in Italy on the imaging alone. I have spent four years since that trip processing the data. The Lazarus Project had already imaged the Anglo-Saxon Vercelli Book, the famous Old English Poetic codex (Vercelli, Biblioteca Capitolare, MS XVII).

26. Fluorescence is the absorption of light at a shorter wavelength and re-emitting it at a longer wavelength (see note 19). This frequently causes an object to appear as if it is glowing. Reflectance is what we think of as traditional photography, where the light captured is simply what is reflected back by the object being photographed.

27. Asa Mittman has used our natural-light stitched images in his research and published it in Asa Simon Mittman, 'Reexamining the Vercelli map', in *Ordinare il mondo. Diagrammi e simboli nelle pergamene di Vercelli*, ed. Timoty Leonardi and Marco Rainini (Milan, Vita Pensiero, 2019); and in Mittman, 'The Vercelli map' (see note 11). We hope that the processed images will yield yet more data for him and others in the future.

28. Every digital (non-MSI) image is composed of three channels: red, green and blue. When we look at a normal image, the red channel is occupied by an image band showing red wavelengths (650 nanometres or nm), the green channel has green wavelengths (530 nm), and correspondingly for the blue (450 nm). During image processing, we may insert other wavelengths (bands) into those channels, and pseudo-colours result from the new combinations.

29. For a handy guide, aimed at the nonspecialist, to the use of Photoshop to improve manuscript legibility see Julia Craig-McFeely and Alan Lock, *Digital Restoration Workbook*, (Oxford, OSSC Publications, 2006; https://www.diamm.ac.uk/publications/digital-restoration-workbook/). On the opportunities and difficulties of such digital editing, see Julia Craig-McFeely, 'From perfect to preposterous: how digital restoration can both help and hinder our reading of damaged sources', in *Cantus Scriptus: Technologies of Medieval Songs*, Proceedings of the 3rd Annual Lawrence J. Schoenberg Symposium on Manuscript Studies in the Digital Age, 20–21 November, 2010, ed. Lynn Ransom and Emma Dillon (Piscataway, NJ, Georgia Press, 2012), 125–41.

30. It is not impossible that Capello's transcription 'caos' was correct, but no such place can be identified whereas the reading 'tilos' points to Telos, referred to in Isidore, *Etymologiae, XIV.3.5*, among other ancient authors, 'where the vegetation is green in every season'. I am grateful to Alexander Scafi for this reference.

31. The website *Digital Mappa*, for *mappaemundi*, is at https://www.digitalmappa.org/.

Plate 13. The Vercelli *mappamundi* as it is today, showing the extensive damage from humidity and obliteration of toponyms, city signs and other topographical features. Scarcely anything can be made out with the naked eye for Europe, the Mediterranean west of the Adriatic (bottom left quarter and centre), and the adjacent parts of northern Africa. At the top, northeastern Asia has suffered similarly. Dimensions today approx. 84 × 72 cm. Vercelli, Archivio Capitolare di Vercelli, Rotoli figurati, 6 [Mappamondo]. Reproduced with permission from Archivio Capitolare di Vercelli. See p. 181.

Plate 14. Detail from the multi-spectral image of the thirteenth-century Vercelli *mappamundi*, Stage 1: as seen by seen by the naked eye under natural light (MSI tile C02R04). In this state, almost nothing is discernible of this part of western Europe, usually thought to be Spain. The long narrow white patch is a hole in the parchment (see Fig. 2). Below the left end of the hole, traces of a group of short lines can be made out. Elsewhere a scatter of ghostly rectangles over the land would seem to indicate former city signs. The white branched line on the right resembles a river. Processed by Helen Davies, the Lazarus Project, University of Rochester. Reproduced with permission from Archivio Capitolare di Vercelli. © Fondazione Museo del Tesoro del Duomo e Archivio Capitolare di Vercelli, Italy. See p. 185.

