

Reconstructing the Fragmented Library of Mondsee Abbey

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The Benedictine monastery of Mondsee was an important local centre for book production in Upper Austria already shortly after its foundation in 748. A central factor for the growth of the library were the monastic reform movements, which prompted the production of new liturgical books and consequently the discarding of older ones. When a bookbinding workshop was installed in the 15th century many of these manuscripts, regarded as useless, were cut up and re-used in bindings for new manuscripts, incunabula or archival materials. The aim of our two-year project funded by the Austrian Academy of Science (Go Digital 2.0) is to bring these historical objects in one virtual collection, where their digital facsimile and scholarly descriptions will be freely accessible online to a wide group of scholars from the fields of philology, codicology, history of the book and bookbinding.

After a short glance at the history of Mondsee and the fate of the fragments in particular, this article gives an overview of the different procedures established in the project for the detecting and processing of the detached and in-situ fragments. Particular focus lays on the technical challenges encountered by the digitalisation, such as the work with small in-situ fragments partially hidden within the bookbinding. Discussed are also ways to address some disadvantages of digital facsimiles, namely the loss of information about the materiality of physical objects.

Key words:

Fragments, Manuscripts, Mondsee, Digitisation, Medieval library.

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INTRODUCTION

The history of the Abbey St. Michael in Mondsee has been the object of extensive studies [Wolfram 1989; Kaltenecker 1994; Heilingsetzer 2001]. In connection with the current research, it is useful to list succinctly several events, which influenced the literary activity and the book production in the monastery. The first known product of Mondsee scribes is the so-called Montpellier Psalter (Montpellier, Bibliothèque interuniversitaire, H 409) written probably for a family member of the founder of the monastery – the Duke of Bavaria Odilo from the house of the Agilofinger [Bischoff 1980]. As Mondsee changed its possessor in 787 and became an imperial abbey, it acquired not only land properties but also established a busy scriptorium. The textual witnesses from that period, almost exclusively fragments, are datable based on their palaeographical features to the end of the eighth century. A more direct regional connection with Bavarian monasteries was established in 831 as King Louis the Pious placed the abbey under the control of the Bishop of Regensburg. The so-called Bathurich-Pontificale (Cod. Ser. n. 2762, [F-zml0](#)) written by a Mondsee scribe is an example for the collaboration and exchange also encompassing the scriptorial activities between the two institutions. The Hungarian raids in the tenth century had a detrimental effect on the book production in Mondsee. The monastery entered a new period of prosperity in the second half of the eleventh and the twelfth centuries with the introduction of the Hirsau reform, which prompted the copying of new liturgical books. Fires and devastation marked the next two centuries, from which the abbey recovered only in the fifteenth century thanks to the reform movement initiated by the Abbey of Melk and the close connections with the university in Vienna. Due to the new monastic reform, the old books containing the Hirsau liturgical texts were no longer of use. Many of them were recycled as bookbinding waste when Abbot Benedikt II Eck (1463-1499) decided to refurbish the library and rebind almost all Mondsee codices.

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FROM MANUSCRIPTS TO FRAGMENTS

Although parchment books could last for centuries, quite often manuscripts and charters lost their value while remaining physically intact. Among the binding waste used in Mondsee, there is a significant number of charters, letters or notes for the day-to-day life. While such documents were often only relevant for a limited time before their content became obsolete, the parchment from which they were made remained a precious and robust material. One finds such leaves used as pastedowns (Fragm. 820, F-qwea), sometimes preserving even typical codicological features (Cod. 3586, F-ylan). Another reason for medieval librarians to discard manuscripts is probably also the development of the writing system, which made earlier scripts illegible for the subsequent generations of readers. In such cases, the importance of the text played hardly any role, for even diligently written and decorated books of the Bible landed at the binding workshop as is evident by a group of early Carolingian fragments from the Old Testament (Cod. Ser. n. 3753, Cod. 15347, Fragn. 6 and Fragn. 10, F-hyhn) or the Letters of Saint Paul (Cod. Ser. n. 2065). Another group are texts that were in constant use such as schoolbooks. A fragment from Donatus *Ars minor* (Cod. 3586, F-r8r7) written in clear Northern Textualis came to serve as a pastedown in a fifteenth-century Mondsee binding not because the script was incomprehensible, but plausibly because the pages got worn off, the text became damaged and needed to be replaced by a new (printed) copy. The lion share of fragments in the case of Mondsee, however, consists of liturgical texts from the eleventh to the fourteenth century, which even if in good physical shape were no longer conformant with the newly introduced Melk reform.

One way to reuse them was to try to scrape or wash off the older text and write a new one, thus producing a palimpsest. From the material that came down to us, it seems this was a rare practice in Mondsee. There is only one whole manuscript, a liturgical book dated to 1478 written by the monk Jacobus Keser (Cod. 1992). In most cases, however, the parchment leaves ended up as bookbinding waste in the hands of the bookbinder, who reused them in the form of pastedowns, flyleaves, covers, spine lining, and so on. Naturally, little survived from the initial manuscript, which was cut to pieces for the most part without any attention to the text or the illumination. Still, fragments are often our only evidence for the existence of these dismembered books, which makes them of great importance to historians of texts, script and library holdings.

MONDSEE FRAGMENTS TODAY

To find the fragments used as bookbinding waste one needs to trace the host volumes, that is, the Mondsee books and archival material. For the 1000 anniversary of the abbey in 1748, the abbot Bernardus Lidl published the so-called *Chronicon Lunaelacense* [Lidl 1749], the second part of which contains a catalogue of all the manuscripts from the ninth to the sixteenth century. According to it, the library possessed at the time 1013 manuscripts. After the dissolution of the abbey in 1791 almost all of them, namely over 760, were incorporated into the court library in Vienna, today the “Austrian National Library” (ÖNB). The incunabula and rare books from Mondsee remained in Upper Austria and many are kept today in the “Library of Upper Austria” (OÖLB). In the OÖLB repository, the Mondsee books were mixed with those previously belonging to other monastic and church institutions. It is, however, still possible to establish a Mondsee provenance for about 290 incunabula thanks to their characteristics such as spine labels, red and black shelfmarks and owners’ inscriptions. At least part of the archive of the monastery with over 500 boxes, 289 archival manuscripts and 323 charters survived in the “Archive of Upper Austria” (OÖLA).

The fates of fragments in the ÖNB is similar to that in other large libraries in Europe [Unterkircher 1988; Fingernagel 2010; Kaska and Simader (in print)]. It was only in the early nineteenth century that librarians and scholars showed interest in binding waste and an appreciation of their historical value. One of the first fragments to attract the attention of scholars were the so-called Mondsee Fragments, representing a collection of Christian texts written in Old High German in the early ninth century [Krotz 2002]. In 1833 Stephan Endlicher, a scribe at the court library later joined by August H. Hoffmann von Fallersleben, examined all Mondsee manuscripts in search of these old German fragments. They detached the fragments from the bindings and managed thus to reconstruct 27 leaves from the original manuscript, preserved today under shelfmark Cod. 3093*.

The practice of detaching early medieval and illuminated fragments from bookbindings continued, and for the most part, librarians placed them in booklets now kept predominantly in the collection *Codices Series nova*. Fragments, which librarians could not order or reconstruct, or considered less important remained in the fragment collection, where they are kept under shelfmarks Fragn. + numerus currens. Interested strictly in the textual content or illumination, scholars in the nineteenth century usually omitted to mark down the host volumes of the detached

fragments, so that vital information about the provenance of both binding and fragment got irreversibly lost. The same happened by the restoration of a manuscript when the binding was often renewed and many fragments detached. Only since the 1930s, there is sufficient documentation recording the host volume and the position of the fragments within the binding. For the Mondsee project concretely, this means that there are further undocumented Mondsee fragments within the collection, the provenance of which remain untraceable.

Significantly fewer binding waste was removed from the incunabula at the OÖLB. Among the circa 15 detached fragments there are pieces from an early Carolingian homiliary, calendar sheets, letters and pieces of liturgical music. Similarly, in the OÖLA among the so-called Buchdeckelfunde one finds listed around 20 pre-sixteenth-century fragments detached from Mondsee archival manuscripts. Unclear until now was the number of in-situ fragments in both collections, as studies on medieval bookbinding practice show that binders used old manuscripts as waste for both incunabula and as wrappers for archival material [Pickwoad 2000].

Mondsee fragments have already been the object of scholarly research: Kurt Holter [1950] and Bernhard Bischoff [1980] discussed many of the earliest witnesses from palaeographical point of view; Carl Pfaff [1967] studied the Mondsee scriptorium in the High Middle Ages, while Robert Klugseder [2012] collected and analysed all music texts produced in the monastery. The majority of the fragments, however, remain unknown to the general researcher community. The main reason for that is that such historical objects are notoriously difficult and time-consuming to describe, lacking virtually all of the aids of identification that manuscript researchers otherwise use, such as title page or rubrication stating the title and author or incipit [Unterkircher 1988]. The digital turn in the humanities has significantly facilitated the identification of texts using internet search engines and full-text specialised databases such as the Library of Latin Texts, Patrologia Latina Database, Repertorium biblicum, Acta Sanctorum Database and Cantus Index, to name just a few. The possibility to publish description and digital images online is another reason for the rise of fragmentology [Duba and Flüeler 2018].

PROJECT

The primary goal of the project funded by the Austrian Academy of Science (Go Digital 2.0) was to digitise the Mondsee fragments and to make them available as open access documents via the Fragmentarium web application¹. Each document is supplied with a detailed scholarly description of its content, codicological features, and known provenance. Users of Fragmentarium can easily search and filter the metadata or apply specialised facets to refine their queries. In that way, specialised scholars and the general audience can get to know these historical objects, some of which due to their fragile state are often not to be consulted in situ.

A close examination of the material by the project team was necessary in order to reconstruct fragmented manuscripts and to bring together fragments and their host volumes. A further aim was to explore the phenomena of discarding and recycling manuscripts for bookbinding in Mondsee.

The two-year project was hosted in the ÖNB with advisor Andreas Fingernagel and project manager Katharina Kaska. The team included two researchers (Ivana Dobcheva and Larissa Rasinger) and one photographer (Veronika Wöber). The initial step was to inspect all host volumes coming from the Mondsee library in order to see if there are in situ fragments in their bindings. This turned out to be the case in 358 of the 760 manuscripts in the ÖNB and in 118 of the 293 incunabula in the OÖLB. The number of singular fragments is, however, significantly higher, since very often fragments from several original manuscripts were used as binding waste in one binding. Hence, one should count with about 1050 singular fragments – here including the detached ones now stored in the collections *Codices series nova* and *Fragmenta*. While some are too small, illegible or hidden within the bindings to be properly investigated, the researchers managed to provide a full or partial description of around 700 fragments.

DIGITALISATION

The project also had the particular aim to develop guidelines for digitising fragments. The researchers and photographer worked in close collaboration, assuring best possible practice when it comes to objects that are difficult to access or document visually. All larger formats or fragments, which had to be digitised in a higher resolution (600 PPI), were scanned with the in-house scanner in the ÖNB, the Zeutschel OS 1400. The advantage of this A1-format linescanner is the low light pollution on the object - while the scanning process is done, only a small

¹ <http://fragmentarium.ms>

beam of light moves over the page. Images were saved in TIF-format. For colour, density and scale reference it is important to include a colour chart with every object – in this case the standardised Kodak Colour Control Patch. The photographer digitised each page and section of the binding on its own, whereby she paid attention to choose the right angle, so the page does not get contorted. In this way, it is easier to put several pictures from the same element together and visualise it digitally.

Thanks to the cooperation with the “Institute of Austrian Historical Research” (IÖG), the team had at their disposal a second mobile scanning machine – the Traveller’s Conservation Copy Stand – TCCS 4232. It is equipped with a portable camera stand with a Canon Camera and two lines of LED lights on each side. Depending on the dimension of the object and the resulting distance between the page and the lens of the camera, it has about 400 to 500 PPI resolution. To avoid stray light, the digitalisation was conducted in a dark room. For the Mondsee project, it was advantageous to have such a compact scanner, which could be positioned in the immediate vicinity of the manuscript storage, thus minimising the time (and personnel) needed to move the objects a relatively long way across the library to the digitisation centre.

Challenges by the digitalisation of fragments

Pastedowns and flyleaves are probably the least problematic fragments to digitise. A binding technique, not exceptional to Mondsee, was to hook the endleaves around and sewn with the outermost gathering – in this way strengthening the connection between the book block and the boards. Even if the hooks are blank (pertaining, for instance, to the margin of the original leaf), they were nevertheless digitised so that no information is lost about the codicological features of the original manuscript (such as original size of the leaf or existing pricking in the margin) or particular binding practice in Mondsee. One way to facilitate the online users is to include all codicological details in the description and explain the way the fragment is or was inserted in the binding. In the Fragmentarium app users can look at the digital facsimile and at the same time read the description in a toggle sidebar, as by Cod. 1118 (F-6l^{he}).

Significantly smaller and trickier to digitise is the type of binding waste called by Nicholas Pickwoad [2000] comb guard. He refers to it as a feature present exclusively in south German bindings. If the pastedowns are intact, such fragments are visible only as small slips cut at the height of the supports hooked around the outermost gathering. This technique seems to be well known in Mondsee, where one encounters it especially in bindings from the late fifteenth and sixteenth century. Although the visible parts are too small for adequately determining the content, it is often possible to define which group of fragments they belong to by comparing the script, the height of a single line, the illumination and musical notation. In this way, the team could successfully identify the fragment in Cod. 4073 (F-kiwq) as another piece from a thirteenth-century breviary which came down to us today only as binding waste.

Sewing guards (also referred to as centre strips) are one of the most challenging fragments to describe. These narrow strips of parchment, sometimes only a centimetre wide, were used to strengthen the fold in paper quires. Over 190 Mondsee manuscripts include such strips, which were often cut from not one but several manuscripts. In the past, the usual practice was to detach such fragments by making tiny cuts on the level of the sewing stations to release the guard from the sewing thread (see for instance *Fragm. 4a*, F-rea⁰). Nowadays librarians, restorer and scholars do not relent to separate the two historical objects (host volume and fragment), which share at least partly a common history. Fortunately, there are methods to digitise a large percentage of the guards with the help of a glass prism, specially devised by Manfred Mayer, an engineer and conservator at the University Library Graz in Austria.

The photographer positions the prism at the opening of the sewing support so that the camera takes one picture of the inner part. For photographing the outer side of the fragment, the prism needs to be repositioned between the quire fold and recto of the sewing support and its verso respectively.



Fig. 1. Prism at the opening of a sewing guard (© CC-BY-NC)

Rigid or fragile bindings that cannot be opened up to 90 degrees pose a particular challenge for the photographer, who has to proceed with extra care. Most important in these cases is to avoid any damage to the medieval bindings, even at the cost of some information being lost. If the prism does not get to the bottom of the fold, a part of the image in the middle of each sewing guard remains unphotographed, as shown below: the letter “e” is visible in the in situ observation, but is unfortunately cut off in the scanned image (Fig 2a and b).



Fig. 2. Sewing support in Cod. 3820 a) by in-situ observation; b) image through the prism with missing middle section; c) reconstructed page (© CC-BY-NC)

The processing (including taking the images, renaming, rotating and mirroring them, joining the two outer images to form one) is extremely time-consuming. Despite all of this, when one matches all the scans of the small parchment strips together like a puzzle, one gets a fascinating glimpse on how the original page would have looked like (Fig. 2c).

Due to time limitation, it was impossible to digitise all sewing guards within the duration of the project. The priority lied on fragments written in Carolingian minuscule, while for the rest a compromised solution was reached – to take at least one image per group of strips, belonging to one original manuscript. In this way, scholars interested in the fragments can have at least one visual example and perhaps order further images or consult the fragments in-situ. The fully digitised sets were used as case studies for fragmentation practices. It was, for instance, interesting to probe if bookbinders prepared the binding waste in advance or cut the discarded manuscript leaves ‘ad hoc’. The above-cited example of Cod. 3820 (F-f72y) demonstrates that the binder used two leaves from a breviary as pastedowns hooked around and sewn with the outermost gatherings and another two cut in vertical strips for the sewing stations.

Further challenges for the digitisation are limp binding. Making a cover from old parchment leaves was a cheap alternative to leather binding. Cod. 4070 (E-cfrj), for instance, is a laced-in limp parchment binding, for which the binder folded the discarded leaf vertically in the middle to get a more stable cover before wrapping it around the book block. The slips of the sewing supports, on which the gatherings are sewn, exit through the covering leaf at the spine edge and re-enter underneath the covering, where they are left loose. One part of the fragment (that is, one side of the text) is visible by in-situ examination only through a narrow slip in the covering, which makes photographing it a delicate matter (Fig. 3).

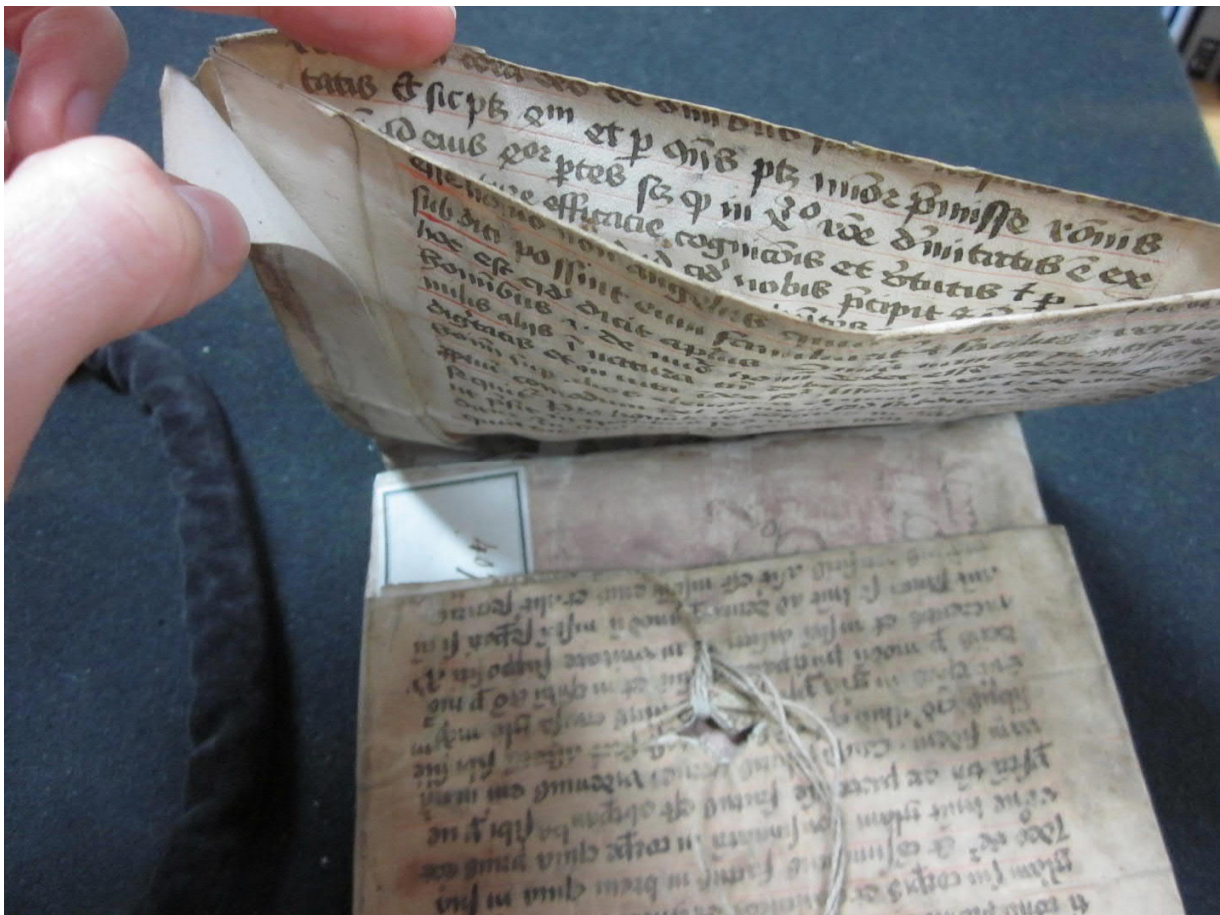


Fig. 3. A glimpse at the inner side of the limp binding of Cod. 4070 (© CC-BY-NC)

Since the parchment warps through the years of storage and often becomes brittle, it is necessary to make several scans in order to reproduce individual parts without distortion. The pictures are again assembled to build a virtual reconstruction of the original page. For Cod. 4070, a manuscript with a comparatively small size (145 x 115 mm) it was necessary to make about twenty pictures in order to assemble one side of the parchment (see Fig. 4). Since the inside of the folded parchment is in its entirety inaccessible in the current state of the binding, a full virtual reconstruction of the page could not be achieved.

