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New Approaches Using Image Processing of Spectral Data from Synchrotron X-ray-Fluorescence Element Mapping to Recover Erased Text from the Vienna Dexippus Palimpsest

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Methods for digital recovery of erased scripts in palimpsests have substantially matured over the last two decades. Noticeable development has been achieved in both the imaging (capture, cameras, lenses, sensors, lighting) and image processing (techniques, software) focused on this part of our cultural heritage. Furthermore, the number of scientists in imaging and image analysis working to recover texts from illegible manuscripts has increased during that time. Hand in hand with this development, scholars working on palimpsests have gradually gained experience with the new tools and developed skills necessary for using digital images in their work.[1]

The problem with fragments of manuscripts hidden in palimpsests is that they are—entirely or partly—invisible to the naked eye. The text was erased many centuries ago by washing off and/or scraping off the characters from the parchment to make the expensive writing material ready for re-use. The palimpsested folios

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[*] The authors, listed here in the alphabetical order, are participating in this paper in the following roles; their individual contribution is highlighted in the text: Roger L. Easton, Jr. (image scientist), Leif Glaser (physicist), Jana Grusková (classical scholar, co-editor of the Vienna Dexippus fragments), Katharina Kaska (librarian, manuscript scholar, physicist), David Kelbe (image scientist), Keith T. Knox (image scientist), Gunther Martin (classical scholar, co-editor of the Vienna Dexippus fragments), Ivan Shevchuk (MSI technician). For a comprehensive overview on the entire digital recovery of the Vienna Dexippus palimpsest, see *Insights* 2020.

[1] For recent advances in palimpsest studies and close cooperation of specialists from various disciplines in this process see the contributions of the volume RAPP – ROSSETTO – GRUSKOVÁ – KESSEL (eds.) 2023.

were then reformatted by cutting them and often rotating them in various ways. The new text covered the faint remnants of the original script, usually to a great extent. In many palimpsests additional damage has been caused by chemical reagents that were used in the 19th century in order to make the erased scripts visible. A basic tool used for studying a palimpsest has been an ultraviolet lamp.

There are various digital methods for recovery of an erased script in a palimpsest, as described below. For all of them, the process relies on a very close cooperation among three groups of specialists. On the one hand, there are scholars who have the appropriate philological and palaeographical expertise in the corresponding part of our cultural heritage and are in charge of examining and analysing the palimpsest in question; they are in need of seeing the erased script as well as other details of the original manuscript. To the second group belong specialists with the expertise in imaging and image processing of palimpsests, i.e. who thus possess skills required to render visible the invisible remnants of the hidden written artefact. The third group of specialists involved in this process are the librarians and the conservators who are in charge of protecting the manuscript currently under study as a historical document (usually on behalf of the institution where it is kept). Prior to applying any imaging, these last-mentioned specialists must determine, whether the specific imaging, including handling and transport, will be safe for the object, because the protection and preservation of the historical document have absolute priority over recovering the text, even if that text is unique.

Usually, scholars who have been working on a palimpsest and need to see invisible parts of the erased script for continuing their research, initiate an imaging session by inviting a particular team of specialists in digital recovery and collect all necessary funding. To obtain optimal results, the scholars often have to cooperate with various imaging teams who use different techniques, as in the case of the Vienna Dexippus palimpsest or some other palimpsests of the Austrian National Library. In the past decade, another method of managing the scholarship on palimpsests has been established: organisations that have teams specialised in digital recovery, such as EMEL (see p. 196) or CSMC (see n. 22), organize projects with assembled multidisciplinary research teams including scholars, focusing on particular palimpsests (e.g. the Sinai palimpsests). In both cases, the images are made first available to the scholars concerned, who are experts in relevant philological and historical disciplines and in charge of examining and interpreting the evidence preserved in the palimpsest. After publication of their results, the digital images are often released to the public. This makes palimpsests attractive objects that generate interest in the fascinating world of digital humanities.

METHODS FOR DIGITAL RECOVERY OF ERASED SCRIPTS

In some cases, simple imaging under ultraviolet (UV) light with a good-quality digital camera and subsequent image enhancement is sufficient for rendering visible an erased script (which in Greek manuscripts was usually written in an iron-gall ink). The UV light induces fluorescence in the parchment, which enhances its contrast with areas of the erased script. Often very sophisticated methods are needed to optimize the visibility.