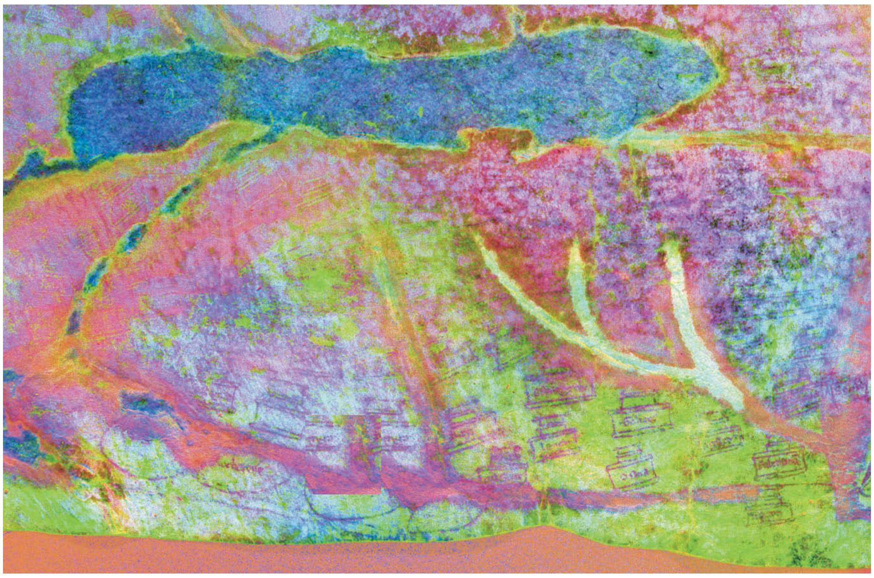

Plate 15. Preliminary multi-spectral imaging, Stage 2. The same detail of the Vercelli map as in Plate 14 in pseudo-colours and considerably improved by significant digital processing. The city signs are clearly seen although the names remain illegible. The use of transmissive light has revealed where the acidic content of the pigment used in this part of the map to delineate the rivers has reduced the thickness of the parchment. MSI Tile C02R04. Processed by Helen Davies, Lazarus Project, University of Rochester. Reproduced with permission from Archivio Capitolare di Vercelli. © Fondazione Museo del Tesoro del Duomo e Archivio Capitolare di Vercelli, Italy. See p. 186.

Plate 16. The same part of the Vercelli map as shown in Plates 14 and 15: Stage 3. Here, especially intensive processing of the MSI data has sharpened the city outlines and, most importantly, rendered legible their names (see text and Fig. 2). Detail from Tile C02R04. Processed by Nicole Polegraze, Rochester Institute of Technology, and Helen Davies, the Lazarus Project, University of Rochester. Reproduced with permission from Archivio Capitolare di Vercelli. © Fondazione Museo del Tesoro del Duomo e Archivio Capitolare di Vercelli, Italy. See p. 186.

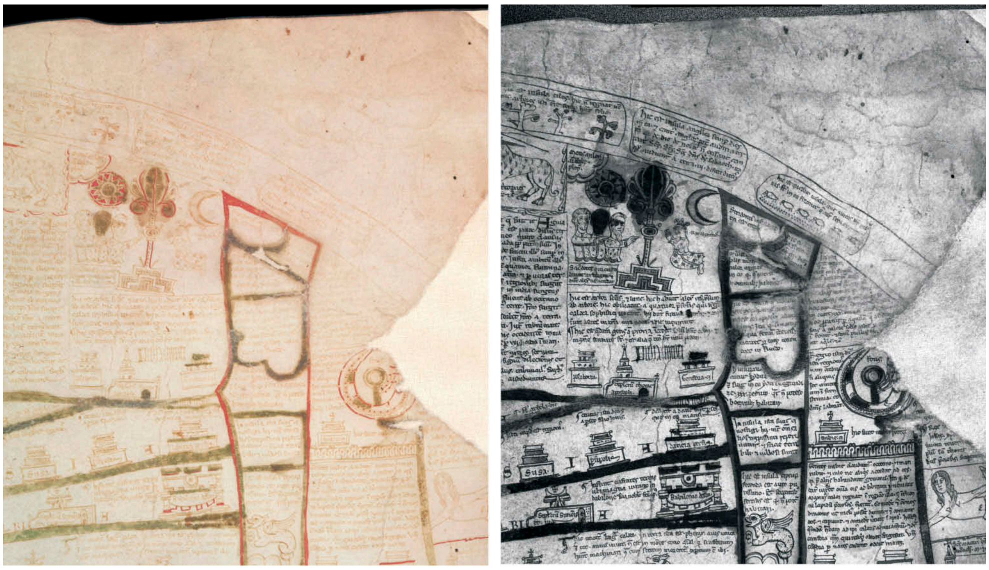

Plate 17. Detail from the upper right edge of the Vercelli map showing the island of *tilos* (Tilos) in the outermost rim as revealed in the multispectral image, processed by Helen Davies, of the damaged map today (left). Compare the legibility of the island's trees and text there with Kamal's image in *Monumenta Cartographica* (1951) (right). Compare the scarcely recognizable text and details of the trees here with Plate 13. © British Library Board, Maps Ref. 156; and Fondazione Museo del Tesoro del Duomo e Archivio Capitolare di Vercelli, Italy. See p. 187.