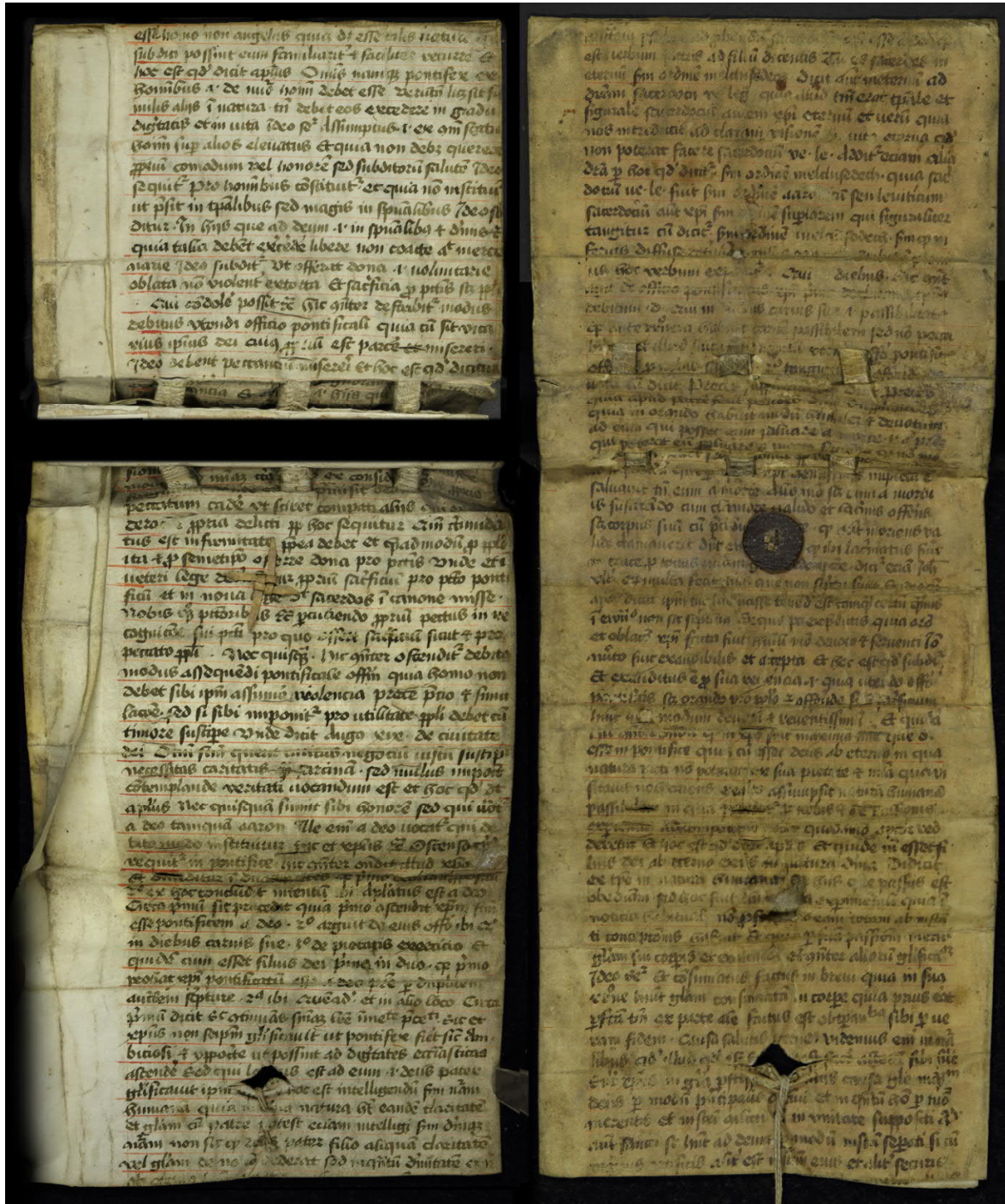


Fig. 4. Virtual reconstruction of one side of the original leaf used for the limp binding of Cod. 4070 (© CC-BY-NC)

Another issue the team dealt with concerned the digital reconstruction of fragments in the digital platform. Our aim was to facilitate scholars who needed to know the gaps between fragment sections in order to extrapolate missing text. For that purpose, it was sometimes necessary to combine separated fragments into one reconstructed page. In Cod. 3585 (F-xa56) the binders used four vertical strips from one leaf and placed it as transverse spine linings. In order to enable users online to have an experience as real as possible of examining the object and get a precise idea of how much text is hidden, the photographer connected the images of the left and right board, where the fragments are pasted, placing the image of the fore edge in the middle. Another virtual reconstruction shows two of the fragments reconstructed to one long strip with two sections hidden by the book block. In the Fragmentarium app, the fragment is presented with the help of multiple IIIf sequences for displaying the real physical state of the fragments, and another for the virtual reconstruction.

In cases where the binding waste had one written and one blank side (as is usually the case with charters) the binders preferred having the blank side visible in the binding. Both pastedowns in Cod. 3740 (F-4qif) are glued in this way, with the written side of the charters pasted to the boards. The text is hardly visible by the naked eye through the paper, however, under ultraviolet light the ink becomes much more evident. The images made were then horizontally flipped to get a mirrored projection (Fig. 5).

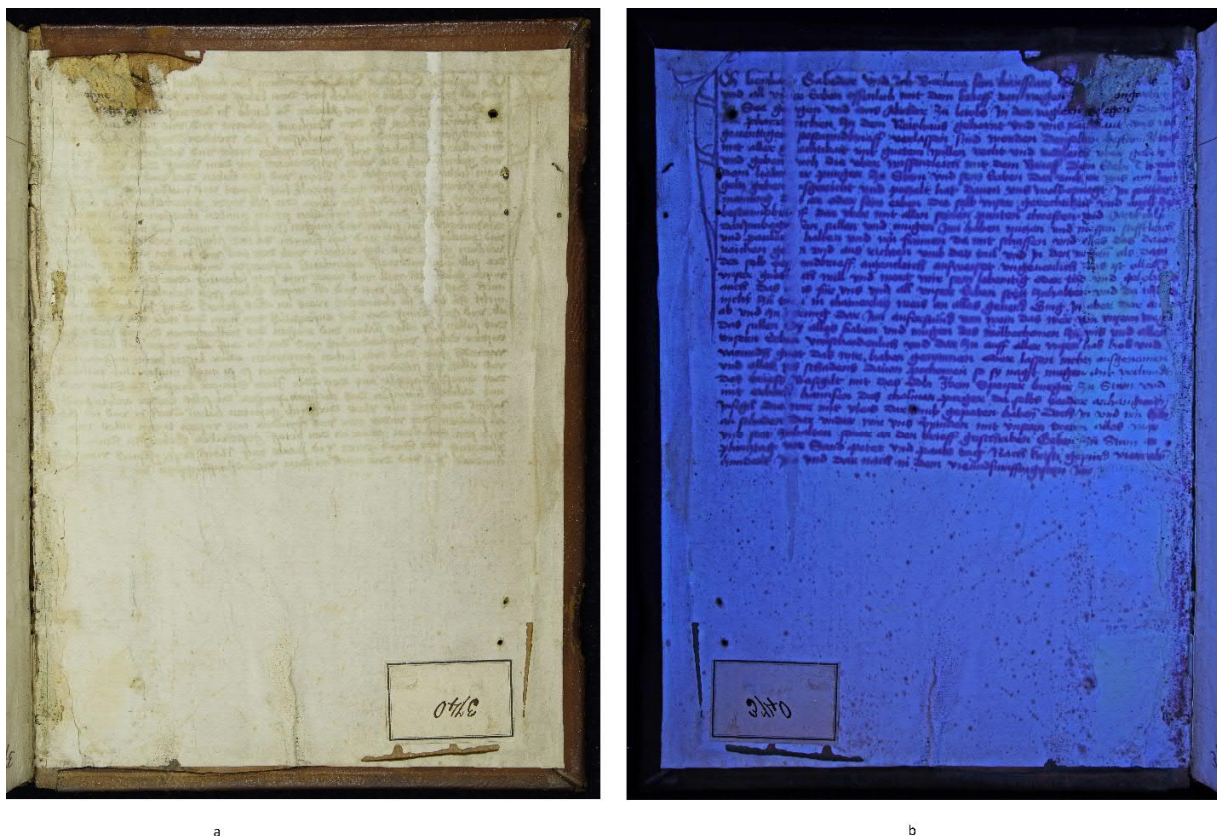


Fig. 5. Charter used as pastedown in Cod. 3740 a) image with normal light and b) image under UV light, horizontally flipped (© CC-BY-NC)

A fundamental principle guiding the project was that the material would be of interest to a wide range of scholars. The study of bookbinding, in particular, is closely related to that of fragmentology. On the one hand, binding historians examine detached and in situ fragments in restored bindings for glue residue, stains, rust and other pieces of evidence from the binding techniques used in the original binding [Sheppard 2000]. On the other hand, the study of a binding can provide many historical clues about the binder workshop, the provenance and possession of the host volume and the in-situ fragment. Thus, to accommodate the need of binding historians and facilitate the examination of the objects online, it was imperative to provide the digitalisation of the whole binding - left and right cover,

pastedowns, spine, head, tail, and fore edge. Additionally, the textual descriptions offer further information about elements of the bookbinding that could not be digitised sufficiently (endbands) or are hardly recognisable on a two-dimensional image (stamps). When it comes to detached fragments, the Fragmentarium app offers the possibility to publish photos of the host volume and the offset from the fragment as additional images, as for instance by *Fragm.* 813 (*F-ts3a*). Thanks to such virtual reconnection, scholars can easily enrich the history of both historical objects.

CONCLUSIONS

The importance of the fragments lays not only in their nature as evidence of a prior manuscript. They are also an essential source for the transmission of text, musicology, diplomatics, and art history. In the case of the Mondsee, the study of the fragments can help trace the growth of the medieval library and examine the development of scribal and literary activities as well as the binding workshops practice. Furthermore, the practices developed in the framework of the project as discussed above could serve as an example of how to digitise, describe and publish large fragment holding in other libraries as well.

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Multispectral Processing Methods to Recover Text from the World Map by Martellus (c. 1491)

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The c. 1491 world map by Henricus Martellus Germanus, in the collection of the Beinecke Rare Book and Manuscript Library of Yale University, is a very important visual and historical object, being very similar to the c. 1492 globe by Martin Behaim and evidently having influenced the 1507 world map by Martin Waldseemüller to a significant degree. Martellus' map is painted on paper sheets mounted on canvas and most of the area is covered with text, nearly all of which has faded to the point where it is not readable to the unaided eye. Because of this condition, the map had been little studied, even though it had the promise of yielding significant insight about the geographical knowledge of the time.

The Martellus map was imaged by a team of scientists and scholars in August 2014. Though significant information was recovered during the imaging session, the subsequent spectral image processing required more than a year. Because of the different colors used for both texts and backgrounds (to represent different types of physical features), customized processing methods were necessary to recover many of the writings. From the results, it is estimated that more than 80 % of the writings have now been recovered, vs. less than 10 % available to the eye from the original map.

This paper will review the spectral image processing methods used to recover the texts, including discussions of necessary preprocessing methods to balance the contrast of the text and background, useful segmentation algorithms, as well as post processing methods used to enhance the text visibility further.

Key words:

Martellus World Map, multispectral imaging, spectral image processing, principal component analysis, independent component analysis, minimum noise fraction transform.

CHNT Reference:

Roger L. Easton, Jr. et al. Processing Methods to Recover Text Information from Multispectral Imagery of the World Map by Henricus Martellus (c. 1491).

INTRODUCTION

The large world map (c. 2 m × 1.22 m), made by Henricus Martellus about the year 1491, is widely acknowledged to be of great importance in the history of cartography. The map likely was the best contemporary cartographic representation of the geographical concepts of the earth when Christopher Columbus made his first voyage, and there are good reasons for the belief that Columbus saw this map or another similar one by Martellus, and that the map influenced Columbus's ideas about the world's geography.

Because of the fading of its descriptive texts and place names, the map had been little studied since it first came to the attention of scholars in 1959. An effort to image the map was supported by funding from the USA National Endowment for the Humanities in 2014. The team visited the Beinecke Rare Book and Manuscript Library at Yale

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University to collect imagery of the map for subsequent image processing with the goal of recovering the texts on the map and making it available to scholarship. The map proved to be an excellent candidate for spectral imaging, and this paper describes the imaging processing methods applied to the data and the results obtained. The visual appearance of the map is shown in Fig. 1.



Fig. 1. Visual appearance of the c. 1491 world map by Henricus Martellus Germanus. The various texts are not visible at this scale, but processing reveals that the landforms are covered with texts. Text on the water surfaces is placed only on the islands and cartouches

IMAGE COLLECTION

Because of their relevance to the subsequent image processing, it will be useful to consider the illumination and camera system used for multispectral image collection, which is very similar to that currently used at a number of institutions, including the British Library, the Centre for the Study of Manuscript Cultures at the University of Hamburg, and St. Catherine's Monastery [Easton et al. 2010]. The map was illuminated by light from panels of light emitting diodes (LEDs) in 12 bands from the near-ultraviolet band centered at 365 nm, five bands in the visible range (centered at 450 nm, 470 nm, 505 nm, 535 nm, 570 nm, 635 nm), and five bands in the infrared region (centered at 700 nm, 735 nm, 780 nm, 870 nm, 940 nm). In addition, (and important for subsequent processing), spectral images of induced fluorescence were collected by illuminating the map with light at 365 nm and 455 nm and imaging through four Wratten gelatin filters, which transmitted blue, green, orange, and red light. The blue filter #47 transmits light in the range $410 \text{ nm} \lesssim \lambda \lesssim 500 \text{ nm}$, the green filter #58 transmits $500 \text{ nm} \lesssim \lambda \lesssim 580 \text{ nm}$, orange #22 passes wavelengths longer than 560 nm, and #25 passes wavelengths longer than 590 nm. In addition, images generated by ultraviolet illumination were collected through "ultraviolet passing" and "ultraviolet blocking" filters. Images using the former modality produce an image of the reflected ultraviolet light, while the latter images the integrated fluorescence. A total of 22 spectra bands were collected for each map tile: 12 in reflection, six in fluorescence under ultraviolet illumination, and four in fluorescence under blue illumination.

Note that images are collected over at wavelengths in the range $365 \text{ nm} \lesssim \lambda \lesssim 940 \text{ nm}$, which is nearly twice the bandwidth of visible light ($400 \text{ nm} \lesssim \lambda \lesssim 700 \text{ nm}$). For this reason, it was important to use a "spectral" lens that is designed for this purpose rather than using an "off-the-shelf" normal lens designed for imaging only in the visible

range would be noticeably defocused for light near the extrema of the wavelengths of illumination. A macro lens with focal length $f = 120$ mm and focal ratio $f/4.5$ was designed and fabricated to specification by Brian Caldwell of *Caldwell Photographic*. This lens allows collection of images over the full range at the same focus setting and with resolution near the diffraction limit.

Imagery was collected using the E7 camera from Megavision, Inc., which includes the KAF-50100 50-megapixel sensor, with 8176×6132 pixels of size $6 \mu\text{m}$ square, resulting in a sensor with dimensions $49.1 \text{ mm} \times 36.8 \text{ mm}$. The larger pixels in this sensor results in improved noise statistics when compared to newer sensors with smaller pixels. This compromise between pixel count and noise response is very important when imaging faint sources, as in the case of fluorescence generated by ultraviolet stimulation but observed in red light. The images have 13 bits of measured dynamic range.

Due to its large size, the map was imaged in 55 “tiles” (11 horizontally by five vertically) with the sensor oriented in “portrait” format (long dimension vertical), with 15 % overlap for subsequent stitching of collected images. Each tile covered an area of approximately $280 \text{ mm} \times 210 \text{ mm}$ at a resolution of approximately 29.2 pixels per mm (~ 735 pixels per inch).

The map was supported on a large easel that allowed the map to be translated horizontally and vertically to position individual tiles in front of the lights and camera in the same geometry. To ensure the same plate scale for each tile, vertical lines of light from solid-state lasers were projected at tilts so that the lines converged to form a single line when the map was positioned at the proper distance from the camera. The camera and laser line projectors were mounted on a “StackShot” focusing rail that allowed precise movement of both towards or away from the map. By adjusting the distance of the camera using the StackShot until the lines of laser light merged, it was possible to ensure accurate focus for each tile easily and quickly. The time required to collect a full set of images for one tile was approximately four minutes.

Because statistical image processing was planned, accurate calibration of the spectral imagery was important. The reflectance was calibrated from images of reference targets composed of both broadband reflectance standards made of Spectralon[®] by Labsphere, Inc. (with three broadband reflectances of 2 %, 50 %, and 99 % over the range $250 \text{ nm} \lesssim \lambda \lesssim 2500 \text{ nm}$) and a ColorChecker chart from X Rite Photo. It is important to note that the reflectances of the X Rite chart are calibrated only for visible light and are not well suited to use outside of this range. Since it was not possible to include the standard objects in each tile, the standards were imaged at the beginning and conclusion of each collection and the statistics transferred to images of the individual tiles.

The image data were saved as “raw” digital negative files and as “flattened” files evaluated from the ratio of the raw data and the flat-field images. The metadata from the image collection are recorded during image capture and inserted in the header of the raw and flattened image files.

A snapshot showing the map on the imaging easel and the camera is presented in Fig. 2.



Fig. 2. Martellus map mounted on moveable easel with Megavision E7 camera

The wavelengths, f /stops, and exposure times for each band are listed in Fig. 3. All reflection bands were imaged at $f/12.5$. Note the larger apertures and longer exposure times for the fluorescence bands, which were necessary to reduce the ultraviolet exposure to the map. Despite these longer exposures, the fluorescence bands often exhibited significant variations due to the statistical uncertainties. The statistical “salt-and-pepper” noise was generally reduced by applying at 3×3 median filter to these fluorescence bands before subsequent processing.

Reflection			Fluorescence				
Center λ	f /#	Exp time (s)	Illumination	Filter	f /#	Exp. Time (s)	
365nm	$f/12.5$	5.244 s	365nm	B47	$f/5.6$	20.000 s	
450nm	$f/12.5$	0.613 s		G58	$f/5.6$	20.000 s	
470nm	$f/12.5$	0.542 s		O22	$f/5.6$	20.000 s	
505nm	$f/12.5$	0.800 s		R25	$f/5.6$	20.000 s	
535nm	$f/12.5$	0.874 s		UV block	$f/5.6$	5.000 s	
580nm	$f/12.5$	0.893 s		UV pass	$f/5.6$	20.000 s	
625nm	$f/12.5$	0.500 s		450nm	B47	$f/5.6$	0.500 s
700nm	$f/12.5$	11.648 s			G58	$f/5.6$	5.000 s
735nm	$f/12.5$	5.100 s			O22	$f/5.6$	5.000 s
780nm	$f/12.5$	3.809 s			R25	$f/5.6$	10.000 s
870nm	$f/12.5$	3.449 s					
940nm	$f/12.5$	11.784 s					

$\Delta\lambda \approx 40\text{nm}$

Fig. 3. The wavelengths, f /stop settings, bandpass filter, and exposure times for the 22 collected bands

IMAGE PROCESSING

The goal of the image processing is to select combinations of the collected spectral bands that enhance the visibility of the faded writings. This objective is closely related to that of recovering erased text from erased and overwritten (“palimpsested”) parchment manuscripts, which fortunately is a familiar task for the imaging team, having worked on the Archimedes palimpsest [Christens-Barry et al. 2011], the Syriac-Galen medical palimpsest [Easton et al. 2018], the “New Finds” palimpsests from St. Catherine’s Monastery, and the “Dexippus” palimpsest in Vienna, among others.

In palimpsest imaging, the goal is enhancement and/or segmentation of two (occasionally of three) texts that usually were written in iron gall ink. The erased writings often could be made readable by “deterministic” methods, which could be as simple as choosing the best band for reading the text from the set of collected images or by rendering two or three selected bands in pseudocolor. In the case of the Martellus map, where text is written in several colors of pigment laid over different background colors, and is therefore significantly more complex than processing of most palimpsest imagery.

Because of the different background pigments in the scene, particularly near coastlines, it was useful to “preprocess” the spectral imagery to normalize the contrast. This was accomplished by a method we have dubbed “blur and divide,” but which was called “pseudo-unsharp masking” during an effort to enhance details in images of solar corona and comet tails, where the wide variation in background often obscures the fine details of interest [Matuska et al. 1978]. The name was applied based on the resemblance to the well-known photographic method of “unsharp masking,” where a blurred negative is combined with the original positive to a difference “sharpened” image. Because the “blur-and-divide” operation removes much of the wide variation in the image statistics, the results of the subsequent image processing tools often exhibit improvements.

The ENVI[®] software package from Harris Corporation was used for most of the spectral image processing of the Martellus map. ENVI[®] is commonly used to process environmental spectral imagery collected from aircraft and spacecraft, but is very appropriate for this “near-field” remote sensing task. It includes a wide range of imaging software tools, including some for common image processing (such as contrast enhancement and registration/stitching), but its primary value in this project is due to the efficient software for statistical image

segmentation. ENVI[®] operates on spatial-spectral image “cubes” (three-dimensional data arrays) created from the images, followed by gray-scale calibration based on the images captured of the Spectralon[®] and X Rite reflectance standards.

The first steps in the task workflow are the “preprocessing” (creation of the image cubes, calibration based on the reflectance standards, and pseudo-unsharp “blur and divide”). The bands are examined for noticeable features and to select local areas where the statistics are evaluated that are to be used in the subsequent transformations. Because the final image results depend on the statistics, this adds another level to the iterative nature of the workflow. The bands are processed using methods to be described, and the resulting output images were rendered in RGB “pseudocolor,” and subsequently enhanced in Adobe Photoshop[®] to rotate the hue angle of the pseudocolor rendering and/or to enhance the contrast. The images selected from the processing were delivered to one of the authors (CVD), who assessed the result and delivered feedback and identified regions for the subsequent iteration.

The first processing method applied usually was the well-known Principal Component Analysis (PCA), but the Minimum Noise Fraction Transform (MNF), and Independent Component Analysis (ICA) were also used with good results. Because of the different combinations of pigments used for text and background and the different conditions in different locations on the map, a wide variety of processing methods were applied to the same tile. Often, the results of one process showed the locations of previously unseen text, which led to subsequent processing for that region. The processing proceeded iteratively and the best results from these were subsequently combined to produce output images of readable text.

PCA was originally suggested by Pearson [1901]. The process combines N images in a set of spectral bands to create a new set of N uncorrelated bands using only second-order statistics. In other words, the data are assumed to be Gaussian distributed. The two sets are “equivalent” because both “forward” and “inverse” transformations are specified, which allows the original band set to be reconstructed from the PCA bands. Because the new bands are “uncorrelated,” any statistical similarities among the images in the original set of bands will not exist in the set resulting from the processing. The bands in the PCA set are sequenced by statistical “variance;” the band with the largest variance (and therefore the widest range in numerical values) appears first in the sequence, while each succeeding processed band exhibits less variance than the previous output band in the sequence. In this way, the highest-order calculated bands exhibit the smallest variance and therefore the smallest variation in image contrast. Often these highest-order bands include any random “noise” variations in the image data, while the lowest-order bands include the “true” image structure. Since the noise is now segregated from bands with “nonrandom” (i.e., “real”) variations in structure, the noise may be discarded and the PCA calculation inverted to reconstruct the original image bands without the random noise. By this method, PCA becomes useful for “denoising” the image data. It also is a method for evaluating the effective number of image bands in the original data.