Multispectral imaging (MSI) has repeatedly proved to be a crucial method for recovering scripts hidden in palimpsests.[2] With the help of a special lighting system, numerous coloured filters and a camera with a broadband detector, images are captured of a folio that is illuminated with light over a wide range of wavelengths, including those visible to the human eye (i.e. red, green, and blue) and those invisible, i.e. UV and infrared (IR). Each of the multiple wavelength bands interacts differently with the manuscript surface. Each of the recorded spectral images contains information from a band of the electromagnetic spectrum and may reveal details that can enhance the visibility of components present in the imaged manuscript page (inks, parchment surface, holes, stains etc.). A prerequisite for the successful recovery of an erased script is the accurate and nearly pixel-to-pixel registered collection of corresponding reflection, transmission, and fluorescence behaviour of its remnants or footprints in the parchment, when filtered to certain frequencies of light.[3] The captured digital images are subsequently processed to enhance the visibility of the text of interest and all other details in the reused folios. The image processing is being performed by scientists with knowledge and skills to combine the captured raw images by special software and to create, by using various methods, processed images that reveal the erased text, i.e. enhance its visibility. Among the usually most helpful are principal component analysis (PCA), independent component analysis (ICA), and band ratios followed by pseudocolor rendering (see below). The image scientists cooperate closely with the philologists who are in charge of deciphering the text; they evaluate the processed images, provide crucial feedback to the scientists and identify remaining illegible areas.

For badly damaged palimpsests of unique cultural value, repeated imaging efforts and a combination of various cutting-edge approaches of digital recovery are needed to achieve optimal results, i.e. to recover the textual witness in question as completely as possible. By using various sets of high-quality processed images that were generated from different imaging systems (different cameras, sensors, lamps etc.) or captured with modified setups of a single system (e.g., different filters, more illumination bands, different lamps), the scholars (philologists) in charge of deciphering the text can profit from the advantages of each method and see details of the erased script in a variety of appearances. By identifying all extant remnants of the erased script and analysing them in depth—both palaeographically and philologically (detecting individual characters, ligatures, words, syntactic units, sentences etc.)—the philologists make progress in the decipherment. Of course, every

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[2] See KNOX 2023; EASTON – KELBE 2023.

[3] See EASTON – KELBE 2014.

new imaging session has to be clearly justified and, as already emphasised, the highest priority must be given to ensuring the safety of the manuscript.

In areas of the undertext that have remained inaccessible via multispectral imaging, i.e. are still invisible—the so-called "problematic areas"—X-ray fluorescence (XRF) element mapping can usually help to recover additional information on the erased and concealed script. A special XRF-scanning device designed for a non-invasive elemental analysis of large samples is needed, along with an expert who operates it as well as image scientists who process the collected data in order to recover as much information about the undertext as possible. The philologists in charge of studying the palimpsest must, of course, participate in the experiment as well to select the areas of interest and evaluate the resulting images. Since this method usually requires the manuscript to be transported under special conditions to the scanning device, it can be used only for palimpsests of unique cultural value. In XRF analysis, individual locations on the manuscript are exposed to hard X-rays. The high energy of the X-rays is sufficient to ionize atoms of the different elements in the ink and parchment. The material is irradiated by the incident beam. Electrons from inner atomic shells are "ejected" and so-called "core holes" in the electronic configuration of the atom remain. Electrons in higher-energy shells then spontaneously drop into the core holes and simultaneously release other photons with energies characteristic of the material, i.e. emit X-rays at element-specific energies. For each position on the parchment, the flux of the emitted X-rays can be measured as intensity that can be compared for each element, such as iron, calcium, zinc, and copper, in a qualitative or semi-quantitative way.[4] Using the above-mentioned special XRF-element-mapping laboratory device, such as the M6 JetStream from Bruker Nano GmbH, data over large areas (of more than a few characters) can be scanned and recorded by analytical software in sufficiently accurate optical images with a full spectrum per pixel in one dataset. In this process, individual element intensities of every measurement are translated into maps of single elements. If the XRF-element-mapping laboratory device demonstrates the capability to recover the "problematic" text, but only in small scanned areas of several characters within a reasonable scanning time,[5] then scanning of larger areas or even entire pages necessitates the use of fast XRF-element-mapping at a storage ring, i.e. a synchrotron-based beam facility, which generates substantially more X-rays in the scanning beam. This requires an application for a beam time. Again, care must be taken to ensure safety of the manuscript: first, by determining the optimal non-invasive beam parameters (shortest possible X-ray exposure etc.) in cooperation with librarians and conservators, and then by implementing them.