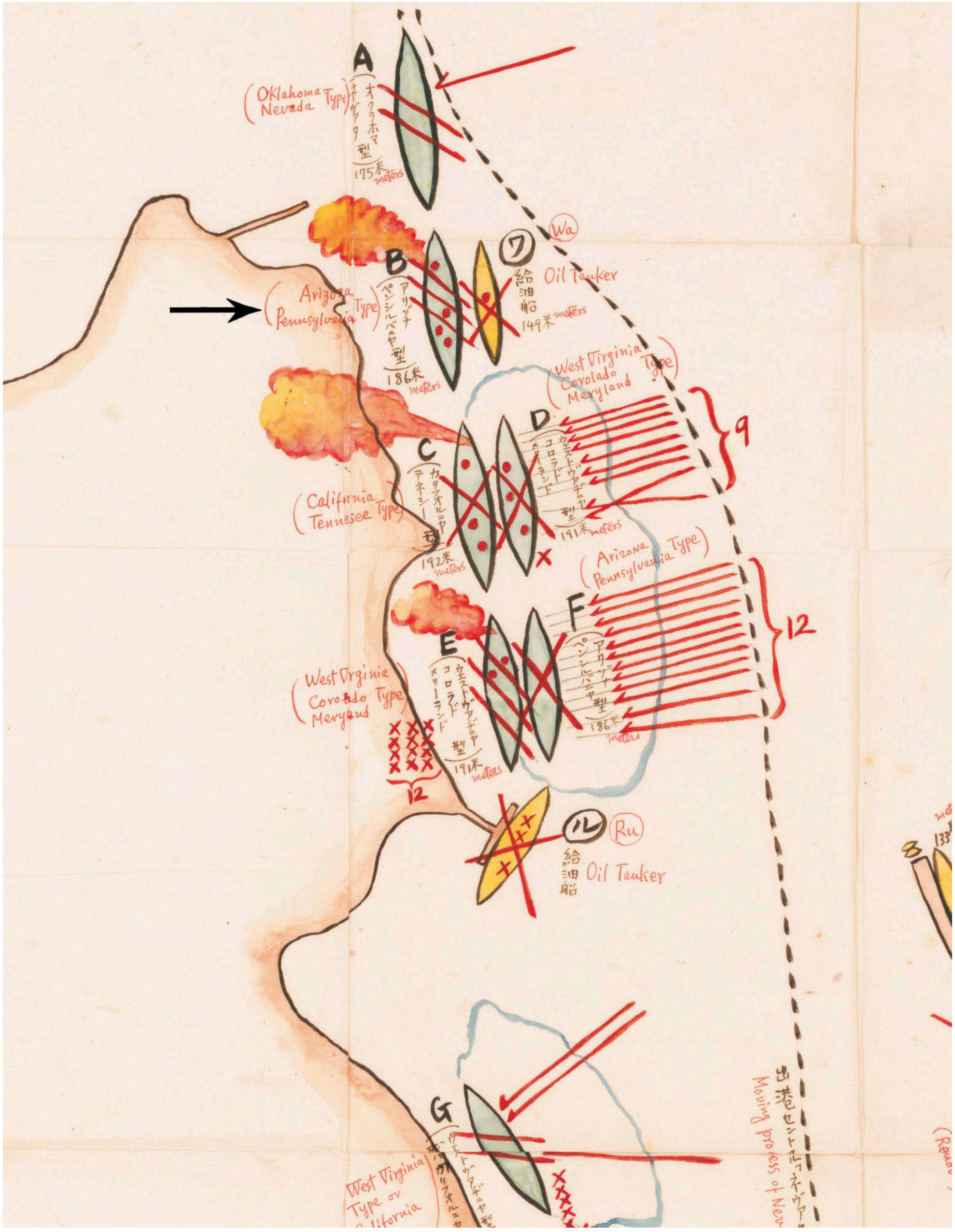

Plate 18. Mitsuo Fuchida's map of Pearl Harbor, Hawaii (1941). Detail showing which of the vessels on Battleship Row had been hit. These are depicted burning. The identity of each ship is noted in Japanese. The English translation may have been added later by Fuchida himself. Fuchida, however, had failed to note that the USS *Arizona* (arrowed) had been sunk. Here and in the key (see Plate 19) it is shown as seriously damaged. Washington, DC, Library of Congress, G4382.P4R3 1941 .F8. (Reproduced courtesy of the Library of Congress, Geography and Map Division.) See p. 195.