MNF [Green et al. 1988] also transforms the set of N image bands into a new set of N bands that are sequenced according to a noise-content description of “image quality.” It has been used effectively for “denoising” of hyperspectral image data. Its end result is similar to that from PCA, but MNF often does a better and more reliable job of identifying and removing noise from the data than is possible with PCA alone. The goal of MNF is to identify component bands that are more important to the signal-to-noise ratio (SNR) of the ensemble of bands.

The goal of ICA [Hyvarinen 1999] is to separate the N spectral input bands into individual “signals” generated by individual constituent components. In this sense, ICA resembles PCA, but the output bands are statistically “independent” rather than statistically “uncorrelated.” Since the former criterion is stronger than that in PCA, the assumptions made about the image data in ICA are less stringent and higher-order statistical correlations are used. A common illustration of ICA is to solve the so-called “cocktail party problem,” where a listener hears a mixture of sounds from several independent conversations, but needs to isolate the individual chats. The collected dataset comprises recordings from different microphones scattered about the room, where each records a combination of sounds from all conversations. An individual recorded signal from the microphones is analogous to the set of spectral image bands and the individual conversations are analogous to individual features on the map. The ICA calculation looks for differences in the measured signals that satisfy the condition for statistical independence. If the different conversations are truly independent (as they would usually be in a cocktail party), ICA usually is able to segment the signals into their constituent components. In the map problem, the statistical independence of the individual signals is less certain due to the overlap of the pigment spectra.

Not surprisingly, the output bands obtained from the different algorithms exhibited variations in the visibility of the text with location. For this reason, individual bands from the different methods often were combined to form pseudocolor images. These were exported to “general-purpose” image processing tools, such as Adobe Photoshop[®]

for subsequent enhancement of contrast and to rotate the hue angle with the goal of maximizing the visibility of the texts of interest.

RESULTS

Though it might be desirable to illustrate the value of the different image processing methods for the entire map, the limitations of space make it necessary to select a small number of examples. One specific region on the map was selected for illustration, where texts were written in at least two different pigments. The location is the coast of southwest Africa, where the brownish pigment used for the landmass evidently is “thicker” at the boundary with the blue pigment used for the Atlantic Ocean. This additional thickness can obscure the writings for the names of rivers and villages near the coast. One example for the tile C03R04 (third column, fourth row) is shown in Fig. 4. Very little, if any, text is visible to the eye (Fig. 4a), but significant text is readable in Fig. 4b, which is a pseudocolor image evaluated from all 22 bands and displayed with PC bands 2, 8 and 22 in the red, green, and blue channels, respectively. The additional pigment thickness produces a “murky” area near the coast that can obscure some characters. In these conditions, evaluating the ratio of each band and its replica blurred over a scale larger than the text characters (a 201×201 window was used in this case), can reveal additional writings, as shown in Fig. 4c, which is a pseudocolor constructed from the ICA transformation of the original set of 22 bands. .

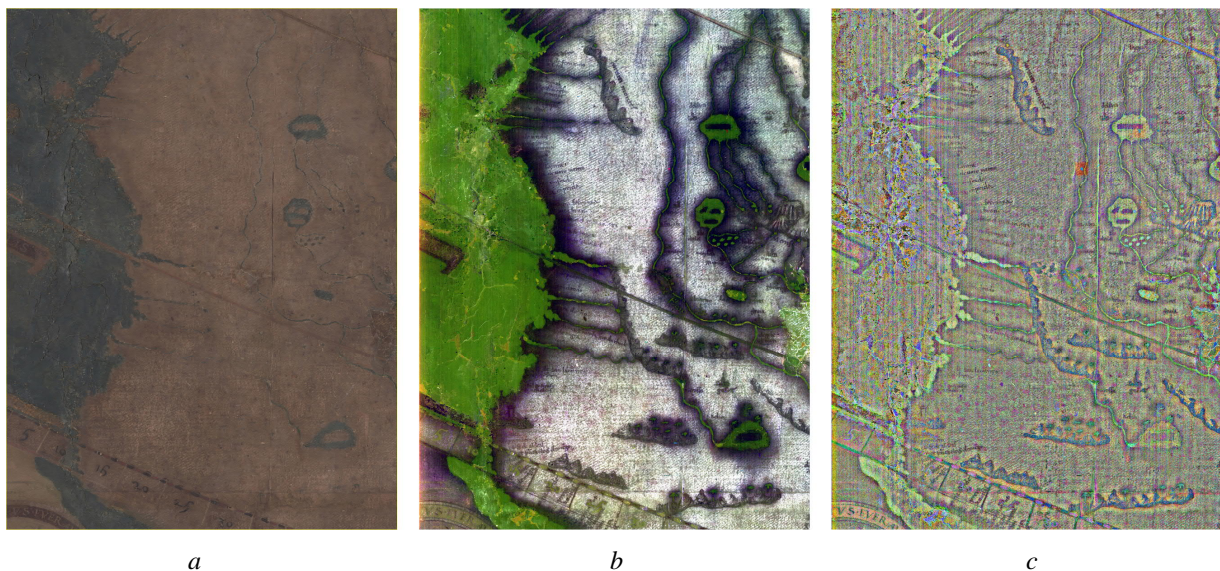


Fig. 4. Tile C03R04 of the Martellus map showing the coast of southwestern Africa a) visual appearance, showing very little text, b) pseudocolor image from PCA bands (PC band 2 in red, band 8 in green, band 22 in blue), and c) pseudocolor image from three ICA bands after implementing “blur and divide” over a region of 201 pixels square (IC band 17 in red, band 18 in green, band 20 in blue)

However, some text is still not visible in these output images, even with the “blur and divide.” For example, consider the results in Fig. 5, which shows a magnified section of the same tile C03R04. Some text is clearly visible in the first example, which is the ratio of two image bands (red fluorescence under blue illumination divided by the infrared band centered at 940nm), but gaps between the writings over the river courses suggests that additional text might exist. The recovery of this text was difficult, suggesting that the particular pigment for that writing has faded more than the other pigments. Some characters were recovered by combining PCA and ICA processing of subsets of the original image bands. A result is shown in Fig. 5.

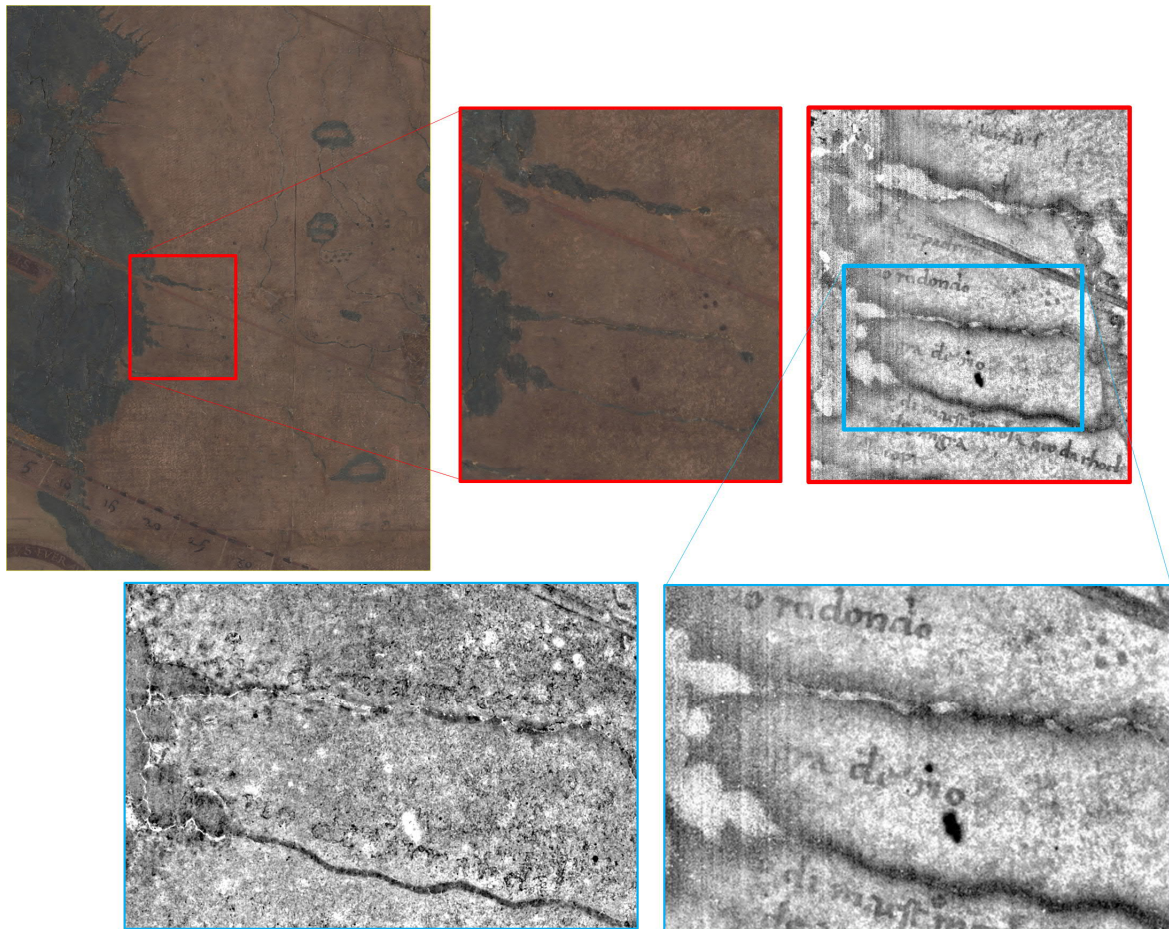


Fig. 5. Processing to recover river names from tile C03R04 of the Martellus map. The visual appearance of the magnified section is compared to processing results after “blur and divide” of PCA on 6 selected bands (bottom left) and infrared band ratios (bottom right), showing that different text is enhanced by the different processing. The PCA revealed names of rivers not available in the band ratio image

CONCLUSIONS

Significant text was recovered from the Martellus map by image processing applied to multispectral image data. The results have led to significant new understanding of the map in the history of cartography. The readings obtained from the imaging have been published [Van Duzer 2018]. This paper offers a more complete description of the methods used.

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Improving Iron Gall Ink Palimpsest X-ray Fluorescence Element Mapping Analysis

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In the recent years multispectral imaging and X-ray Fluorescence element mapping have established themselves as a well working two step approach, when dealing with faded, erased or overwritten text in iron gall ink. During the last years a lot was done to improve the mere technical side of the techniques. Especially in the case of XRF mapping experiments the acquisition speed needed to be increased to allow mapping in the high resolution demanded by the challenges at hand. High resolution in moderate times can now be achieved, but with the price of proportionally increased amount of data that needs to be processed ideally in parallel to the measurement. The classical approach in XRF spectroscopy of elemental fitting of the spectral data does not even come close to fulfill any on the fly processing time constraints and will consume too much processing time in the foreseeable future. In this paper we will discuss the applicability of modern statistical data processing methods to XRF mapping of iron gall ink palimpsests. We will present a comparison of a new approach based on principle and independent component analysis (PCA and ICA) and the standard element mapping method. We will show that a reduction in processing time of almost two orders of magnitude can easily be achieved.

Key words:

Archaeometry, Statistical analysis, PCA, XRF, Iron Gall Ink.

CHNT Reference:

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INTRODUCTION

Parchment has been a well-established writing support in the last two thousand years. As a sturdy material parchment allowed to be reusing after prior writing had been scraped off or chemically removed. Reused parchment is called palimpsest and can contain any ink type used at the time of its creation, as e.g. iron gall, plant – or soot-ink. A significant portion of known palimpsests contain at least one erased layer of iron gall ink, while a new text in iron gall ink has been written on top. Iron gall ink can be removed mechanically or chemically. Mechanical removal of preexisting writing is very time consuming but usually leaves no detectable residuals of the removed text, only scratch marks from the scraping. Chemical removal of iron gall ink writing is much less time consuming and very effective for the naked eye, hence ink was mainly removed by chemical means with a sponge preferentially soaked in lemon juice. The lemon juice destroys the black colored iron gallic acid complex and removes some of the ink, but leaves residuals of the metallic contribution of the ink at the position of the erased text. After centuries the erased writing often reappears faintly in yellowish-brown characters due to continuous slow forming of iron oxide from the residual iron of the erased ink. These ghostly traces of slightly brown text often identify a page as a palimpsest. Sometimes iron gall ink just fades due to the unfavorable storage conditions, while again the metallic contributions of the ink stay put at the position of the former text.

The recovering of the overwritten texts from palimpsests went through several stages of technology [Albrecht 2015; Rabin et al. 2015 and references within], of which the earlier were strongly, the latter slightly or non-invasive. During the beginning often chemicals were used that worked for a short time and sometimes allowed to have photographs taken from the under-text, but often left the document in a much more degraded state. This approach

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was mostly replaced when artificial “ultraviolet” (UV) light became available. Reading texts under constant illuminations with UV light caused less damage to a manuscript than the chemical treatment, but still affected the state of the object by increased aging due to the UV radiation. Additionally the newer technology caused damage to the readers’ eyes and often delivered still inadequate results. UV light causes parchment to fluoresce, while this fluorescence is suppressed in regions where the parchment had been in contact with gallic acid, as in places where iron gall ink had been. Developments during the last 20 years in the field allow now non-destructive investigations without any harm to object and reader. A nice set of tools is available for scholars and scientists to digitally recreate the lost texts. Especially when dealing with hidden (faded, covered or erased) iron gall ink the following processing protocol has proven most effective: Objects with suspected hidden writing in Iron Gall Ink will first be measured with “multispectral imaging” (MSI) [Easton et al. 2010] where a special photographic camera with an optional set of filters is used together with with LED light panels. In most cases this first step is already sufficient to recover the lost text completely. In the other cases or for very delicate regions that remain illegible, the document will be tested for the presence of iron gall ink residues using an “X-ray fluorescence” (XRF) spectrometer. If that test is positive the ink to be recovered possesses metallic components and X-ray based scanning techniques can be applied. XRF mapping [Bergmann 2011; Glaser and Deckers 2015] often allows recovering more or other parts of the lost text. MSI digitally reconstructs text by statistical analysis of the local dispersive surface response function of the investigated object in the “ultraviolet” (UV), “visible” (VIS) and “infrared” (IR) range of the electromagnetic spectrum and thus is almost completely surface sensitive. If in cases where the surface is completely covered with e.g. a gold paint as in the case of the Archimedes palimpsest [Bergmann 2007; Easton et al. 2011] or if the text of interest has been glued as support material face down as in a book cover a mere optical, surface sensitive method cannot deliver any useful result. These are classic cases, where XRF mapping is the method of choice.

The XRF signal contains the sum of information from the entire thickness of an object (usually a single page) at a specific point, sampling over the spot size of the primary X-ray beam. With carbon based writing supports, as parchment, papyrus or paper the X-rays penetrate the object completely with only a small portion being absorbed. The method as spot based has no intrinsic spatial resolution; the lateral resolution needs to be achieved by selective detection. Usually the lateral resolution is achieved by focusing the X-ray beam to a small spot while mapping the surface with this spot, measuring one spectrum at a time. This mapping approach is time consuming, even if every single measurement is extremely short as e.g. 100 ms and thus allowing measuring an impressive amount of 800.000 points in a day. 100 ms is a reasonable time for modern laboratory based systems or storage ring based measurement. Times of measurement per point can be reduced even down to the low ms-range, but usually the necessary counting statistics of a spectrum requires longer counting times per point. In order to reproduce a legible text from the mapping experiment, the resolution must be sufficiently high (some 150-300 dpi or better). In total, the amount of measurements exceeds a million in many cases (see Table 1) making XRF mapping a time-consuming measuring technique. A small area of 1 cm² in 150 dpi can be mapped in less than 10 minutes if a point takes only 100 ms, an A4 page in the same resolution and same sampling speed already takes 2-3 days, while higher resolution of 600 dpi causes the time to jump to 1½ months. Spending days on a single page may be all right for a few selected cases, but considering the tens of thousands of unread palimpsests known at this point even a day per page is too long to measure all of them. For serial investigations of e.g. codices 1 day of measuring time for each page is already too much:

The usual time for processing of XRF data is even longer for each spectrum than the 100 ms time assumed to measure it and each measured point has to be analyzed separately. When proceeding normal protocol each XRF spectrum is background subtracted and fitted with multichannel analyzer software as e.g. *AXIL*¹ [Vekemans et al. 1994] or *PyMCA*² [Solé et al. 2007] to identify the amount of (primarily) metals, that are contained in the object at each measured position. After analyzing all spectra the individually derived amount of metallic components at each point is used to create element maps of the measured region of the object. Those element maps or some of them may contain the hidden text. The main reason one can digitally recreate old iron gall ink writing with XRF mapping experiments is the above described imperfect removal of the ink in the palimpsest creation. Typically the metallic contributions that remain of the former ink consist of iron, copper, zinc and lead. While iron has an essential role in forming the black colored complex in all iron gall inks and thus is usually present in a relative large amount, the presence and relative amount in respect to iron of all other metals (the inks fingerprint) often allows to distinguish between one ink and another [Hahn et al. 2004; Malzer et al. 2004]. Iron, copper and zinc in highly variable stoichiometric ratios were part of almost all historic vitriol's with vitriol's being commercially traded. Lead (if

¹ AXIL code available (as bAXIL) at: <http://www.brightspec.be/brightspec/>

² PyMCA code available at: <http://pymca.sourceforge.net/>

present) is assumed to be incorporated through the local water used and may in the future be a mean to identify the provenience of an ink with lead isotope analysis. These metallic residuals, especially of the differently impure vitriol used in the mixing process of all historic inks is the starting point to argue for a different, a statistical approach for data processing when dealing with XRF mapping experiments of manuscripts.

Table 1. Number of XRF measurements for a given area and resolution

Resolution in dpi	100	150	300	600
Area				
1 cm x 1 cm	1.55×10^3	3.5×10^3	14×10^3	56×10^3
10 cm x 10 cm	0.15×10^6	0.35×10^6	1.4×10^6	5.6×10^6
21 cm x 29.7 cm (page A4)	0.24×10^6	0.55×10^6	2.2×10^6	34.8×10^6

ARGUMENTS FOR STATISTICAL XRF ANALYSIS

With often over a million spectra measured on a single page and measuring times of 10 ms - 100 ms (even with some modern transportable systems), the time consumed in processing is exceeding the measuring time significantly. The use of more detectors increases this problem by a factor equal to the number of detectors. This processing time problem can be addressed by brute force, just massively upgrading the hardware for processing and extensive parallel processing, which eventually will be very expensive and in cases where the equipment needs to be mobile may even become unpractical. To achieve a factor of e.g. 100 in processing speed by more and faster hardware is a big investment, even if the starting point is just a standard PC with a regular i7 processor. Thus any real time or near real time processing is not possible when keeping to the conventional XRF analysis methods, but is nevertheless urgently needed. Fast feedback during a measurement is essential to avoid time loss, especially if the measurements are performed under severe time constraints.

Those time constraints may on the one hand be due to the access time to an object granted by a library, museum or monastery or on the other hand the measurement time available due to the equipment/facility used for the measurement. Mobile equipment often needs to be shared and cannot remain at a location in-definitely or be fixed on one task, while at a storage ring facility beam-time is granted for short time periods only and with an advance time of almost a year. Those boundary conditions often cause measurement situations, where re-measuring something may become virtually impossible. Hence the first attempt needs to be a success and thus real time evaluation is essential. The applied evaluation method must be efficient enough to keep up even with fast mapping speeds (2-5 ms per point) and needs to provide results that allow evaluating a measurements level of success, ideally without the necessity of any special processing hardware upgrades. The results from standard XRF analysis factorize the signal into elemental contributions and are therefore very useful to characterize an individual ink by delivering the individual fingerprint. The situation of trying to decipher a lost text provides a different question. The signal contribution from text of interest needs to be separated from the total signal, while element maps which most of the time will contain contributions from new and erased text do not necessarily give the best contrast for reading the erased text.

There are several components that contribute to the signal measured with XRF at each position. Let's assume a palimpsest which has one layer of erased text on both sides and one layer of new text also on both sides: The measured XRF signal at each point is composed of signal from the new and the erased ink from either or both sides of the parchment, as well as signal from the parchment itself and possibly also signal from dirt or other contamination (again from either or both sides of the parchment). The contribution of the inks (and dirt) from the two sides of the parchment are typically separated by using detectors on opposite sides of the page, thus considering the respective absorption of XRF signal passing through the page [Bergmann and Knox 2009]. The XRF signal mixture that remains for each side nevertheless is at least that of the two different inks, the parchment and the contamination on that side. Splitting this XRF signal mixture into element maps (as the standard XRF analysis does) may help to digitally recreate a hidden text, but may not provide the best results. If the two inks have the same trace elements (non-iron metallic components), only with different stoichiometric contribution or if either dirt or parchment have their contribution in the spectral range, where the inks are most diverse, no element map would

supply a really good reading contrast to identify the erased text. The results one should therefore aim to achieve for best reading contrast is ideally a complete disentanglement of the total XRF signals into the original mixed components. Those initial components from the example above are: Ink A, Ink B, parchment and multiple dirt components (as sand, mold, stains). Assuming a mapping experiment with at least tens of thousands of spectra measured a statistical approach is reasonable. Comparing all measured spectra for statistical similarities and differences is a task that mathematical procedures as “principle component analysis” (PCA) and “independent component analysis” (ICA) are designed for. Using comparative measures one no longer aims for clean separated elemental contributions, but for a basis set of signals, that reappear in different intensities in many of the measured spectra, as it is shown in the schematic example in Fig. 1. Every time ink A is present, it leaves its entire metallic fingerprint; the same is true for ink B. The only difference between two measured points with the both inks present is their relative amount due to the individual ink concentration at those points. The same holds true for the different dirt components or the parchment (which can e.g. vary in thickness). Mathematically speaking the best result in means of reading contrast for the erased text, could be achieved if a basis for all XRF measurements is found, were each basis vector represents one of the physical components. This is what PCA is designed to do: Separation not by elements (which are at least 5 or 6 in each ink), but by the inks fingerprints (just 2 in this case). This way ideally one map for each initial contribution could be reconstructed. Of course this is hypothetical and there are effects attached to real samples that will make life more difficult.