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[4] See HAHN – MALZER – KANNGIEẞER – BECKHOFF 2004.

[5] I.e. several months of continuous scanning would be needed to obtain sufficient results.

THE VIENNA DEXIPPUS PALIMPSEST AND ITS JOURNEY FROM THE DISCOVERY TO THE SYNCHROTRON

Among the Greek manuscript treasures of the Austrian National Library (ANL) in Vienna are several palimpsests. Many of the erased scripts were described and the undertexts identified during the general cataloguing in the 1960s to 1990s, others could only be examined more closely in the 21st century, thanks to modern technology. A new chapter began with the European project "Rinascimento virtuale – Digitale Palimpsestforschung" (2001–2004).[6] In 2003 and 2004 the Austrian Academy of Sciences (ÖAW) and the Austrian National Library undertook a re-examination of all Vienna Greek palimpsests, a task that was entrusted to Jana Grusková, a classicist with expertise in manuscript research. One of the manuscripts under study was the Codex hist. gr. 73, a tenth-century copy of *Constitutiones apostolorum* (fols. 1–184, *Constitutions of the Holy Apostles*), a canonical collection of the fourth century AD.[7] At the end of the codex, there are eleven palimpsested parchment leaves of Christian content, fols. 185–195, which were added in the thirteenth century. By examining these eleven folios under ultraviolet light, Grusková observed that they come from two different older Greek manuscripts of the eleventh century. While the undertext on the first seven folios was identified, the scarce remnants of the almost completely invisible text on fols. 192r–195v did not match with any known work. In 2007, Grusková resumed the examination of these folios for a book on the Greek palimpsests of the ANL she was preparing within a project of the ÖAW led by the Byzantinist Otto Kresten.[8] Using an ultraviolet lamp, UV photographs from the 1960s and some simple digital images, she made new attempts at deciphering the undertext. Based on a philological analysis of the portions of the text that she had deciphered by 2009, amounting to about 15% of the eight surviving manuscript pages she concluded that the fragments could belong to the lost ancient work *Scythica* by the Athenian historian Dexippus (Δέξιππος) of the third century AD. A publication of this discovery with a preliminary transcription of one page (fol. 195r) followed in 2010.[9] Immediately afterwards, Grusková invited Gunther Martin, a classicist and an expert on Dexippus, to cooperate with her on further deciphering and examining the Vienna fragments, pursuing an ultimate goal of preparing a critical edition of the new text.[10]

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[6] See KRESTEN in GRUSKOVÁ – MARTIN – KRESTEN 2018, 69–73; GRUSKOVÁ 2010, 20–23.

[7] The book came to the library from Constantinople in the sixteenth century.

[8] See GRUSKOVÁ 2010.

[9] See GRUSKOVÁ 2010, 42–43, 50–53, 181 (Fig. 9). Books and articles on the Goths by the historian Herwig Wolfram and a monograph on Dexippus by Gunther Martin (including an edition of all known fragments) published in 2006 provided important help, see *op. cit.*

[10] Cf. GRUSKOVÁ – MARTIN – KRESTEN 2018, 69; *Insights* 2020, 946–947.

To render the erased undertext visible, state-of-the-art methods of digital recovery had to be employed.[11] In 2012, Kresten and Grusková secured funding from the Österreichischer Wissenschaftsfonds FWF (Austrian Science Fund) for the project FWF "Important Textual Witnesses in Vienna Greek Palimpsests" to continue the research on several Greek palimpsests, among them the Vienna Dexippus.[12] Subsequently, they invited the Early Manuscripts Electronic Library (EMEL) to perform multispectral imaging on the four folios. The session took place in 2013 at the ANL; it was supervised by Grusková, on behalf of the project, and by Michael Phelps, the director of EMEL, who assembled a team of renowned image scientists and engineers for this purpose. The multispectral camera MegaVision developed by Kenneth Boydston and an illumination system designed by William A. Christens Barry were used. Boydston imaged the palimpsest with the assistance of Damianos Kasotakis and Michael Phelps.[13] The captured data was subsequently processed by image scientists Roger L. Easton, Jr., Keith T. Knox, David Kelbe, and William A. Christens-Barry. They applied a variety of processing methods, working in close cooperation with Grusková and Martin, who were in charge of evaluating the processed images. The effectiveness of processing techniques noticeably varied, even from one area of a page to the next. Much better results were achieved on the "flesh" sides of the parchment leaves (Fig. 1–2), whereas the "hair" pages remained partly, sometimes even mostly, illegible (Fig. 3–4). In general, the parts of the erased script obscured by the upper text could not be made visible.