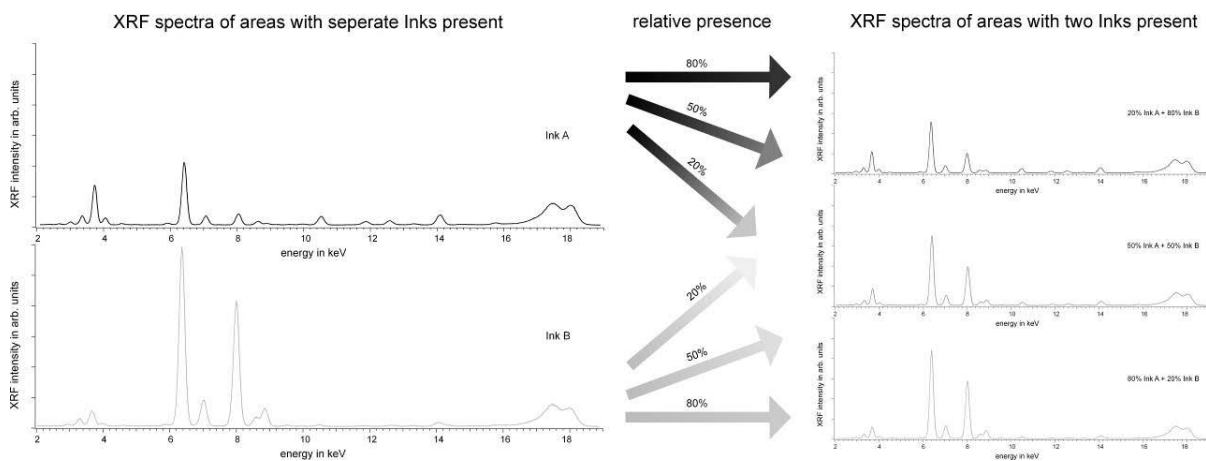


Fig. 1. Normalized XRF spectra of two Inks A and B on the left side and the recorded XRF spectra of a combination of those two inks on the right side with different relative amounts of the two inks present.

Each ink being present will contribute to the XRF signal alone in some spectra, while together with the second ink in others. These two occurrences of the ink will be separated by the PCA. When both inks are present the upper ink will absorb some of the fluorescence emitted from the lower ink. The absorption is stronger for low Z elements, since X-rays with higher energy are less likely absorbed in matter. This effect will lead to a slightly different contribution of the ink measured by the detector at this position and will create a PCA component representing the difference to the unmodified ink XRF fingerprint. For real measurements one may additionally assume noise and general inhomogeneity in all contributions that way additional PCA components representing this inhomogeneity are to be expected. Some of those contributions are less significant for PCA than others, since PCA repeatedly separates the most contrast containing contribution left in the data set. Therefore in the assumed example above among the expected first component found by PCA analysis should be the main ingredients (as the two inks and parchment) mixing into the various individual XRF measurements. Several additional PCA components are expected to address those correction terms. Hence the best readability contrast for any erased text is expected in one of the first PCA components. One very positive feature to be expected from this mere statistical approach run on a complete data set is that the computation time should be orders of magnitude shorter than that of using a multiple fitting algorithm on each spectrum separately. Due to the layered structure of the inks (one overwriting the previously erased ink) and the parchment, it is completely reasonable that some PCA components one will receive from upper layers have artificially negative contributions. For the total XRF spectrum it would be physically impossible to have negative contributions anywhere, but if an upper layer absorbs part of the signal emitted from a lower layer, this would lead

to a negative contribution in the energy spectrum representing the signal from the upper ink, since the ink removed signal of a specific energy emitted from the lower ink, before it could be recorded as XRF spectrum. With this in mind the standard PCA and ICA without any additions as non-negative matrix factorization is best suited for the task. It may be noted that non-negative matrix factorization has been applied successfully for XRF mapping of paintings [Alfeld et al. 2014]. The minimum requirement on results achieved with this new XRF analysis approach is that they should at least be of the quality and usability of that what the standard approach delivers. If that can be accomplished in much shorter time a lot is already gained. The data set used is from a XRF mapping experiment at the storage ring *DORIS III*³ at the “Deutsches Elektronen-Synchrotron” (DESY) in Hamburg (Germany) and was initially evaluated using the AXIL program.

THE DATA SET AND PROCESSING

The measurements were performed at Beamline L of *DORIS III* at *DESY* in Hamburg (Germany) using a horizontally polarized, monochromatic X-ray beam with a photon energy of 18 keV and a flux of 10^9 photons per second. The beam was slit down to 70 μm horizontally and 100 μm vertically, creating a 100 μm x 100 μm footprint on the object that was mounted under 45° to the incoming beam. A single VORTEX “Silicon Drift Detector” (SDD) was used from the front side of the parchment, under 90° in respect to the incoming photons. This geometry setting is usually used at a storage ring to make use of the effect that there is no elastic scattering at this angle due to the horizontal polarization. This improves the quality of the spectra, because the elastically scattered photons do not carry useful information, but increase the background and can lead to saturation effects. The XRF signal was pre-processed by a XIAMap multichannel analyzer and recorded using the *ONLINE*⁴ beamline control software. The palimpsest (Cod. Lips. Rep. I 62, f 17 of the University Library Leipzig) was mounted on a 2D stage and moved continuously in front of the beam, measuring 2048 channel XRF spectra with 7 Hz (7 spectra per second). The stage was set to move 150 μm between two spectral readouts, while horizontal lines separated by 150 μm were measured. This way the resolution achieved was slightly better than 150 dpi. The element maps of calcium, iron, copper and zinc of the upper right corner of the page (302 lines of 721 points each) are shown in Fig. 2. Noticeable is a slightly smeared area in the copper map, where the copper had been washed out from the writing at some point in time, while no other element was affected.

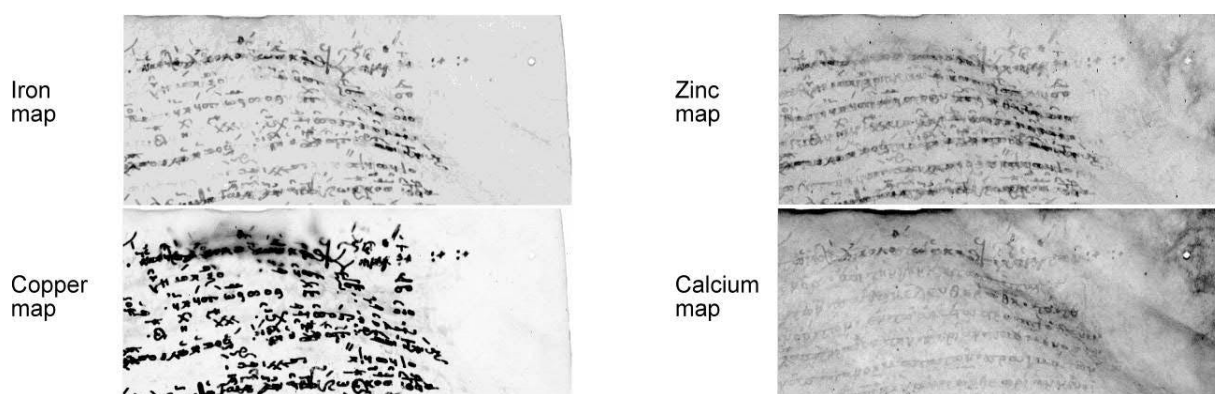


Fig. 2. Results from normal XRF mapping analysis. Element maps of calcium, iron, copper and zinc. Black corresponds to much intensity in all element maps.

XRF processing was performed on a scientific Linux PC using the *AXIL* code, always processing 4 spectra simultaneously. The results were element maps for potassium, calcium, titan, manganese, iron, nickel, copper, zinc, and lead. The lead originated mainly from a red band on top of the page and was slightly distributed equally over the entire page, but was also in traces part of the upper ink. In this case only element distribution maps of calcium, iron,

³ “Doppel-Ring-Speicher” (*DORIS*) was a storage ring initially build at *DESY* in 1974 for particle physics experiments. After the third upgrade (III) in 1993 the now called *DORIS III* functioned fully as X-ray source until it's decommissioning in 2012 (<https://doris.desy.de/>). It was replaced by the 8 times larger storage ring based light source the “Positron-Electron-Tandem-Ring-Accelerator” (*PETRA*), likewise in the third upgrade stage (http://photon-science.desy.de/facilities/petra_iii/).

⁴ <http://hasyweb.desy.de/services/computing/online/online.pdf>

copper and zinc were helpful to distinguish upper from lower text [Deckers and Glaser 2011] hence those will be used now to compare with the PCA and ICA results.

PCA and ICA processing was done on a Kubuntu⁵ PC using ENVI5.5⁶. The data was saved in band sequential order and processed in ENVI. No pre-processing steps (except for binning in most cases) were undertaken before computing PCA and ICA components with the default settings. Full scene was used as input statistic information for both methods. The measured spectra were stacked in a cube such that channel maps could be generated and used as input pictures for the PCA and ICA. As a time optimization test the channel maps were first processed for all 2048 channels. Secondly all physically irrelevant channels were removed: The first 200 channels were cut, because they were below any element that could be detected by the SDD during this measurement with the air paths involved: Essentially anything in a spectrum representing elements before Potassium in the periodic table of the elements could not be real signal if anything were to be recorded there. Additionally the last 348 channels were cut, because they were representing energies above the energy of the primary photons and thus could be discarded as noise. Then the remaining 1500 channels were binned to 375 bins of 4 channels each. Finally the binning was more intensified, creating 125 bins out of the 1500 channels with 12 original channels in each bin. The results of the PCA were compared and no differences between the 3 sets were found in the main components of each of the 3 PCA runs. This was expected, since the information from a single element was spread over more than 30 channels in the original XRF spectrum of 2048 channels, due to the limited energy resolution of a SDD. Further analysis was then performed using the data cubes with 125 bins only, to maximize the time efficiency of the processing. PCA and ICA were run separately on the data sets.

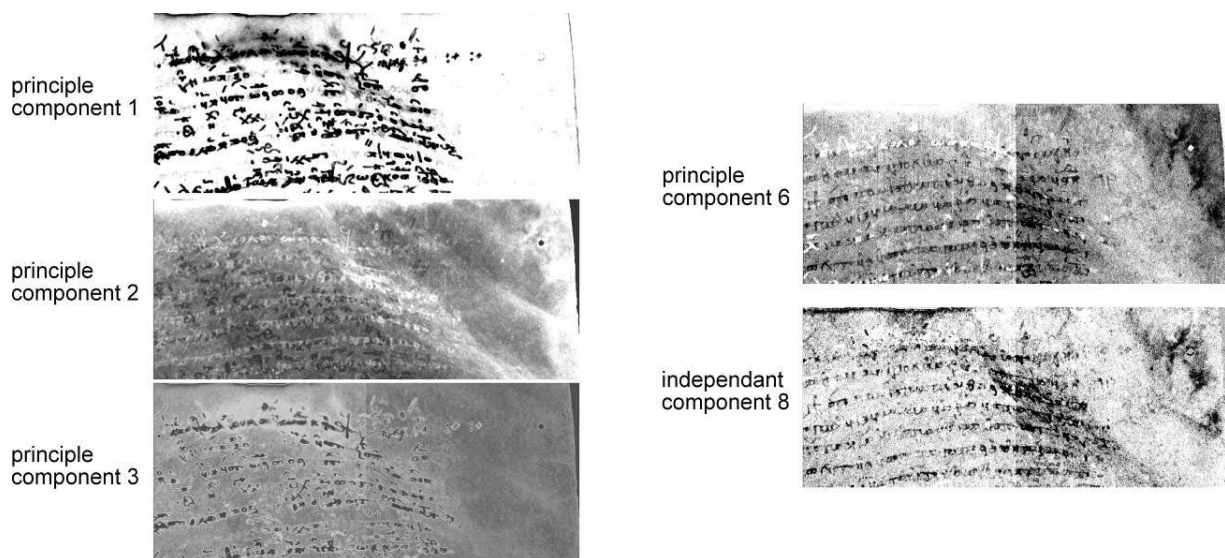


Fig. 3. Contrast maps created on basis of the components of the PCA and ICA analysis of the binned data sets. Black corresponds to highest above average value and white to lowest below average intensity in all components shown.

As expected PCA proved more useful with principal components 1, 2, 3, and 6 being of most significance in this case, while only the 8th independent component using ICA seemed to hold any useful information about the lower text. The PCA results are shown in Fig. 3. The picture from the first principle component shows a lot of the upper text, especially from the copper signal of the ink, since copper has the highest signal to background ratio with almost no copper in the parchment. Nice to see is the slightly smeared region as can be seen in the copper map in Fig. 2. The second principle component reveals some information about absorption in the measurement as explained above in the example with the two inks present at the same position. Due partial absorption by the upper ink there will be a principle component in the analysis, that has negative components (or below average in a normalized picture) for the

⁵ <https://kubuntu.org/>

⁶ harrisgeospatial.com

fluorescence absorbed by the ink. Here the contributions from the front side upper text are below average in intensity (light in color) and those from the backside are above average (darker color). The third principle component gives another picture from the upper text, this time showing mainly the differences between the copper and the iron based signal, where dominant regions of iron gives an above average signal and dominant regions of copper a below average total signal. Principle component no. 6 eventually reveals the underwriting as positive and some parts of the upper writing as negative contributions. The readability comparison standard is the Calcium map of Fig. 2 since that one was used to identify the text in the first analysis. The 8th component of the ICA gives a very similar result for the hidden text, only containing more noise and is as such less useful. The overall results look neither better than the element maps nor worse and can be used to read the erased text. The inherent feature of the PCA to produce a component, that shows which text is on which side is a bonus that can be useful, if a detector can only be placed on one side, as in the case of the used data set. The processing time for the classical XRF data analysis was 10 h for the 217.000 data points (even more when the parallel processing had not been used), while the complete data processing including binning, PCA and ICA was less than 20 minutes with most time spend on the processing of PCA and ICA. As ICA was not that successful in this case, a reduction to perform only PCA as fast analysis tool is reasonable and would get the total time down to about 10 minutes. A further acceleration of the analysis with more sophisticated algorithms is possible and will be reported elsewhere. When assuming the fastest expected scan speed reasonable today of 2 ms per point, the 217.000 points would be measured in slightly over 10 minutes⁷. The standard analysis had taken 10 hours. The expected speed gain for the analysis has been accomplished in full, while the resulting pictures were as expected slightly different, but equally useful.

CONCLUSION AND OUTLOOK

Especially PCA appears to work in favor of a quick processing alternative. The results are comparable in quality and deliver readable text quality, which allows judging the measurements success. The interpretation of the pictures in the sense of what they represent physically demands some additional input and understanding of XRF as method, the detectors used, as well as PCA, but especially in case of the PCA component 2 (in this case) the indication of whether a letter is on the front or the back of the page is a useful extra feature. For a quick and easy real time view of an ongoing measurement and for the mere identification and digitization of a hidden text PCA can be applied. Since no further assumptions or user interactions are needed the analysis method ideally qualifies for the intended application field. PCA can be performed automatically from a script using the entire spectra from a detector or optimized, when physically irrelevant regions of the spectrum and binning sizes can be given. For classical ink identification a handful of subsets from the original data can be summed up numerically and then processed with the standard XRF programs. This way the speed advantage of the statistical processing can be combined with the physical accuracy of the sophisticated analysis tools. In this example standard software was used for the PCA (IDL based ENVI), if the analysis protocol has been established and the code is run in e.g. Python or C++ further time saving can be expected, which is more advisable the more individual detectors are used during an experiment. Last but not least all processing can be done on standard hardware and platform independent, especially after the next step to implement open source code in Python.

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⁷ 434 s for the mere mapping plus at least 1s for changing of each of the 302 lines (stage deceleration, lineshift and stage acceleration) gives a lower limit of 12 minutes for this mapping region with 2ms exposure per point

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Recovery of Lost Text: What Scholars and Scientists Learn from Collaboration

KEITH T. KNOX, Early Manuscripts Electronic Library, HI, USA

Modern multispectral imaging can be applied to erased or damaged manuscripts to help scholars recover text that otherwise is not visible. Several image processing algorithms have been developed over the last two decades to mathematically manipulate the multispectral digital image data to enhance the legibility of the erased writing and suppress the interference caused by any overwriting. This paper will describe three image processing algorithms and the types of processed images that they produce. These methods were developed as a direct result of the interactions and feedback that the imaging scientists received from the scholars on the individual projects. For example, the utility of pseudocolor, to enhance the differences between the ultraviolet and visible light responses of erased iron gall characters, resulted from feedback from the scholars on the Archimedes Palimpsest project. The use of light transmitted through the parchment to reveal erased characters was initiated when a scholar on the Sinai Palimpsests Project saw otherwise invisible writing while viewing a lamp through the leaf. Lastly, the most recently developed algorithm, the triple ratio, resulted from the observation of an anomaly in a single processed image on the Zacynthius Project. When the anomaly was brought to the author's attention, the subsequent investigation resulted in the discovery of the triple ratio algorithm. The key to the development of all of these algorithms is the close collaboration between the imaging scientists and the scholars, and the sharing of ideas and observations between them.

Key words:

Text Recovery, Manuscripts, Palimpsests, Multispectral Imaging.

CHNT Reference:

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INTRODUCTION

Multispectral imaging is the process of imaging an object, in this case a manuscript leaf, under many different wavelengths of light. From the different responses of the leaf and the text to the different wavelengths, or colors, of the illumination, it is possible to separate different types of text from each other. Although this sounds very straightforward, the actual process is never this simple or straightforward. Different parts of a given leaf, or different leaves, will be exposed to different environment conditions and therefore undergo different degradations, making their responses to light different, even if all of the text has been written at the same time.

When imaging a manuscript for text recovery there are several decisions that have to be made before and during the process. Before one can start the capture process, the type of imaging modality to be used must be chosen. Among the available choices are the wavelengths of light to be used, whether the light is reflected or transmitted through the manuscript, and whether the color of the fluorescence from ultraviolet illumination will be analyzed. The scholar has likely studied this manuscript for some time and understands the nature of the parchment and its condition. The scientist, on the other hand, understands how different degradations and different inks respond to the various wavelengths of light and methods of illumination. Together, the scholar and the scientist must decide together how to image the manuscript. The scholar knows what he wants to recover, while the scientist understands how images can be captured. Neither one alone can decide what is needed to capture the necessary data.

After capture comes the processing of the data. Again, the scholar is likely familiar with the condition of the inks and the erased writing, while the scientist knows what algorithms can extract low-contrast information from noisy backgrounds. Although the scientist can apply different algorithms, he does not know where to apply them or

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whether or not they have been successful. It is the scholar that can direct the scientist to the most promising regions of the parchment and can say whether or not anything was recovered. The scholar does not know what to apply, or what the results might mean, but he knows what he is trying to read. The scientist knows what techniques to apply and how to interpret the results, but not where to apply them. The two must work together to be successful.

In the last step, extended image processing is done to recover everything possible. This step takes the most time of all three steps. It happens after the imaging and the first round of processing are complete. It consists of multiple iterations of scholars requesting regions to be processed and evaluating what the imaging scientists can produce with additional sophisticated processing algorithms. The scholar knows the language of the manuscript and can distinguish real characters being revealed from noise that is being enhanced. On the other hand, the scientist knows the algorithms and can identify artifacts that might be produced by a specific algorithm. The scientist can also use a variety of methods to maximize the visibility of the recovered text. This extended processing step absolutely requires that the scholar and scientist work together closely to accomplish the goal of recovering the text.

MULTISPECTRAL IMAGING

Multispectral images are made by using a digital camera to capture the response of the inks and parchment to different wavelengths of light. There are two ways of accomplishing this capture. One is to illuminate the leaf with white light and to filter the light entering the camera to restrict to specific wavelengths of the light on the sensor. The difficulty with the method is that the filters will introduce shifts into the images that misalign the spectral images. This makes the spectral analysis of the leaf difficult, since the pixels of the images do not line up.

The second way of capturing multispectral data is to filter the light that illuminates the parchment leaf. Any shift in the illumination does not shift the captured digital images. In that way, the spectral analysis of any portion of the leaf is now possible since the digital images at every wavelength are in perfect alignment, given that the manuscript does not move during the multiple exposures at the different wavelengths. At the same time, because the illumination is filtered, less light in total falls on the manuscript.

This system of illuminating the manuscript with light of different wavelengths is the method used in the MegaVision imaging system [Easton et al. 2010] shown in Fig. 1. On either side of the camera and the copy stand are two panels of LEDs, which contain several LEDs that emit light at different wavelengths. To make the system work over a broad range of wavelengths, from ultraviolet to the near infrared, requires a special lens that is designed to remain in focus across that broad range of wavelengths.