On the basis of a detailed palaeographical analysis combined with thorough philological scrutiny, Grusková and Martin deciphered and analyzed about 60% of the erased text. During this process, they examined each image in depth, optimizing the legibility of individual details in Adobe Photoshop®. The results reaffirmed the identification with the *Scythica* by Dexippus. Furthermore, it emerged that the eleventh-century manuscript, which the four folios once belonged to, was a full-text copy of this ancient work. The analysis also revealed that the text is richer in historical evidence and issues of philological relevance than had been expected. In total, three fragments of the original work, fr. I–III, have survived. Their chronological order has been identified. In 2014 and 2015 Martin and Grusková published their preliminary results on the Vienna fragments, to which they gave the name *Dexippus Vindobonensis* or *Scythica Vindobonensia*.[14]

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[11] See GRUSKOVÁ – MARTIN – KRESTEN 2018, 69–92. Kresten and Grusková relied on their own experience and the results of other projects, especially the encouraging Archimedes Palimpsest Project (2000–2011), see EASTON – CHRISTENS-BARRY – KNOX 2011.

[12] The FWF Project P 24523-G19 was led by O. Kresten and hosted by the ÖAW (Byzantine Research); the research was carried out by J. Grusková in international cooperation (GRUSKOVÁ 2012). See GRUSKOVÁ – MARTIN – KRESTEN 69; *Insights* 2020, 946–947, 950.

[13] Cf. *Insights* 2020, 950–951.

[14] See MARTIN – GRUSKOVÁ 2014a; MARTIN – GRUSKOVÁ 2014b; GRUSKOVÁ – MARTIN 2014; GRUSKOVÁ – MARTIN 2015; GRUSKOVÁ – MARTIN 2017; MARTIN – GRUSKOVÁ 2022.

> The *Scythica Vindobonensia* cover a period in which our knowledge of history and literature suffers from large gaps. They contain a detailed account of incursions by the "Scythians", which was a collective archaizing term for Goths and other tribes, into the Roman provinces in the Balkans around and after the mid-third century AD. The period was marked by catastrophic events and serious political commotions that significantly weakened the Roman Empire. At that time the incursions of new peoples from north of the Danube into the territory of the Roman Empire reached a new peak. The history of these incursions between about 250 and 275 AD and their repulsion by the Romans was dealt with in detail in the work *Scythica* by Dexippus of Athens, a contemporary and well-informed eyewitness. This work was a very important source for later historiographers. However, only excerpts quoted by other authors had been known until the discovery. Thanks to the *Scythica Vindobonensia* we can now read parts of the lost original.

These preliminary results on the Vienna Dexippus palimpsest met with great interest in the scholarly community. Publications by other scholars worldwide soon followed. The *Scythica Vindobonensia* were classified as being of very high importance for our understanding of the history of the third century AD and the crisis of the Roman Empire in this period, as well as for many aspects of various disciplines, such as classical literature, ancient history, Gothic studies, Byzantine studies, ancient epigraphy.[15]

In 2015, Kresten, Grusková, and Martin joined with Fritz Mitthof, an expert in late antiquity who had supported their research from the perspective of ancient history since 2014, to acquire funding from the Austrian Science Fund for further research. The main goal of the new project entitled "Scythica Vindobonensia"[16] was for Grusková and Martin to complete the decipherment of the text and the detailed analysis of the fragments and to prepare a critical edition with a translation and a comprehensive commentary. The project was led by Fritz Mitthof and Otto Kresten, as the national research partner. It also aimed at a broader historiographical, historical and archaeological contextualization.[17] Furthermore, a colloquium of the two editors with specialists in Greek palaeography – (in alphabetical order) Giuseppe De Gregorio, Ernst Gamillscheg, Otto Kresten, Brigitte Mondrain and Nigel Wilson – was organised in 2017 in Vienna to discuss problematic issues in relation to the manuscript and the decipherment.[18]

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[15] For a bibliography see Mitthof – Martin – Grusková 2020, 565–570.

[16] The FWF project P 28112-G25 "Scythica Vindobonensia" (2015–2020) was conducted at the University of Vienna (Institute of Ancient History, Papyrology and Epigraphy) and the Austrian Academy of Sciences (Institute for Medieval Research, Dpt. of Byzantine Research), see Grusková – Martin – Kresten 69.

[17] See e.g. the contributions in the volume Mitthof – Martin – Grusková 2020.