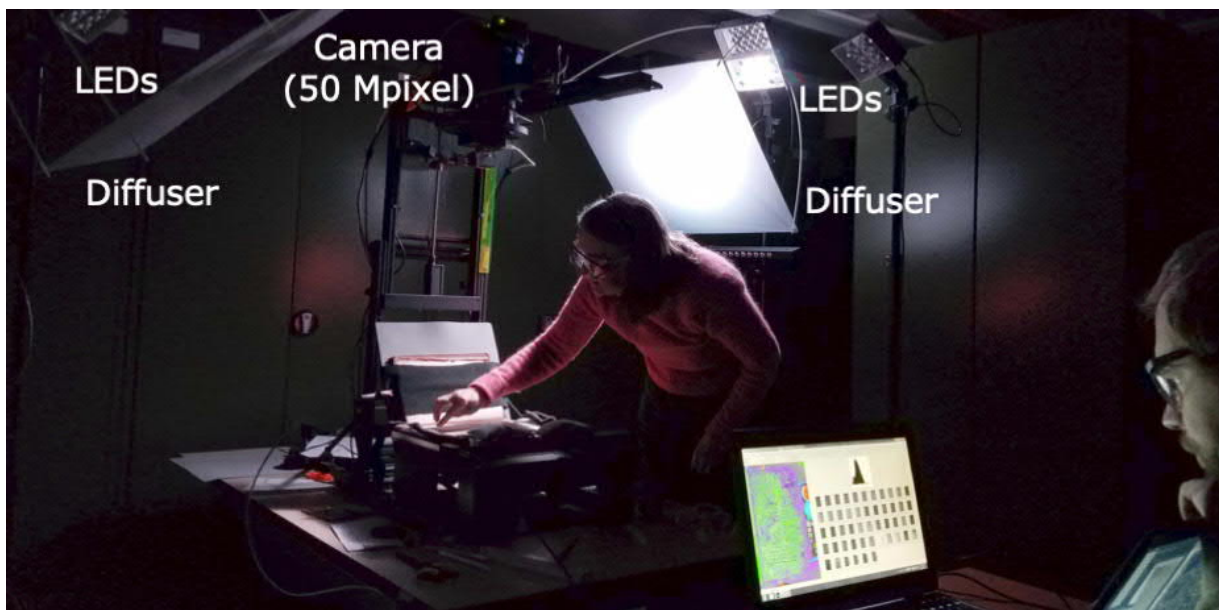


Fig. 1. The MegaVision Archival and Cultural Heritage Imaging System being operated by Dale Stewart and Ivan Shevchuk at Berlin's State Library in 2016

The fifteen wavelengths at which the LEDs emit are shown in the graph in Fig. 2. Note that the wavelength range of each LED is narrow, but all of them overlap to cover the complete range of sensitivity of the camera sensor, i.e. from ultraviolet to the near infrared, as shown in Fig. 2. Although the camera can see in the ultraviolet and the infrared regions, the human eye can only see visible light, i.e. at the blue, green, and red wavelengths.

How the illumination interacts with the manuscript leaf is also shown in Fig. 2. Of the light that falls on the leaf, some is reflected, some is transmitted through the leaf, some is absorbed, and some (mainly ultraviolet light) is absorbed and re-radiated at a longer wavelength. This re-radiated light is called fluorescence. Typically, ultraviolet fluorescence is re-radiated at visible wavelengths, converting it into light that the eye can see.

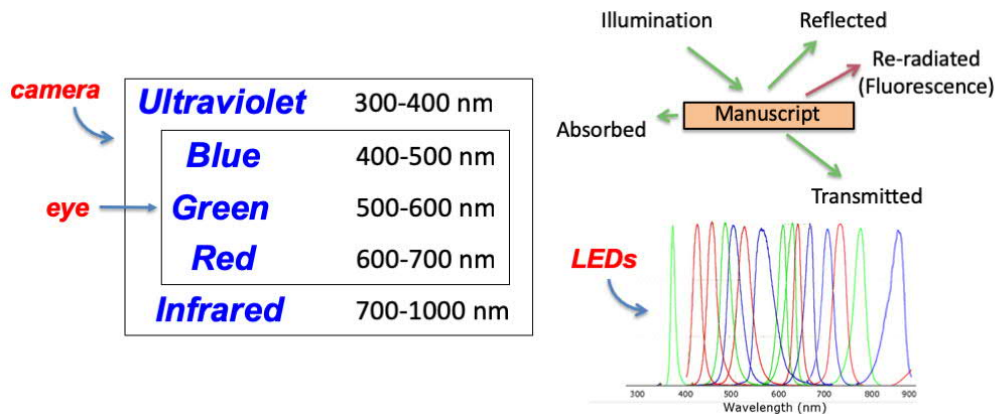


Fig. 2. Light from individual LEDs at specific wavelengths interact with the manuscript to reveal erased text

Shorter wavelength light, i.e. ultraviolet, only penetrates the leaf a short distance before it is absorbed. On the other hand, light of longer wavelengths, i.e. infrared, penetrates deeper into the leaf and is more likely to be transmitted through the leaf. By placing underneath the leaf, a light sheet that emits visible and infrared light upward, the transmitted light can be captured by the camera. As will be seen in a later section, this transmitted light will be useful in recovering characters that are no longer visible, but have eroded into the parchment making it thinner.

IMAGE PROCESSING

The camera in the multispectral system captures a digital image of a manuscript leaf. The camera is panchromatic, meaning that it responds to any wavelength of light from the ultraviolet to the near infrared. Each digital image results from illumination of only one wavelength of light, and by itself is a monochrome or black & white image.

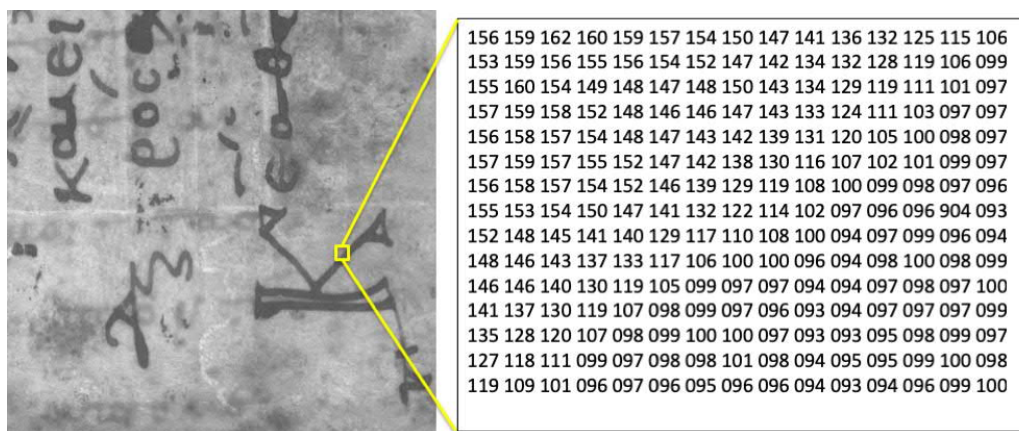


Fig. 3. A digital image is an array of numbers that represent brightness variations in the image seen by the camera

An example digital image, shown in Fig. 3, is actually just an array of numbers that are captured by the camera and stored in the computer. The numbers that correspond to a very small section of the image on the left, outlined in yellow, are enumerated on the right. The numbers are larger where the image is brighter and smaller where the image is darker. The dark edge of the character can be seen in the decrease in values from top left to lower right.

Normal images appear as regions of light and dark and are seen by the eye. The camera converts such images into an array of numbers. If that array is converted back into regions of light and dark, turning large numbers into bright regions and low numbers dark, then an image again can be seen by the eye. That is what has been done in Fig. 3.

Image processing is the act of performing mathematical computations on the arrays of numbers that represent an image, so that when the numbers are reconverted back to bright and dark regions, the appearance of the image has changed. In this way, low contrast erased text can be enhanced – making it more visible to the scholar.

There are two types of image processing that are applied to manuscript data. The first is a simple combination of individual multispectral images of different wavelengths, which enhances one writing and suppresses the other. The second type consists of very sophisticated statistical processing methods that utilize many individual multispectral images to look for slight changes. These methods are able to extract low contrast information from the data.

It is the first type of image processing, simple combinations of individual multispectral images, that is the subject of this paper. These image processing methods operate without human intervention and can be automated. As a result, these are the methods that are first applied to the data, immediately after capture. The development of the routines described here has happened over the last two decades as a direct result of interactions with the scholars working on these projects. It is possible that these routines would not have been developed without this interaction.

PSEUDOCOLOR IMAGES

The pseudocolor image, for manuscript imaging, was developed on the Archimedes Palimpsest project [Knox 2008] as a direct result of feedback from the scholars on the project, as described below. The pseudocolor image was made by combining images taken under ultraviolet illumination and visible illumination into a single, color image.

The Archimedes Palimpsest [Netz and Noel 2007] is a parchment manuscript, written in iron gall ink, that was erased and overwritten. Under ultraviolet illumination, the parchment fluoresces, glowing in a nice blue color. Because the parchment fluoresces, the erased characters, which do not glow, have a much higher contrast and they become visible. In an image taken under visible light, the underwriting is very faint and barely visible, especially through the red filter. The ultraviolet, visible (red filter) and natural light images are shown in Fig.4.

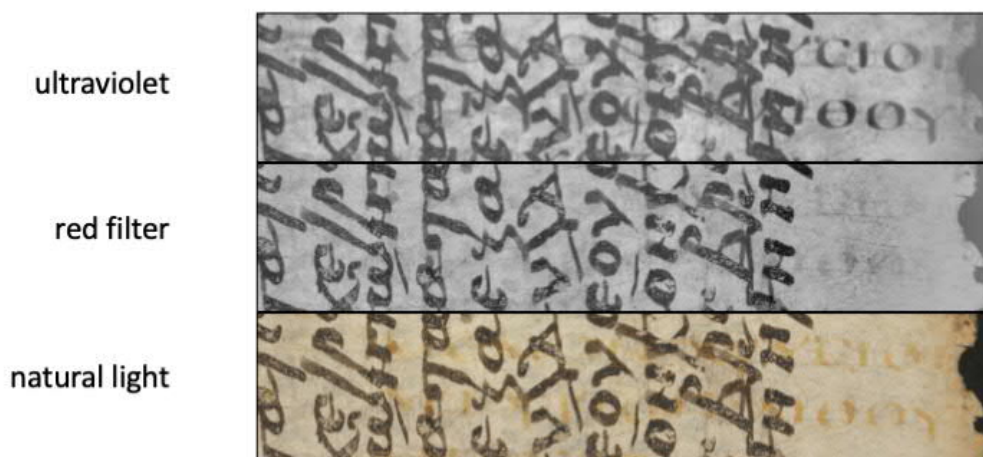


Fig. 4. The parchment and the inks respond differently to different wavelengths of light. Illuminated with natural light (bottom), the erased iron gall ink appears as red stains. Under red light (middle), the reddish stains disappear. Under ultraviolet illumination (top), the contrast of the erased text is significantly increased. ©St. Catherine's Monastery of the Sinai, used with permission

The first concept that the imaging scientists tried [Easton 2011] was to use the visible image to suppress the overwriting in the ultraviolet image, by forming a difference image. In this way, only the erased writing was left on the page. From a distance, the difference image appeared to be filled with the erased writing, now made visible. From the imaging scientists' viewpoint, it was a complete success.

From the viewpoint of the scholars on the project, Reviel Netz and Natalie Tchernetska, this difference image was not helpful. The problem was, by making the overwriting disappear, i.e. look like the parchment, it left gaps where the overwriting had been. The scholars complained that when they came to a gap, they could not tell if it was a real gap, or if it was a place where the underwriting had been overwritten. Instead of using the difference image, the scholars would read the ultraviolet image, until they came to a region of overlapping characters, then they would refer to the visible image to distinguish between the underwriting and the overwriting.

After listening to the scholars' feedback, it was determined that the solution was to use the difference information, between the ultraviolet and visible images, to enhance the underwriting rather than suppress the overwriting. By combining the ultraviolet and visible (red filter) images in a single pseudocolor image, the overwriting is still visible but neutral, i.e. gray or black, while the underwriting can be enhanced with color, e.g. turning the underwriting red.

The pseudocolor technique was further developed in the Sinai Palimpsests Project¹, a five-year effort to recover text from over 70 palimpsests in the library of Saint Catherine's Monastery in the Sinai Desert in Egypt. An example of a pseudocolor rendition of a portion of a Greek palimpsest from the Saint Catherine's Library is shown in Fig. 5, compared to its natural light image.

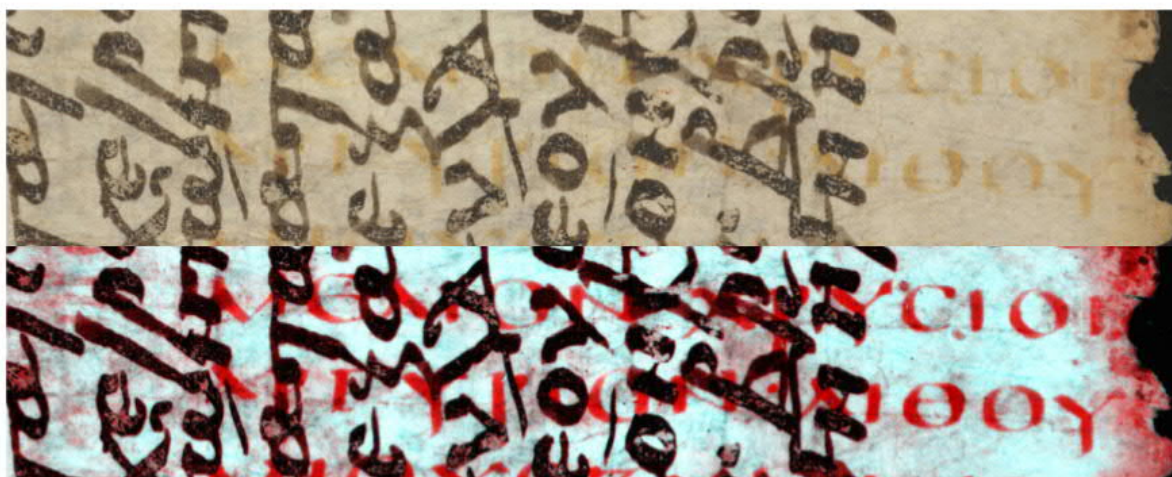


Fig. 5. The natural light image (top) compared to the pseudocolor processed image (bottom). The increased contrast of the pseudocolor image makes the erased text legible, even in the regions that overlap with the overwriting. © St. Catherine's Monastery of the Sinai, used with permission

In the natural light image in Fig. 5 (top), the horizontal underwriting is barely visible, and is slightly red. With red illumination, or under white light and a red filter, the underwriting essentially disappears, as it does in Fig. 4. Under ultraviolet illumination, both the overwriting and underwriting become darker and higher contrast. The pseudocolor image is constructed by putting the visible (red filter) image in the red separation of the pseudocolor image, and the ultraviolet image in the green and the blue separations. Since the overwriting is dark in all three color separations, it shows up as a neutral color, i.e. as gray or black. On the other hand, the underwriting is dark in the green and blue separations and bright in the red separation, making it appear red in color.

The goal of the pseudocolor image was to fill in the gaps of the difference image, and put both the visible and ultraviolet images in one pseudocolor image. In this way, the scholars did not have to refer back and forth between the two images to read the underwriting. That was accomplished, but there was an additional unforeseen advantage resulting from this combination. By combining the two images, the black & white contrast of the underwriting in the

¹ <http://sinaipalimpsests.org/>

ultraviolet image was maintained, but in addition, by rendering of the underwriting in color, the black & white contrast was augmented with color contrast. The combination of the black & white contrast along with the color contrast, gives the underwriting even higher visual contrast than either the ultraviolet or visible images have by themselves. The scholars on the Archimedes Palimpsest project were adamant in their conclusion that the pseudocolor image made the underwriting more visible than any other rendition done before it [Netz and Noel 2007].

Note that enhancing the underwriting in red is not required. Other color enhancements are possible. A small percentage of scholars will be red-green color blind and the red enhancement will therefore not be as effective for them.

TRANSMISSION RATIO IMAGES

One problem that was encountered in the Archimedes Palimpsest project occurred when there were no erased character stains in the parchment. The chemical residuals had eroded the parchment leaving slight cavities in the parchment. Because there were no stains in these locations, there was nothing to suppress the fluorescence of the parchment, and the erased characters did not become visible under ultraviolet illumination. In the Archimedes Palimpsest project, this occurred on only four pages. For those pages, the writing could be read by using with raking light, i.e. light hitting the leaf at a very shallow angle. The raking light casts shadows that make the missing characters visible.

This occurred again in the Sinai Palimpsest project in an interesting way. At the beginning of the project, the director of the project and scholar, Michael Phelps, was reviewing the manuscripts in the library, looking for good examples of palimpsests to image. While looking at one manuscript with a colleague, the two of them concluded that one particular page had no erased writing at all. However, when the colleague turned the page, a bright light across the room crossed behind it and a flash of white characters were revealed on the page. After an investigation, they realized that there was erased writing on the page, but that the characters had eroded away, leaving no residual stains. In addition, the resulting cavities were exactly in the shape of the missing characters. What had been discovered was that transmitted light would reveal eroded characters that were otherwise invisible. This led to the development by William Christens-Barry of a light sheet to send light through the leaf from underneath.

In Fig. 6 are shown two images of a manuscript from the library of Saint Catherine's Monastery, for which the manuscript is illuminated from below with infrared light (940 nm) and separately, from above with infrared light. Note that in the upper image, the transmission image, the erased characters appear as white characters on the parchment. There are no stains in those regions, but the parchment is thinner, and the localized cavities are in the shape of the characters. Because the parchment is thinner where the characters are located, light coming from underneath is scattered less by the parchment there, and more light comes through, making the characters brighter than the surrounding parchment. Note also that the visible ink on both sides of the leaf block the light and they therefore show up as dark characters in this image.

The lower image in Fig. 6 is an infrared reflectance image. It also shows the existing ink on the front surface, as does the transmission image. Curiously, though, the erased characters show up dark in infrared light. Since the infrared light penetrates deeper into the parchment and is scattered sideways and upwards, there is less parchment in the region of the letters to scatter light upwards. This makes the erased character regions darker in infrared reflectance.

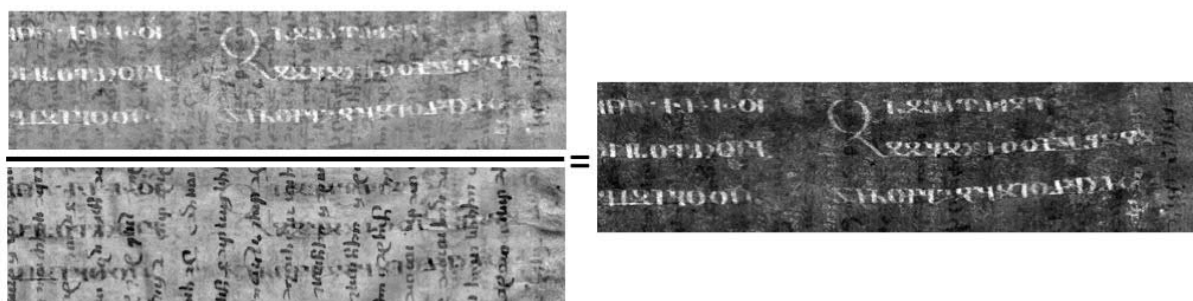


Fig. 6. When the infrared transmission image (top) is divided by the infrared reflectance image (bottom), in the ratio image (right) the erased text is enhanced (white) and the overwriting is suppressed. © St. Catherine's Monastery of the Sinai, used with permission

The infrared transmission image (upper image in Fig. 6) has white erased characters and dark overwriting. As described earlier, the reflectance image has dark erased characters and dark overwriting. By taking the ratio of the two images, the erased characters are enhanced, while the overwriting is suppressed. Dividing by dark characters (small numbers) makes the numerator image brighter (larger numbers). Dividing the white characters by dark characters makes them brighter. Dividing the dark characters (overwriting) by dark characters suppresses their visibility. The ratio of the transmission image and the reflectance image is shown in Fig. 6, on the right. The erased characters are now clearly visible as white characters on a dark background. One advantage of this method is that if the light can get through any of the overwriting, then the white characters will be complete without gaps. This is different from the normal circumstances with ultraviolet imaging, where the overwriting blocks the underlying erased writing.

This occurrence of erased characters eroding the parchment occurs more frequently on the flesh side of the leaf. Characters are seldom eroded on the hair side. The characters on the hair side are made visible with ultraviolet light.

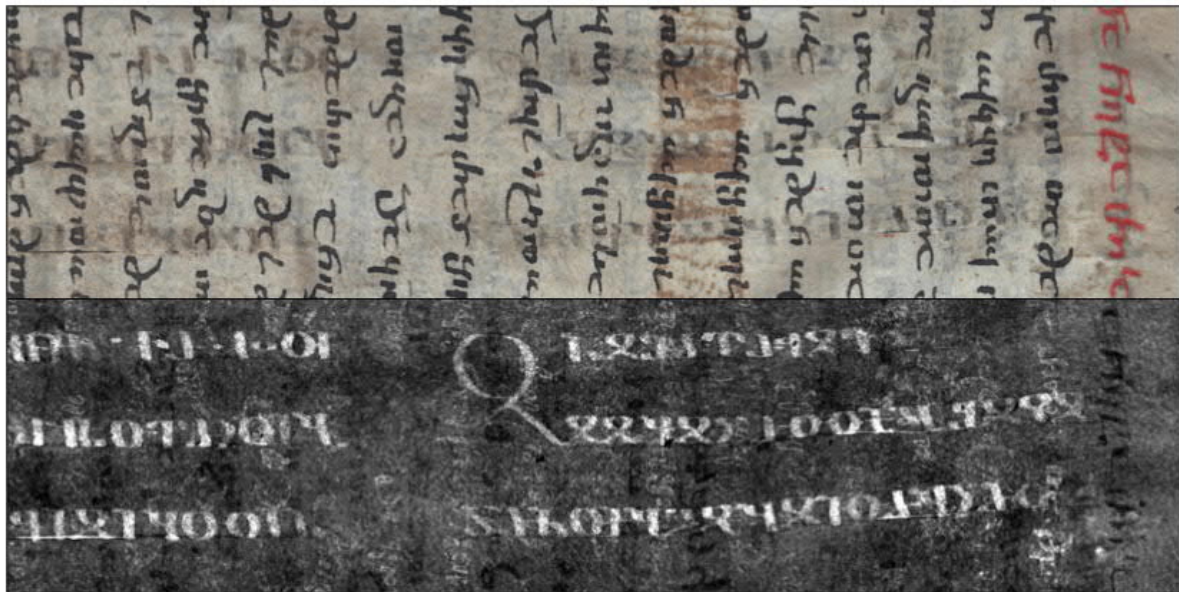


Fig. 7. A comparison of the natural light image (top) with the transmission ratio image (bottom) of the same region.
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In Fig. 7, the natural light image of the leaf is shown with the transmission ratio image. The erased characters are barely visible in natural light, but are very clear in the transmission ratio image. The erased characters in the natural light image appear to be neutral in color, rather than reddish as iron gall stains appear. As with the infrared illumination, this is because the stains have been eroded away, leaving cavities. These cavities scatter less light back to the camera making them darker than the parchment around them, but neutral in color.

TRIPLE RATIO IMAGES

In July 2018, the manuscript codex Zacynthius was imaged at the University of Cambridge Library in Cambridge, England. The manuscript is a Greek New Testament codex [Greenlee 1959] thought to have been written in the 8th Century and then erased and overwritten in the 12th or 13th Century.

For the first step in processing, the standard pseudocolor processing (described earlier) was completed. In Fig. 8, the natural light image is shown on the left, with the pseudocolor image in the middle and a sharpie image on the right. The sharpie image [Easton et al. 2010] is merely the difference of the two color separations contained in the pseudocolor image. This suppresses the overwriting, emphasizing the underwriting, but leaving gaps where the overlaps occur.



Fig. 8. A small region of one leaf of Codex Zacynthius. The natural light is shown on the left, the pseudocolor image in the middle and the sharpie image (difference image) on the right

In the natural light image, in Fig. 8, the erased text is horizontal and appears as reddish markings against a lighter reddish parchment. To confuse the issue, there are red inks marks in the overwriting. These red marks show up red in the pseudocolor image, seen in the middle of Fig. 8. They are easily confused with the enhanced red erased text. They are less confusing in the sharpie image, seen on the right in Fig. 8. Even so, neither the pseudocolor image nor the sharpie image was fully satisfying to the scholars for legibility.

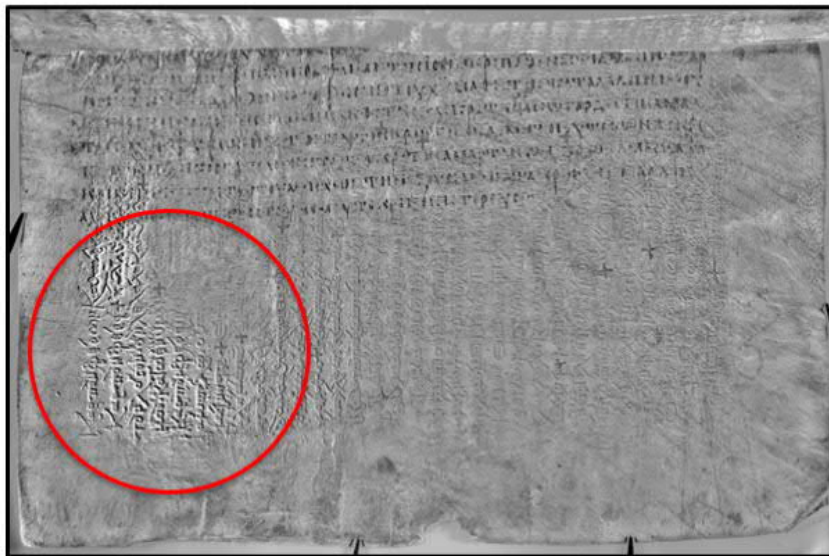


Fig. 9. A difference image of one complete leaf of Codex Zacynthius. Within the red circle the overtext shows edge effects that might indicate a localized shift between the two images used in the difference calculation

Near the end of the imaging session a problem was pointed out by the imaging scientist Roger Easton that the sharpie of one leaf (and only one leaf) had a very specific problem, as seen in Fig. 9. Within the red circle is a region where the text in one image appears to be locally shifted with respect to the other image. This might have occurred if a corner of the leaf curled up as the series of exposures that were taken, making one image different from the rest.

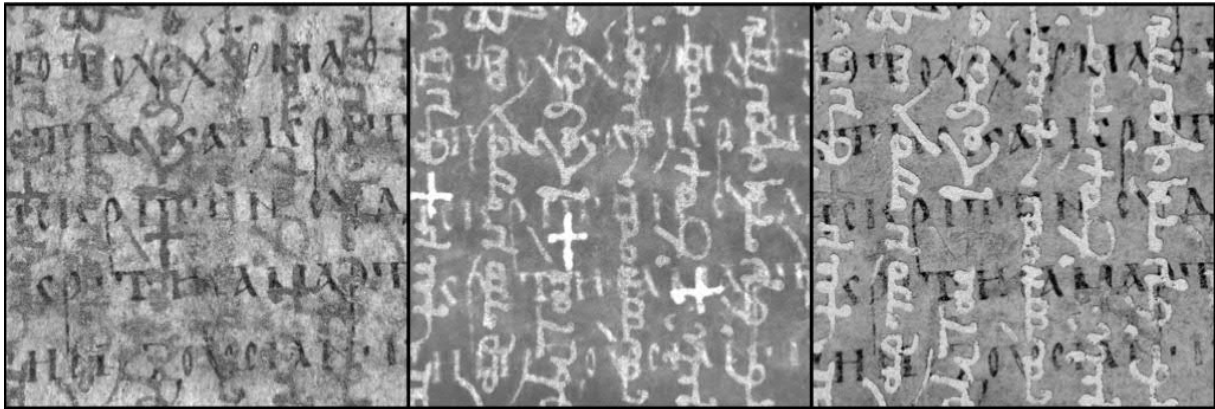


Fig. 10. Three different ratios of individual wavelength images. On the left is the ratio of two images through an orange filter with different wavelengths of ultraviolet illumination. In the middle is the ratio of two fluorescence images through a blue filter. The right image is the ratio of the red and green reflectance images

The way to test the hypothesis that one image is shifted from another is to take the ratio of the two images. A shift of one image in a ratio causes significant edge effects with white line and black lines at the edges of the characters. Something similar appears in Fig. 9, leading to the conclusion that a shift might be involved.

To test this hypothesis, the ratio was computed of the two potential shifted images, the reflectance images under red and green light. This ratio is shown in Fig. 10, on the right. No shift was evident, but a surprising result occurred – the erased text was beautifully rendered, much better than in any other rendition. In addition, the overwriting was suppressed, making the erased text even more visible. A study of several other ratios showed that ratios of fluorescence images also revealed the underwriting, but in different ways. That led to the possibility of combining three different ratios into one color image. A new type of image, called a triple ratio, was formed by putting in the red separation a ratio of two fluorescence images taken through an orange filter, in the green separation a ratio of two fluorescence images through a blue filter, and in the blue separation, a ratio of the red and green reflectance images.



Fig. 11. The natural light image (left), compared to the pseudocolor image (middle), and the triple ratio image (right). The scholars concluded that the triple ratio image gave the best legibility of the erased text

A comparison of the new triple ratio image can be seen in Fig. 11. The natural light image, the pseudocolor image, and the triple ratio image are shown from the left to right, respectively. While the erased text is visible in the pseudocolor image, its visibility is reduced by the high contrast of both the red overwriting and the black overwriting. On the other hand, the erased text in the triple ratio is very high contrast, both in black & white contrast and in color contrast between it and the parchment. In addition, the overwriting has greatly reduced contrast, and therefore it introduces much less interference with the legibility of the erased writing.

The new triple ratio image was very easy to implement and all 352 sides of the 176 leaves of the manuscript were processed in this manner. The scholars on the project were very pleased with the results and are busy transcribing the manuscript. In time, there may be a need for additional processing using statistical processing methods, but for now the triple ratio will provide the scholars with most of the information they need to transcribe the erased text.

What caused the glitch in that one image of the one leaf was never determined, but the investigation into that glitch led to the discovery of a new method that will recover almost all of the erased text of Codex Zacynthius.

CONCLUSIONS

Multispectral imaging has been applied for many years to the problem of text recovery from palimpsests [Gippert 2007; Rabin, et al. 2015; Easton et al. 2018; Easton and Kelbe 2014]. Within the last two decades, the power of new digital imaging technologies and digital imaging processing techniques has been added to the toolset being applied to the problem. Even with all of these new capabilities, there is no one method that is guaranteed to recover text from ancient parchment manuscripts.

When these manuscripts were created, the processes of making parchment and ink varied from region to region. There are similarities to these processes, so some general image processing techniques can be applied, with some success. On the other hand, there are enough differences in the ways that the manuscripts were created, or were treated over time, that every new imaging project has required new methods to recover the erased text.

Given that new methods are likely to be needed on a new manuscript, it is imperative that the scholars and the imaging scientists work closely together, as described in this paper, to achieve the maximum recovery of the erased text. The scholar understands the nature of the text. The imaging scientist understands how an algorithm extracts low-contrast information. Neither understanding is sufficient by itself to recover the erased text. Only when the scholar and the scientist pool their knowledge and their efforts can the text recovery be successful.

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Why Do We Need to Study Inks?

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While studying the socio-geographic history of inks, division 4.5 (Analysis of cultural artefacts and assets) of the BAM (Bundesanstalt für Materialforschung und -prüfung) in Berlin together with the Centre for the Study of Manuscript Cultures in Hamburg has developed a protocol for ink analysis. It consists of a primary screening to determine the type of the ink, and a subsequent in-depth analysis using several spectroscopic techniques.

Using this protocol, scientists can assist scholars in addressing a rather broad range of historical questions that cannot be answered unequivocally through scholarly research alone. Among these are investigations on collaboration between scribes and scriptoria, on the usage and annotation of manuscripts and on their path through time and space in general. This research can thus help to reconstruct the circumstances of the production of written heritage as well as their history and transmission.

To facilitate the dialogue between the scholars and the scientists a simple optical tool was developed to allow the scholars to perform preliminary ink analysis required for formulation of the question that in turn can be answered by scientific in-depth investigations. In this paper, ink types and their identification method is accompanied by examples of the recent work conducted on parchment manuscripts in the Austrian National Library.

Key words:

Ink, Manuscripts, Non-destructive analysis, Advanced codicology, XRF.

CHNT Reference:

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INTRODUCTION

Determination of chemical composition of writing materials generates important data for addressing cultural-historical questions that cannot be solved by historical and philological methods alone. In its individual materiality, each manuscript contains evidence of the production processes as well as a wide variety of traces from use, storage, and conservation treatments. The traces that can be measured and ascribed to certain events provide insights into the history of a manuscript.

There are at least two prerequisites for the successful implementation of such measurements. The first and the most important one for the investigation of historical objects is the use of techniques that are non-destructive or require only minimal sampling. In case of sampling, the latter should preferably stay unchanged by analysis and available for further studies. In this respect, “X-ray fluorescence” (XRF) analysis represents one of the best and commonly used methods for obtaining qualitative and semi-quantitative information on a great diversity of materials. In addition to a variety of portable and transportable XRF instruments, a wealth of knowledge and experience has been accumulated in the characterization of historical inks. The second prerequisite is a meaningful question to be answered by scientific analysis. The field of codicology i.e. study of manuscripts as physical objects seems to be the most appropriate field for adoption of a routine determination of the composition of writing materials. In the dialogue between scholars and scientists, a new field of advanced codicology has emerged in the recent years [Hahn et al. 2007; Rabin et al. 2015; Geissbühler et al. 2018; Heiles et al. 2018].

□

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To further facilitate this dialogue, the BAM division of the analysis of the cultural artefacts has developed a simple optical tool for identification of the ink type since its colour was not well suited for this purpose. It is customary to distinguish between three main types of the historical black writing materials used in manuscript production: soot, plant, and iron-gall inks. Soot ink is a fine dispersion of carbon pigments in a water-soluble binding agent; plant-based ink consists of tree bark (tannin) solution; iron-gall ink, produced by mixing iron (II) sulphate with a tannin extract from gall nuts, presents a boundary case between soot and plant ink – a water soluble preliminary stage (similar to inks from the second group) oxidizes and evolves into a black, insoluble material (similar to the carbon pigments of the first group) when the writing is exposed to air. Each ink class has distinct properties that readily permits their differentiation when used as a solitary type rather than a mixture. Carbon inks do not penetrate the substrate (whether papyrus, parchment or paper) and stay well localized on the surface. In contrast, plant inks and iron-gall inks are absorbed by the substrate, and the degree of their absorption depends to a great extent on the nature of the substrate. A typological differentiation can be also made using the interaction of the inks with the infrared light. IR reflectography has been traditionally used to study soot-based pigments or carbon inks: the colour of soot inks is independent of the illumination wavelength in the range 300-2000 nm; plant inks lose opacity close to 750 nm, whereas iron-gall inks become transparent only at a wavelength > 1000 nm [Mrusek et al. 1995]. Using a conventional usb-microscope with a silicon detector and illumination with visible and near-infrared (940 nm) radiation, it is possible to identify the ink type due to the change of its opacity. When the illumination is changed from the visible to the NIR light carbon ink undergoes no change; plant ink becomes invisible; iron-gall ink changes its opacity but doesn't disappear completely. One has mention, however, that the clear distinction between plant inks and iron-gall inks might be difficult in this spectral range if iron-gall inks contain very little iron and are, in fact very close to the tannin inks in their formulation. In cases of doubt, additional measurements, namely using XRF should be conducted.

XRF ANALYSIS OF IRON-GALL INKS

As a matter of fact, iron-gall inks are best studied by the means of the XRF technique. Natural vitriol, the main component of the historical iron-gall inks, consists of a mixture of metallic sulphates (iron sulphate, copper sulphate, manganese sulphate, and zinc sulphate) with relative weight contributions characteristic of the vitriol source or purification procedure [Krekel 1999]. One uses this very property of the iron-gall inks to compare them and to distinguish among them. Specifically, development of the fingerprint model based on the qualitative and quantitative detection of inorganic components of the iron gall inks leads to their comparison and differentiation [Hahn et al. 2004; Hahn 2010]. Using fingerprints of red and iron-gall inks we were able to tackle a number of specific questions that arose upon the classical codicological analysis. One of such cases, a compilation of different Middle High German texts associated with Arturian tales bound into a single manuscript, *Codex germanicus 6* is an excellent example for a manuscript with a complex history of production that could be reconstructed using combination of codicological and XRF analysis of the writing materials. Codicological analysis indicated that the sequence of the texts in the bound codex doesn't correspond to the order, in which they were penned. The exact dates of the copying of the large romances *Parzival* and *Wigalois*, were known from the colophons that accompanied each of the texts. The chronology of the seven out of remaining ten texts could be reconstructed on the basis of classical codicology. Yet three very short texts could be added at any point. Luckily, the codex was written in iron-gall inks and rubricated with red inks, whose composition varied with time. Some two hundred measurements of the inks composition allowed us to establish the chronology of transcription using time dependent variation in the fingerprints of the inks. This chronology confirmed the order of transcription that has been suggested by classical codicology and attributed the time of inscription for the three short texts. Using imaging XRF we were able to document the traces of multiple corrections. These included text cancelling performed in white lead or just crossing out in the red inks as opposed to direct overwriting in black and red inks. We interpret over-painting of initials as a correction of the latter type. It seems that such corrections served to enhance the colour of the inks and were performed during multiple inspections of the manuscript [Rabin et al. 2015; Geissbühler et al. 2018].

XRF ANALYSIS OF CARBON BASED INKS

In the case of carbon based inks, XRF analysis serves to discover the presence of various inorganic contaminants. Carbon inks containing a considerable amount of copper were detected on a small number of the Dead Sea Scrolls [Nir-El and Broshi 1996] and *Tebtunis* papyri [Christiansen 2017] Moreover, carbon inks containing considerable amounts of lead (Pb) were identified on a Herculaneum papyri [Brun et al. 2016]. Since in both cases carbon

constitutes the colourant of the inks we consider these varieties to belong typologically to the class of carbon inks. In the last decades, Raman spectroscopy with its distinct spectrum of carbon became very popular in identification of carbon inks. It was even hoped that this method would lead to identification of the organic precursors for the ink. Unfortunately, our preliminary results show that even a clear distinction between charcoal and soot cannot be seen using this type of spectroscopy. Similarly, the claim that Raman spectroscopy can be used as a non-invasive dating tool could not be confirmed [Goler et al. 2016]. XRF is also one of the important methods for identifying the mixed inks, i.e. inks produced by addition of various metals to the soot inks and intentional mixing of iron-gall and soot-based inks, respectively. Mixed inks received no or little attention in the scholarly and material studies because their identification and recognition of their importance belongs to the discoveries of the last years. Their detection, and especially their classification is quite difficult if one is limited to non-invasive methods. Studies of the extant recipe sources indicate that mixed inks played an important role in the medieval Islamic world. In this respect, the chapter of an excellent study on the written sources of ink recipes, which is dedicated to the inks used by Jews in different epochs and geographical zones is of particular interest to those of us who conduct material analyses and try to correlate the results with written records and existing traditions [Zerdoun Bat-Yehouda 1983]. Comparing the inks proposed by the Jewish philosopher Maimonides, who lived in 12th-century Egypt, with the considerations of Rashi, who lived in 11th-century northern France, we can see that they both advocated use of the inks commonly known and produced in their respective regions. It is Maimonides who proposes to add tannins to the soot inks, but rejects the metallic salt, both of which were practices that were well attested in contemporary Arabic recipes for making ink. In contrast, Rashi was favourable to employing the plant inks in use in contemporary Northern Europe. The last variety is best represented by the thorn or Theophilus' ink whose elaborate recipe is recorded in *De Diversis Artibus* in 12th century AD [Dodwell 1961]. Unfortunately, no systematic study of the historical use of these inks has been ever conducted: its use has been only occasionally reported in different scriptoria. Recently performed studies on the inks used in the Northern Europe in 6-10th centuries CE form a preparation phase of our new project that should explore spreading of the writing materials associated with the insular manuscripts. Here, tannin inks and the appearance of the iron-gall inks build the focus of the research.

When a statistically relevant number of manuscripts with distinct inks from different regions and time periods has been studied the collected data will be assembled into a time-location map that should become a dating and localization tool for the manuscripts of unknown provenance and unsure dating. "Inks of Coptic Manuscripts" [Ghigo et al. 2018], "Ink recipes from the Islamic world" [Colini 2018], "Writing inks of Hebrew fragments in Genizah collection" [Cohen et al. 2017, Rabin 2017], "Inks of late Antiquity" [Rabin and Krutzsch 2019] belong to the projects that are specifically dedicated to this aim and are being conducted at the "Bundesanstalt für Materialforschung und -prüfung" (BAM) and the "Centre for the Studies of Manuscript Cultures" (CSMC). Similarly, identification of the metallic precursor used for the iron-gall inks seems also to be of great interest. As mentioned above, vitriol is easily recognized due to the presence of sulphur as and metals – companions of iron. In contrast, the recipes known in the Islamic manuscripts report that metallic filings or even nails dissolved in acid were also used as iron precursor to the iron-gall inks [Colini et al. 2018]. The existence of such inks has been confirmed by recent scientific analysis [Ghigo 2018]. We hope to be able to add the results of the systematic studies of tannic and early iron-gall inks of the Northern Europe to the database.

In this paper, preliminary results of the analysis of the manuscripts from the collection of the Austrian National library are shown.

EXPERIMENTAL

Visible spectroscopy was carried out with the aid of the spectral photometer SPM 100 (Gretag Imaging AG company Regensburg, Switzerland) equipped with a 3 mm sensor and 2W white light bulb. The measurements were conducted with 10 nm wavelength resolution and 0.5 sec illumination time.

One of the XRF spectrometers used in this work, ARTAX (Bruker GmbH) is well known in the field of cultural heritage and belongs to standard equipment in the majority of large museums. It is equipped with focusing lenses and, therefore, has the X-ray beam spot of 70 μm in diameter. It also features a CCD camera for sample positioning and an electrothermally cooled Xflash detector (SDD, area: 30 mm^2) with an energy resolution of <150 eV at 10 keV. The movable probe is operated by XYZ motors that control positioning for single-spot measurements as well as line and small area scans. Open helium purging in the excitation and detection paths allows for detection of light elements ($Z \geq 13$). All measurements are made using a 30 W low-power Mo tube, operating at 50 kV and 600 μA , and with an acquisition time of 10 - 100 s (live time). The mobile XRF probe moves over the object at a distance of

5 mm and stops for the duration of a single measurement. A line scan consists of several single measurements along a chosen line. With its small beam spot, it is well suited for investigations of fine scripts. For larger areas of interest, a portable XRF spectrometer ELIO (former: XGLab, now: Bruker GmbH) was used. It has a measuring spot of 1 mm in diameter. The instrument is equipped with a 1W low-power rhodium tube and adjustable excitation parameters.

RESULTS

ÖNB Cod. 974: comparison of the red inks

The production of manuscripts in the Cistercian abbey of Heiligenkreuz in Lower Austria (founded 1133) in the 12th century has been thoroughly investigated. On the website www.scriptoria.at examples of hundreds of scribal hands, correctors and rubricators, have already been published in addition to a book dedicated to the early years of the scriptorium [Haidinger and Lackner 2015]. Among the initials in these early books a group of silhouette initials stands out not only in style but also in color. Since the color is also noticeably different from most other Austrian manuscripts of the period information on the composition of the ink is relevant for understanding the workings of the scriptorium. As a point of comparison another initial from a slightly later part of the manuscript with a more standard type of red was also investigated (Fig. 1).