[18] See De Gregorio – Gamillscheg – Grusková – Kresten – Martin – Mondrain – Wilson 2020.

Fig. 1–2: Multispectral imaging – results on flesh sides of the parchment

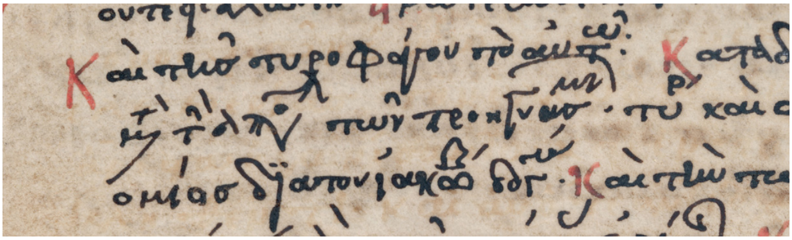

Fig. 1a: EMEL, multispectral imaging 2013: visual appearance image

Fig. 1b: EMEL, multispectral imaging 2013
(fol. 193r, flesh side), image processed by David Kelbe
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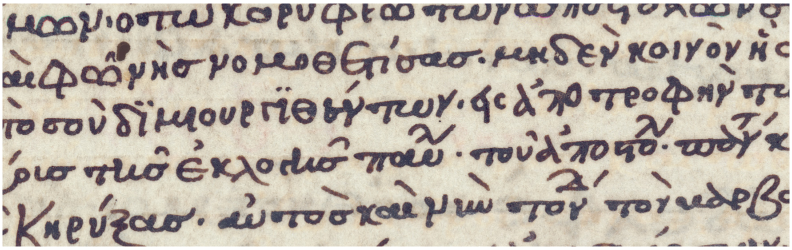

Fig. 2a: EMEL, multispectral imaging 2013: visual appearance image

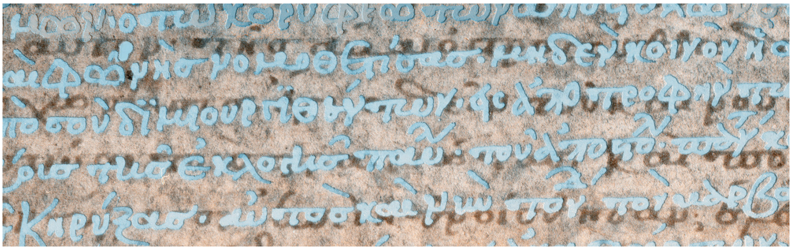

Fig. 2b: EMEL, multispectral imaging 2013
(fol. 194v, flesh side), image processed by David Kelbe
© FWF Project P 24523-G19

Fig. 3–4: Multispectral imaging – results on hair sides of the parchment

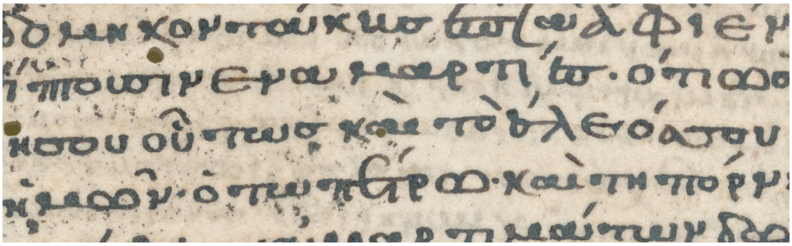

Fig. 3a: EMEL, multispectral imaging 2013: visual appearance image

Fig. 3b: EMEL, multispectral imaging 2013
(fol. 194r, hair side), image processed by Roger L. Easton, Jr.
© FWF Project P 24523-G19