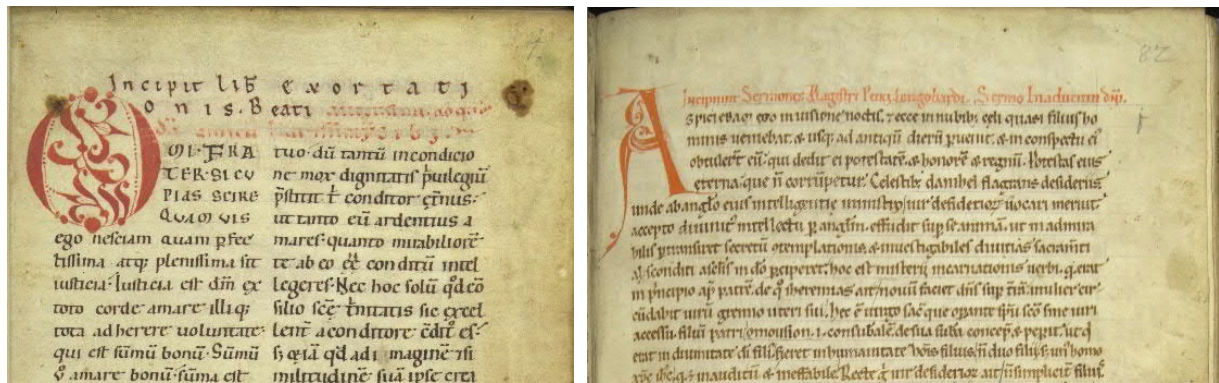


Fig. 1. ÖNB Cod. 974, left: fol. 1r, right: fol. 82r

By means of a spectral photometer, the colour value of a colorant can be quantitatively determined on the basis of its reflective spectrum in the range of visible light (380 nm to 730 nm). With this surface method, the sample to be examined is illuminated with visible light. The sample material interacts with the visible light by absorbing or reflecting it in a specific way, thereby appearing coloured. The reflected light characteristic of a specific pigment is measured with a photometer and recorded in the form of a characteristic reflection curve. This curve represents the correlation between the intensity of the reflected light and its wavelength. Comparison with a databank makes it possible to ascribe the pattern to a certain pigment or dye.

The first derivatives of the reflection curves in Fig. 2 indicate that pure cinnabar (HgS) is responsible for the red colour in fol. 1r (Fig.2, black curve) whereas the colouring on fol. 82r was executed mainly in minium (Pb₃O₄) though a small contribution from cinnabar is clearly seen in the composite curve (Fig.2, red curve). XRF spectra of both colourants confirm the identification made with visible spectroscopy displaying that the pigment from fol. 1r contains basically only mercury whereas the spectrum corresponding to the red from fol. 82r shows lead as a main constituent followed by a small quantity of mercury.

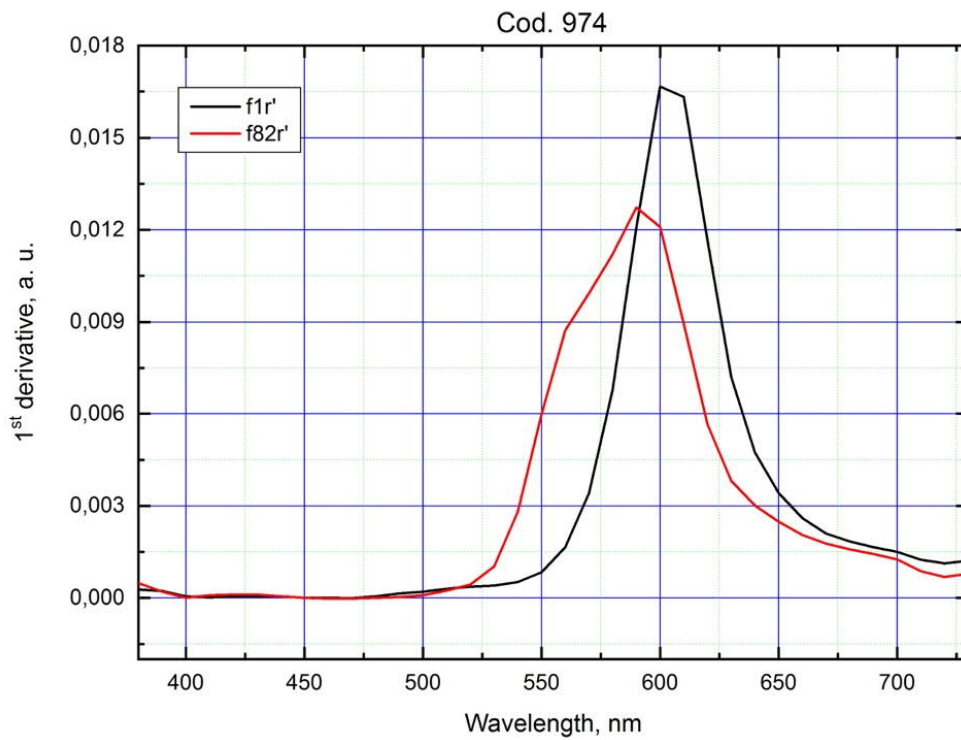


Fig. 2. First derivatives of the reflection curves: black fol. 1r, red: fol. 82r

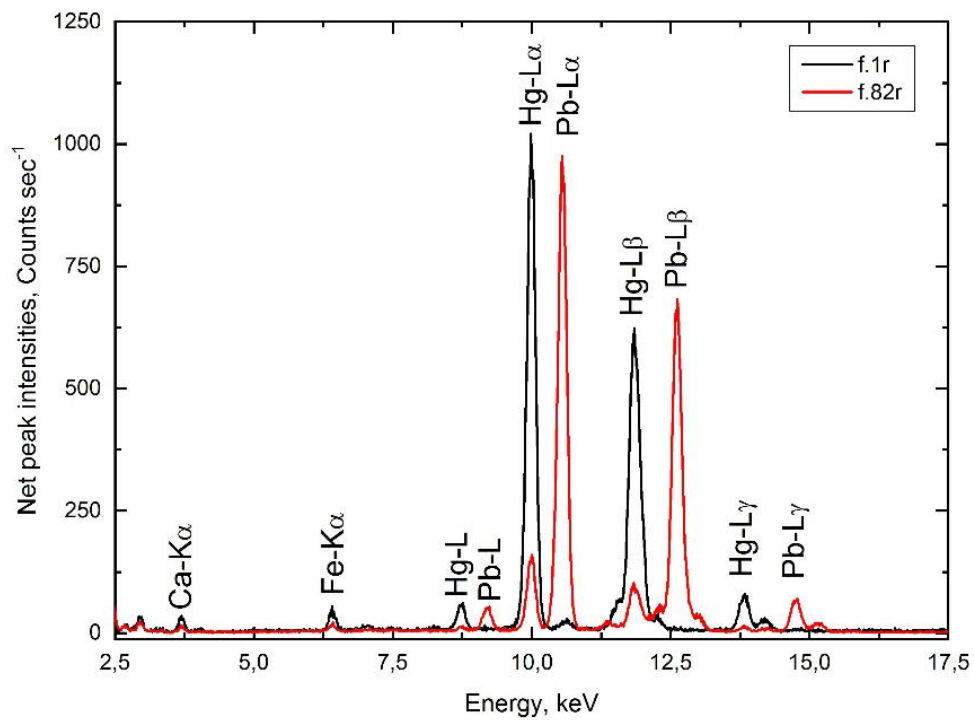


Fig. 3. X-Ray fluorescence spectra of the red pigments from the fol.1r (black) and fol. 82r (red)

Analysis with visible spectroscopy and X-Ray fluorescence conducted on the red inks of fol. 1r and 82r of the codex identified two different colourants used: practically pure cinnabar of the first initial in contrast to the minium of the fol. 82r.

ÖNB, Cod. 808 – Comparison of the seemingly different inks on a single page.



Fig. 4. Cod. 808, fol. 9r with two seemingly different inks. Blue arrow indicates the letters shown in the micrographs on the right, b & d are taken under visible, c & e – under NIR illumination

Working with medieval manuscripts one sometimes encounters strikingly different ink colours within a manuscript or even a single page written by the same scribe. This raises the question whether a different type of ink or a new batch with a slightly different mixture was used, yet again giving hints on how the scriptorium worked. One such sudden change in ink colour can be found in ÖNB Cod. 808 written in Salzburg in the early 9th century and therefore a prime example of Carolingian manuscript production in Austria. Fig.4 demonstrates this ink behaviour of the fol.9r of the manuscript.

Table 1 Elemental composition of the inks (normalized to iron)

Element	Line 22 ($\pm 10\%$)	Line 10 ($\pm 10\%$)
Phosphorus (P)	0.02	0.02
Potassium (K)	0.50	0.27
Calcium (Ca)	0.40	0.40
Manganese (Mn)	0.01	0.01
Iron (Fe)	1.00	1.00

A reflectography test in the Vis / NIR regions demonstrated that the inks from the lines 10 and 22 of the folio 9r disappeared in near infrared light suggesting that the inks are of the tannin type (Fig.4, b/c and d/e). In contrast, XRF analysis of the inks detected elevated intensities of iron indicating that the inks should rather be attributed to the iron-gall type. When one studies and compares various inks in a single manuscript, it is often sufficient to record a characteristic metal pattern of an iron-gall ink and analyze it using a simplified semi-quantitative approach [Rabin et al. 2012]. In this approach, the contributions of the individual metals due to the parchment can be evaluated from the

parchment spectrum and subtracted from the measured data of the inked areas. Even in this first-order approximation, the variations due to ink thickness and degradation do not affect the pattern of the ink. To determine a reliable pattern, the micro XRF measurements were conducted in a so-called line-scan mode. In this mode, a minimum of 10 spectra were collected for characterization of the ink and another 10 for characterization of the writing support (parchment in this case). The spectra were evaluated, corrected for the background due to the writing support and normalized to iron as a main element of the iron-gall ink. The resulting pattern described inorganic composition of the ink under investigation (Table 1).

As can be seen from the table 1 the pale ink in the line 10 has almost identical composition to the dark ink of the line 22. Potassium is the only element whose relative amount doesn't stay constant when comparing two inks. Since potassium can be related to the binder used, one can speculate that the ink from the lower part of the page comes from a different batch as compared to the upper part. It is noteworthy that the inks neither contain sulphur nor copper or zinc, the elements that would un-equivocally prove that vitriol was used for the ink production. It is quite possible that the ink used here could be associated with ink preparation known to us from the ink recipe of Theophilus [Dodwell 1961] – tannin ink, to which some metallic iron was added. In such a case, the ink would disappear under the NIR illumination but would contain iron. Presence of the element phosphorus in these inks is most noteworthy – so far it has been detected only in the carbon inks of antiquity.

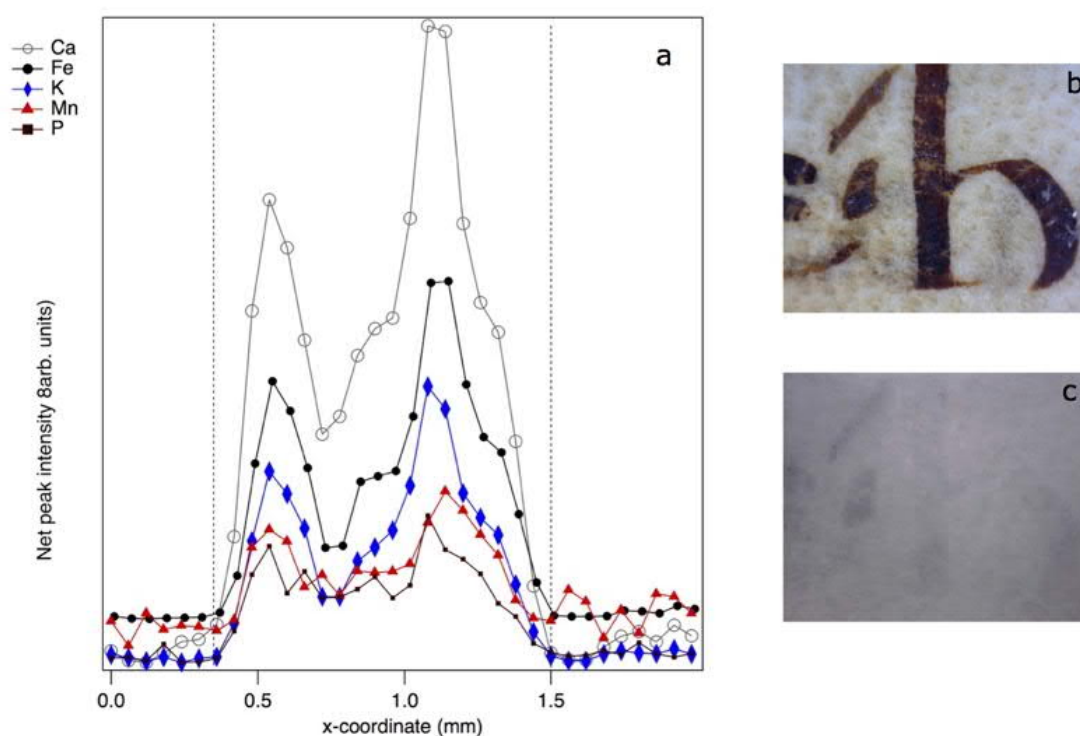


Fig. 5. Intensities of inorganic components of the ink extracted from an XRF-line scan across a letter from fol.3r of (a); micrographs of the letter in visible light (b) and at 940 nm (c). The vertical dotted lines separate the inscribed area from the non-inscribed

ÖNB Cod. Ser. n. 2065

This unusual ink composition has been encountered in this work in another ink, this time in the ink of the codex ÖNB Cod. Ser. n. 2065. The manuscript was written in the late 8th century in yet another famous Carolingian scriptorium in Austria: the Benedictine monastery of Mondsee in Upper Austria. In the 15th century the manuscript was apparently deemed useless and was cut up to be used in new book bindings for the monastic library's ever-expanding collection. What remains today are fragments from over 90 pages that are at the moment being reconstructed on www.fragmentarium.ms.

In Fig. 5a, the authors present the individual intensities of the inorganic components resulting from a line scan across a heterogeneously degraded portion of the ink from fol.3r. Note that the curve form of each contribution follows that of iron, the main component of the ink, the behavior, which is typical for iron-gall ink. The varying thickness and degradation of the ink are reflected by the high variability of the signal for iron and its satellites within the inked area. Note that the elements that constitute the inks are exactly the same elements that were found in the inks of the ÖNB Cod. 808. In contrast to those inks, in this case the ink is still visible at 940 nm (Fig. 5c) unequivocally proving it to be of iron-gall type.

CONCLUSION

This paper shows the successful application of the protocol for ink analysis developed by division “Analysis of Cultural Assets” at the BAM in Berlin in collaboration with the Centre for the Study of Manuscript Cultures in Hamburg. Two-step analysis consisting of XRF and VIS spectroscopy conducted on the red initials of fol. 1r and 82r of the ÖNB Cod. 974 identified two different pigments: practically pure cinnabar of the first initial contrasted with the minium of the fol. 82r. In contrast, seemingly different inks observed on a single page of the ÖNB Cod. 808 demonstrated basically the same composition. The most interesting discovery of this work is identification of an unusual ink composition in the manuscripts without any connection other than geographic proximity and the time period raises a question whether this type of ink could be characteristic for the southern German region and Austrian around 800. Our future research will certainly clarify this question.

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Determining the Origin of Some Marginal Notes of Cod. ÖNB H.O. 42a through Ink Analysis

CLAUDIA RÖMER, University of Vienna, Austria

Cod. ÖNB H.O. 42a is a copy of Muṣṭafā Bostān's (1498-1569/70) *Süleymānnāme* (or, as its second title reads, *Tārīḥ-i sulṭān Süleymān*) on the earlier part of the reign of the Ottoman sultan Süleymān the Magnificent (1520-1566). Previously, scholars believed that its author was called Ferdī. This assumption is based on the alleged occurrence of this pen-name in the author's Persian poem on fol. 6r of cod. ÖNB H.O. 42a. [Yurdaydın 1955] proved that the last verse of this poem had been misunderstood and the author of *Süleymānnāme* was Bostān.

The title in red ink on fol. 1r of cod. ÖNB H.O. 42a says *mü'ellifi Ferdī* "Its author is Ferdī". In the margin of fol. 6r next to the above-mentioned poem, there is a remark in black ink formulated perhaps by a non-first-language speaker (*ṣāhib mü'ellif Ferdī ile taḥalluṣ eder* "the owner author/the Lord author gives his pen-name as Ferdī"). The handwriting of both remarks possibly is European.

The ms. belonged to Hammer-Purgstall, as one can see from the imprint of his Oriental seal. If one could determine the composition of the ink the remark on fol. 6r was written with as well as that of Hammer's seal, one could prove a) whether European or Oriental inks were used and b) whether for Hammer's seal the same ink was used as for the remark on fol. 6r. If so, this would identify Hammer as the author of the remark (and of the erroneous title which is by the same hand). Therefore, a first analysis of the inks of the manuscript versus the inks of the remarks was done. Both remarks, Hammer's seal as well as a piece of normal text were photographed with UV, VIS, NIR. The red ink on fol. 1r vanishes under NIR wavelengths, whereas the black inks of the main text and of the remark on fol. 6r as well as the ink used for Hammer-Purgstall's oriental seal are visible in all three photographs, indicating that possibly none of the black inks used for cod. ÖNB H.O. 42a contains iron gall and thus they could be of Oriental origin.

Key words:

Ink Analysis, VIS NIR UV, 16th Century Ottoman Chronicle.

CHNT Reference:

Claudia Römer 2018. Determining the Origin of Some Marginal Notes of Cod. ÖNB H.O. 42a through Ink Analysis.

Cod. ÖNB H.O. 42a is a 16th-century copy of Muṣṭafā Bostān's (1498-1569/70) *Süleymānnāme* on the earlier part of the reign of Süleymān the Magnificent (1520-1566), comprising the years 1520-1542. Bostān Çelebi's full name was Muṣṭafā bin Mehmed Bostān Tīrevī. He came from Tīre (Tire) in Western Anatolia. Bostān made a career within the *medrese* system (system of religious schools, where some worldly subjects were taught as well), with some of the most renowned scholars of his time as his teachers. After serving as a *müderris* (professor) at various *medreses* himself, he became *cadi* (judge) of Bursa, then of Edirne in 1544, subsequently being promoted to the office of the *cadi* of Istanbul in 1545. In 1547, he was appointed *kazasker* (chief judge) of Anatolia, then of Rumelia. He stayed in office until 1551, when he was deposed on the grounds of having given a verdict unfavourable for the Grand vizier Rüstem Paşa (died 1561). Subsequently, he was acquitted. Bostān Çelebi has become known as the author of a number of mostly religious works. The *Süleymānnāme* is his only historical work [Aykut 1992].

Until now, seven manuscripts of the *Süleymānnāme* have been known, two of them at the Austrian National Library (H.O. 42a and b [Flügel 1865, nos. 998 and 999 respectively – H.O. 42b comprises the years 1520-1529 only, see Yurdaydın 1955: 147, note 38]) and three in Turkey. The other manuscripts are:

□

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- 1) Süleymaniye Kütüphanesi, Aya Sofya no. 3317. It tells the history of Süleyman the Magnificent from 1520-1536 (see [Yurdaydın 1955: 151]).
- 2) Topkapı Sarayı Müzesi Kütüphanesi Revan no. 1283. This manuscript comprises the years 1520-1523 only [Yurdaydın 1955: 149].
- 3) Türk Tarih Kurumu Kütüphanesi no. 18. It contains the years 1520-1539 [Yurdaydın 1955: 164].
- 4) Torino Biblioteca nazionale a IV 14 [Nallino 1900:84, no. 103]. This manuscript was badly burned during World War II [Yurdaydın 1955: 147], so that only fragments of each page have survived. However, it is still partly readable (see [Römer 1992: 238, note 10]).
- 5) HS.or.oct.1142, Staatsbibliothek Preußischer Kulturbesitz Marburg. It describes the years 1520-1539/40 and was copied in 1591. Its title is given as *Ğazavāt-i sulṭān Süleymān*. [Flemming 1968: no 138]; see also [Römer 1992], [Römer 1997]. This manuscript is neither mentioned by [Yurdaydın 1950], [Yurdaydın 1955], nor by [Aykut 1992]. It was found by coincidence in an envelope [Flemming 2018: 37].

Although the facts that have led to the correct identification of the author of the *Süleymānnāme* have been known for a long time within the Ottomanist community, it may be useful to give a short overview of the state of research here.

On the basis of the different manuscripts, Yurdaydın has shown that Bostān Çelebi wrote the *Süleymānnāme* over a longer period, namely between 1524 and 1547, adding chapters and adapting the eulogies to be used after the names of dignitaries according to whether they had died in the meantime [Yurdaydın 1955].

The *Süleymānnāme* is a typical work of 16th-century Ottoman “divan prose” with a large amount of Arabic and Persian elements [Römer 1997]. As such, like many other Ottoman prose works, it contains some of its author’s own poems, each one given under the heading of *li-mü’ellifihī* “by its author” [Römer 1992]. A total of thirty-six of Bostān’s poems could be gleaned from four manuscripts of the *Süleymānnāme*, namely ÖNB H.O. 42a and b, Torino Biblioteca nazionale a IV 14, and HS.or.oct.1142, Staatsbibliothek Preußischer Kulturbesitz Marburg (see the comparative list [Römer 1992:238]). One of these poems, which will be given below (see also Fig. 4), played a prominent role in the discussion about the author of the *Süleymānnāme*.

At some point during the 19th century, the manuscript ÖNB H.O. 42a was newly bound with a European binding, which, on its spine, gives the name of Ferdī as the alleged author’s name in Roman characters, “Suleiman’s Geschichte von Ferdī”. Thus, nothing can be said about its original binding. The manuscript comprises 364 folios. In what follows, discussing the origin of the “Ferdī legend” and the possibilities of tracing it back to its origin with new methods will be at the centre of the present paper. The focus will mainly be on the paratexts of this manuscript¹.

On the second flyleaf (see Fig. 1), the title of the work is given in red ink, saying *tārīḥi* (sic!) *ṣāḥib k̄ānūn Süleymān mü’ellifī Ferdī* “The History of the Owner of the Law, Süleymān. Its author is Ferdī”. First of all, this title differs from the title under which this work is generally known, i.e. *Süleymānnāme*. Besides, the title on the second flyleaf displays a rather unusual way of naming Sultan Süleymān the Magnificent, whose Ottoman epithet was *Ḳānūnī*, the Lawgiver: *Ḳānūnī Sulṭān Süleymān*. Moreover, there is a misspelling in the first word.

This neat handwriting of the so-called *nashī* type of the Arabic script looks more like a European hand, albeit a very beautiful and skilled one.

Fol. 1r contains two owners’ marks (see Figs. 2 and 3):

The first owner who left his seal and the date of his purchase was a certain Muṣṭafā Ḥafīd Naḳṣbendī, whose note written in Arabic can be read as *istaṣḥabahū l-‘abdu l-muḍannab as-sayyid Muṣṭafā Ḥafīd Naḳṣbendī fī 20 [Ramazān] sene 1240*. “This sinful slave [of God], as-sayyid Muṣṭafā Ḥafīd Naḳṣbendī has made it his possession on 20 Ramazān 1240 (9 May 1825)”. So far, nothing could be found out about this person, who from his name can be assumed to have been a member of the Naḳṣbendī confraternity and in view of his use of the title of *as-sayyid* must have traced back his ancestry to the Prophet – whether it be true or not.

His seal reads as follows, *Ḥafīd man ṣabara zaḫara* “Ḥafīd. Whoever is patient is victorious”. Above the purchase remark, there is a so-called *kuyruklu imzā* (a “tailed” signature). “Tailed” signatures were used by finance officials [Velkov 1984]. It is indecipherable.

¹ for studies on paratexts of manuscripts, see https://www.manuscript-cultures.uni-hamburg.de/Projekte_p2_e.html#PBA., retrieved February 16, 2019.

After Muṣṭafā Ḥafīd Naḳṣbendī, the famous Orientalist Joseph Freiherr von Hammer-Purgstall (1774-1856) acquired the manuscript. Hammer's Oriental manuscripts were bought by the then Hofbibliothek in 1842 and form a substantial part of the Oriental manuscript collection of the Austrian National Library. However, Hammer had sold what was to become the H.O. series, *Historia osmanica*, earlier on in 1832 [Flügel 1865:introduction].

Hammer's Oriental seal is to be found in all the manuscripts that once belonged to him. Its text is obviously an attempt at imitating the last two surahs of the Qur'an (nos. 113 and 114), a fact that from today's point of view can only be regarded as a typical orientalist approach. Here, Hammer's somewhat imprecise German translation is given [Hammer-Purgstall 1848], followed by a more accurate rendering in English.

'*abduhū*
*as-sayyāḥ as-sāmīr Yūsuf Ḥāmer*1223
a'ūdū bi-rabbi l-ġāmīr wa-l-'āmir
rabbi d-dāmīr wa-t-tāmīr
min šarri t-tāmīr wa-l-ḥāmīr
wa-min šarri l-asāwid wa-l-aḥāmīr

Gottes Diener

Der Reisende, der die Märchen beim Mondenschein liebende Hamer
 Ich flüchte mich zum Herrn der undurchfurchten See und des bebauten Landes.
 Zum Herrn des Kamels mit dünnen Weichen und des fruchttragenden Palmenbaumes.
 Vor dem Bösen des hergelaufenen Abenteurers und des grossen Schwätzers
 Und von dem Bösen der Schwarzen und Rothen.

God's slave

The traveller who likes nightly amusements, Yūsuf Ḥāmer 1223 (1808/09)
 I take refuge with the Lord of wastelands and the prosperous countryside,
 The Lord of the slender one and the fruit-bearing one,
 From the evil of the jumping one and the pouring one,
 From the evil of the black ones and the red ones.

For a large part of the reign of Süleymān the Magnificent, Hammer in his *Geschichte des Osmanischen Reiches*, vol. 3 [Hammer 1828] has used this manuscript extensively due to its detailed contents, especially as far as nominations into offices and depositions are concerned. Hammer thought that the author of this work was called Ferdī. After Hammer, other scholars followed him and thus "Ferdī"'s history became widely known among Ottomanists [e.g. Thúry 1894].

This assumption was based on the alleged occurrence of this pen-name in a Persian poem of the author on fol. 6r (see Fig. 4). However, as Yurdaydın, who originally believed in Ferdī's existence as well [Yurdaydın 1950] could prove later on, this idea was totally erroneous and *ferdī* only is a normal word in the last verse of this Persian poem by the author of the *Süleymānnāme* [Yurdaydın 1955].

Fardī/fardī, pronounced Ferdī/ferdī in Ottoman, means nothing else than "somebody", in a negative sentence as in the case of this verse, "nobody". Ferdī as a name or pen-name would have meant "the single one", "the special one". Thúry [1894:39-41] had identified a poet of the reigns of Süleymān the Magnificent and Selim II (1566-1574) with the pen-name of Ferdī, who in reality died in 1574 at the beginning of Murad III's (1574-1595) reign and did not leave any work comparable to the *Süleymānnāme* [Yurdaydın 1955:139-140]. Thúry [1894], basing himself on Hammer's view, had brought forth that the copyist of the manuscript according to its colophon was Prince Muṣṭafā, Murad III's son. However, this prince's pen-name was Muḥliṣī [Yurdaydın 1955:147]. Karabacek believed the author and copyist of cod. ÖNB H.O. 42a to be Süleymān's son Prince Muṣṭafā (executed 1553, see, e.g. [Ágoston 2009]), whose pen-name he also thought to be Ferdī [Karabacek 1917; see Yurdaydın 1955:141-142]. The assumption that the copyist of ÖNB H.O. 42a was this prince, however, was correct.

Here, in addition to the transliteration of the above-mentioned Persian poem, an English translation will be given. For its Persian text, see also [Yurdaydın 1955; Römer 1992, including a French translation]. The transliteration has been adapted to the Ottoman pronunciation of Persian. The metre of the poem is *mużāri* ‘(--v/-v-v/v--v/-v-), and its rhyme pattern is aaba cada. (Ottoman poetry uses two metric systems. Divan poetry has adopted and adapted the Arabo-Persian ‘*arūz*’ poetry, which takes into account the long and short syllables of Arabic and Persian words, whereas folk poetry uses Turkic syllabic metres).

şāhib kırān u husrev-u āfāk u dād-ger
zill-i zālī-i Haqq u şehinşāh-i bahr u ber
ten dāde rūzigār be-fermān-i ‘alīyeş
gerdūn be-ħaṭṭ-i emr-i şerīfeş nihāde ser
der devr-i ‘adl u re’fet-i ū der basī-i ħāk
hergiz ne-mānde est zi cevr ü sitem eşer
feryād cüz zi murğ-i çimen ber ney-āmede
ferdī ne-kerde çāk-i giribān meger seher

Lord of the fortunate conjunction, king of the horizons, just sovereign,
 Deep Shadow of God, King of Kings of the land and sea.
 Time has bowed before the [written] line of his exalted order.
 During the era of his justice and highness on the wide earth
 There has remained no trace of sufferance nor distress.
 No complaint has arisen but from the birds of the grassland.
 NOBODY has torn his collar but the morning.

In the margin next to this poem on fol. 6r, there is a remark written with black ink (see Fig. 4). The handwriting resembles the red handwriting on the second flyleaf and seems to be European as well, albeit very fluently written. The way this remark is formulated suggests a non-first-language speaker of Ottoman Turkish. Thus, *şāhib mü’ellif Ferdī ile taħalluş eder* ‘the owner author/the Lord author gives his pen-name as Ferdī’ or ‘The Lord author (= Mr. Author?) names himself by the pen-name of Ferdī’ is somewhat weird. Using the word *şāhib* ‘owner’ before the word *mü’ellif* ‘author’ seems most unusual. The verb *taħalluş etmek* ‘to give one’s *maħlaş*’, i.e. one’s pen-name can occur with the postposition *ile* ‘with’ (see, e.g., [Yurdaydın 1955:137, note 2]). But the verb and the pen-name can also be combined without a postposition (see, e.g., [Kellner-Heinkele 1981:196]: *Medhī taħalluş eder* ‘He uses the pen-name of Medhī’). Yurdaydın discusses both the title on the second flyleaf and the poem. However, he only says that these notes must have been written by a different hand and have to be regarded as later additions. He does not dwell on the linguistic details of the remark on fol. 6r, nor does he suggest a European hand. On the other hand, he says that such remarks that were added later to many manuscripts often contain errors and mistakes [Yurdaydın 1955:137, note 2 and 142 with note 20].

As mentioned above, the first historian and orientalist who used cod. ÖNB H.O. 42a was Hammer, who had purchased it. His references to this manuscript in his footnotes [Hammer 1828] always contain the name of Ferdī, with the folio number following. Therefore, a strong suspicion has arisen that besides being the inventor of a fictitious Ottoman 16th-century historian using the pen-name of Ferdī, he may also have been the author of these two remarks. Thus, he then would be the one who first misunderstood the Persian poem.

European inks contain iron gall, Ottoman inks, however, mostly consist of soot and gum Arabic. There were several recipes, one of which foresaw that an earthenware pot was submerged in the soil and filled with linseed oil and a cotton wick. After the wick was lighted, a plate was held above it so that the soot could be gathered. Subsequently, the soot was scraped off the plate with a feather. The best gum Arabic came from the Sudan, followed by produce from Djidda. It was first cleaned with the help of a sieve and let clear until its texture was like honey. The longer this phase, the better the quality was. Subsequently, some other components like the peel of grenades were added. Eventually, it was mixed with the soot and beaten for some time, with a maximum of 100.000 beats according to one recipe [Kütükoğlu 1994:42-43].

In order to determine whether the writer of this marginal note and of the title on fol. 1r was a European, an analysis of the ink of the manuscript versus the inks of the remarks seemed useful.

Thus, it was a fortunate coincidence that during a project meeting in June 2018 of FWF Project P-30511 *The Oriental Outpost of the Republic of Letters. Sebastian Tegnagel (d. 1636), the Imperial Library in Vienna, and Knowledge about the Orient* (FWF Project P-30511)², a UV, VIS, NIR (ultra-violet, visible, near infra-red) Microscope³ was tried on some comments by Tegnagel in manuscripts that had belonged to him (Tegnagel was the second librarian of the Vienna Hofbibliothek and bought many manuscripts both for the library and for himself. His manuscripts went to the Hofbibliothek after his death [Flügel 1865:Introduction; see also Römer 1998]). Spontaneously during the meeting, it was decided to apply this UV, VIS, NIR Microscope to cod. ÖNB H.O. 42 as well.

This present author's thanks go especially to Hülya Çelik of the Tegnagel project for having brought the microscope and for the permission to use it, as well as to Katharina Kaska of the Manuscript collection of the Austrian National Library for bringing the manuscript to the meeting, which was held in the old reading room of the Manuscript collection.

As a first step the following places in cod. ÖNB H.O. 42 were photographed:

- 1) The title written with red ink on fol. 1r. It vanished nearly completely under near infrared wavelengths, which can penetrate coloured layers as well as iron gall inks, with only a faint shadow being still discernible (Figs. 5a-c).
- 2) The marginal note on fol. 6r next to the "Ferdī" poem. The black ink was visible under all wavelengths, meaning that there possibly is no iron gall ink involved and that the ink may contain carbon/soot. (Figs. 6a-c).
- 3) Hammer's seal. The black ink used for imprinting the seal onto the paper stayed visible under all three wavelengths, meaning that Hammer may have used an ink containing carbon/soot for applying his Oriental seal (Figs. 7a-c).
- 4) The earlier owner's remark. Its black ink remained visible under all three wavelengths as well (Figs. 8a-c). This was a result that was expected, given that Oriental inks normally are composed of soot and gum Arabic.

As a consequence, it becomes clear that the red ink, as was expected, contains pigments that can be penetrated by near infrared wavelengths. All the black inks could be soot inks, although there still is a possibility that they may contain iron gall, which could not be detected by the microscope used here. For, depending on their composition, iron gall inks become transparent at a range between 1000 and 1200 nm, whereas soot inks/carbon inks appear black as they "absorb the infrared light across the entire mid-infrared range" [https://www.manuscript-cultures.uni-hamburg.de/lab_methoden.html], retrieved August 25, 2019].

Thus, so far only very cautious conclusions can be drawn, namely that Hammer may have used soot ink for applying his seal onto cod. ÖNB H.O. 42a. This present author's thanks go to Ira Rabin, Hamburg, for her helpful remarks during the discussion after the paper had been read during the CHNT 23 conference.

The following further investigations will have to be carried out in order to gain more insight:

- 1) If one wants to find out whether Hammer regularly used soot ink when putting his Oriental seal on his own manuscripts, some more of them, especially those of the H.O. series, ought to be investigated.
- 2) The supposition that a European hand might have written the marginal note on fol. 6r next to the "Ferdī" poem (as well as the title on the second flyleaf) has not been falsified so far. With Hammer himself perhaps being at the beginning of the "Ferdī" myth, one might go a step further and suggest that the author of the marginal note on fol. 6r may have been Hammer as well, a supposition that is impossible to prove without the help of more refined methods. Unfortunately and curiously, there does not seem to be any known specimen of Hammer's Arabic handwriting. Therefore, a comparison of the exact chemical composition of the inks used for this marginal note and for Hammer's seal would be ideal.
- 3) In order to exclude that the marginal note was written by the former owner of the manuscript, the chemical composition of its ink ought to be compared to the one of his note on fol. 1r.

² <https://geschichtsforschung.univie.ac.at/forschung/oorpl/>

³ https://www.manuscript-cultures.uni-hamburg.de/Poster/Z02_A4_P2.pdf

- 4) As a complement to these investigations, the composition of the red ink of the title given on the second flyleaf should also be analysed. It will be of special interest to find out the reason for the faint shadow of the text that is visible in Fig. 5c and to identify the chemical element(s) responsible for it.

It is not yet clear when these investigations will be made possible. Once permission is given by the Austrian National Library, the analyses suggested above will be carried out by the Institute of Natural Sciences and Technology in the Arts⁴ within the framework of the activities of the “Centre of Image and Material Analysis in Cultural Heritage” (CIMA)⁵. More specifically, in order to identify the pigments and the chemical elements the inks are composed of, the following non-destructive and non-invasive methods will be applied:

- 1) “X-ray fluorescence analysis” (XRF) will be used to determine the chemical elements the inks consist of.
- 2) RAMAN Spectroscopy will yield another set of data for comparison with the results of the XRF analysis.
- 3) “Infrared Reflectography” (IRR) has the advantage that wavelengths between 900 and 1700 nm give better results than IR photography at shorter wavelengths does. This means that maybe some of the other samples might prove to contain iron and become transparent.

If the inks of Hammer’s seal and the marginal note on fol. 6r turn out to be the same, the author of the “Ferdī” myth will have been found. If, on the other hand, no identity or similarity can be discerned, Hammer’s authorship will neither be falsified nor proven.

FIGURES

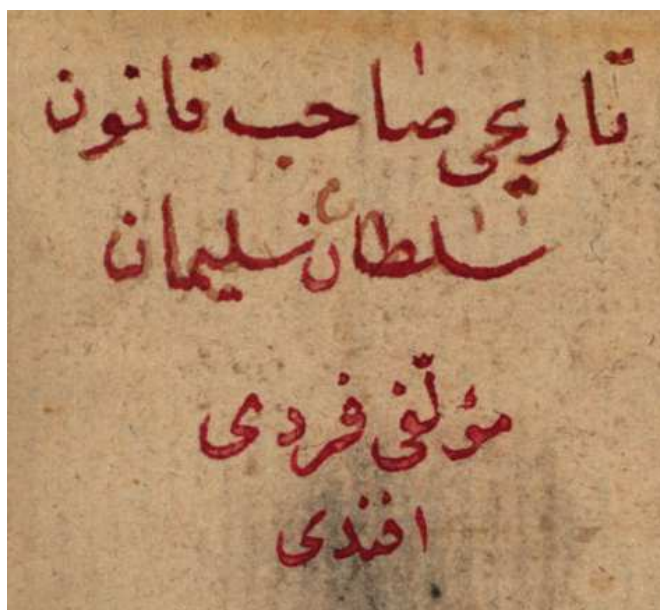


Fig. 1. Cod. ÖNB H.O. 42a⁶, flyleaf no. II

⁴ <http://www.fch.akbild.ac.at/>, retrieved February 16, 2019.

⁵ <https://hrsml.cvl.tuwien.ac.at/>, retrieved February 16, 2019.

⁶ <http://data.onb.ac.at/rep/10002344>



Fig. 2. Cod. ÖNB H.O. 42a⁷, fol.1r; purchaser's seal and remark



Fig. 3. Cod. ÖNB H.O. 42a⁸, fol.1r; Hammer's Oriental seal.

⁷ <http://data.onb.ac.at/rep/10002344>

⁸ <http://data.onb.ac.at/rep/10002344>



Fig. 4. Cod. ÖNB H.O. 42a⁹, fol.6r; “Ferdī” poem with marginal note

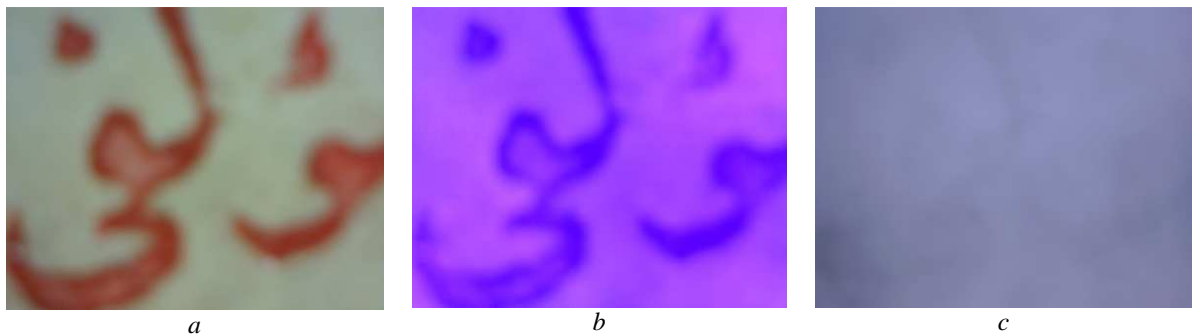


Fig. 5. Cod. ÖNB H.O. 42a¹⁰, flyleaf no. II, title, a) visible; b) ultraviolet; c) near infrared

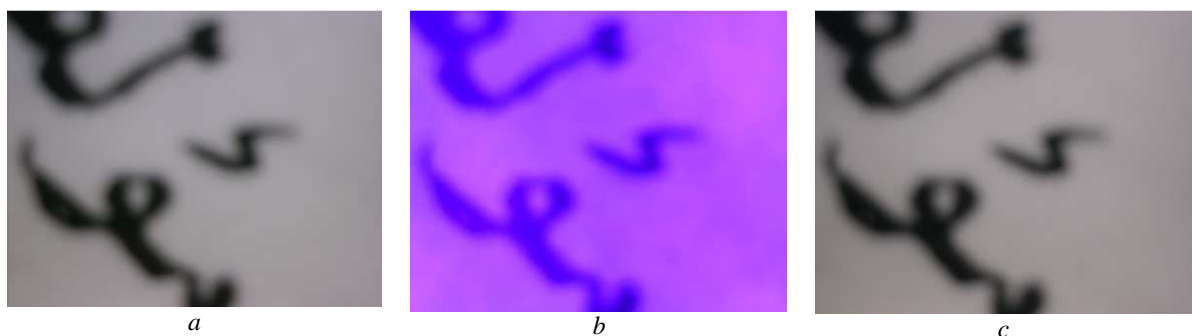


Fig. 6. Cod. ÖNB H.O. 42a¹¹, fol.6r, marginal note next to “Ferdī” poem, a) visible; b) ultraviolet; c) near infrared

⁹ <http://data.onb.ac.at/rep/10002344>

¹⁰ <http://data.onb.ac.at/rep/10002344>

¹¹ <http://data.onb.ac.at/rep/10002344>

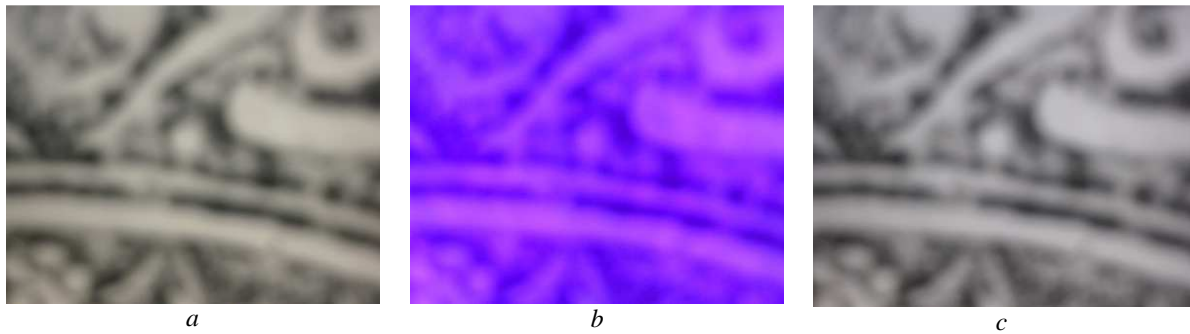


Fig. 7. Cod. ÖNB H.O. 42a¹², fol. 1r; Hammer's Oriental seal, a) visible; b) ultraviolet; c) near infrared

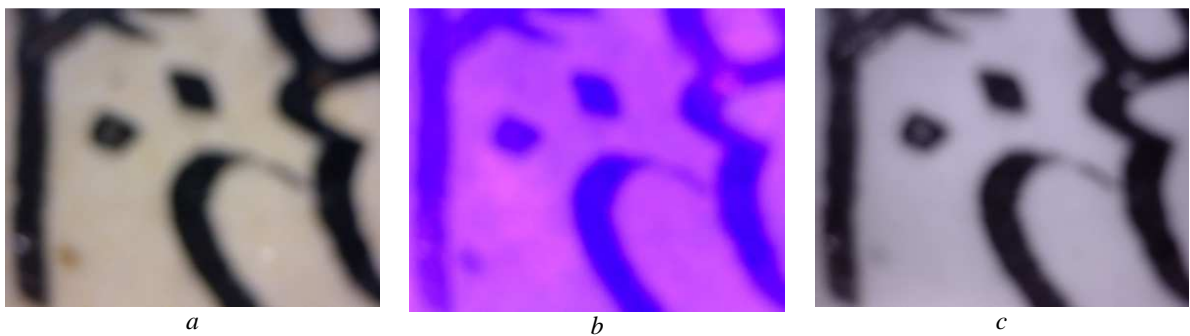


Fig. 8. Cod. ÖNB H.O. 42a¹³, fol. 1r, former owner's remark, a) visible; b) ultraviolet; c) near infrared

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¹² <http://data.onb.ac.at/rep/10002344>

¹³ <http://data.onb.ac.at/rep/10002344>

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