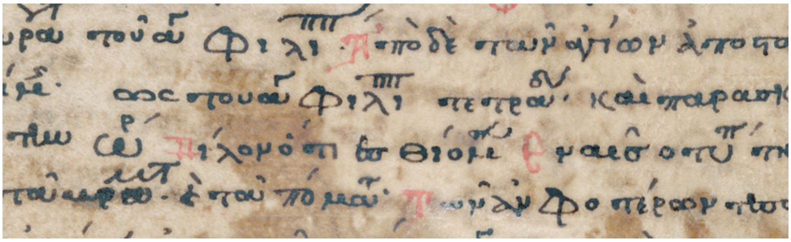

Fig. 4a: EMEL, multispectral imaging 2013: visual appearance image

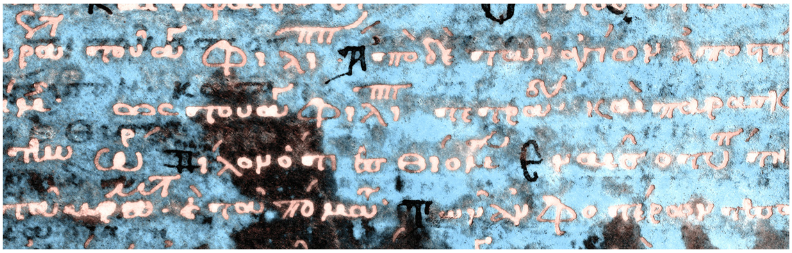

Fig. 4b: EMEL, multispectral imaging 2013
(fol. 192r, hair side), image processed by Roger L. Easton, Jr.
© FWF Project P 24523-G19

For maximizing the visibility of the still illegible 40% of the erased script, additional non-invasive approaches of digital recovery were needed. Kresten and Grusková, supported by the ANL (Andreas Fingernagel, Katharina Kaska), identified in cooperation with EMEL (Michael Phelps, Roger Easton, Keith Knox, William Christens-Barry, Ken Boydston) strategies that might lead to further progress in this respect:[19] First, the project organised additional multispectral imaging. It was carried out by EMEL in 2016 using some new or advanced components and capturing at a higher spatial resolution.[20] The new spectral processed images provided some additional information; however, the majority of the problematic areas, especially on fols. 192r and 193v (hair sides), remained inaccessible.

In 2016, the project "Scythica Vindobonensia" carried out an experiment using XRF element mapping in cooperation with the ANL represented by Katharina Kaska, specialists in material analysis Ira Rabin and Oliver Hahn from the Bundesanstalt für Materialforschung und -prüfung (BAM) in Berlin, and EMEL and its images scientists Keith Knox, Roger L. Easton, Jr., and David Kelbe. The goal was to see if this method could lead to further recovery.[21] The already-mentioned laboratory XRF system capable of scanning large areas, M6 JetStream,[22] was used. Since such a device was not available in Vienna, the ANL allowed Kresten and Grusková to transport the manuscript to Berlin, under special conditions. The experiment showed the calcium (Ca) signal as the only element revealing sufficient information on the undertext to recognise individual letters.[23] However, the signal obtained from the JetStream provided legibility on the tested area of 22×15 mm (10 characters) only after having increased the total measurement time to 17 hours. This meant that recovering all illegible areas would require several hundreds of days of non-stop XRF imaging with the lab setting. Hence, the experiment proved that XRF element mapping can be effectively used for collecting additional data on the erased script in question, but that a storage ring facility (synchrotron light source) is needed.[24] To explore the potential of such an experiment, the physicist Leif Glaser joined the session at the BAM.

Finally, in December 2017, fast-scanning XRF element mapping was applied on the Dexippus palimpsest at the Deutsches Elektronen-Synchrotron (DESY) in Hamburg as a part of the project "Scythica Vindobonensia". The goal has been to render visible the illegible portions of the original script so that the two editors of

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[19] See *Insights* 2020, 953–954.

[20] For more details see *Insights* 2020, 954–955.

[21] See *Insights* 2020, 956–957.

[22] See above, p. 194. This M6 JetStream used at the BAM belonged to the Centre for the Study of Manuscript Cultures, CSMC, University of Hamburg, funded by the Deutsche Forschungsgemeinschaft, DFG.

[23] Though some spots were visible in the map of potassium (K) in the places where the script was expected, they were too unspecific for recognizing letters. See *Insights* 2020, 958.

[24] See *Insights* 2020, 959–960.

the *Scythica Vindobonensia* could complete the decipherment of the fragments and accomplish the work on the critical edition of the text accompanied by a translation and a comprehensive philological and historical commentary.

In the following pages, the DESY experiment will be presented, focusing especially on (1) the methods of image processing that have been used by the image scientists, and (2) the evaluation of the resulting processed images by the two classical scholars, the editors of the text. Since the work is still in progress, the results presented here are preliminary.

During all imaging experiments performed on the Vienna Dexippus palimpsest, the highest priority was to ensure the continued safety of the medieval manuscript. Its conservation was undertaken by Christa Hofmann and Wolfgang Kreuzer from the Conservation Department of the ANL. Before and after each imaging session, special treatments were applied to stabilise the manuscript.[25] Since 2016, all sessions were supervised by the librarian Katharina Kaska.

FAST ELEMENT MAPPING AT A SYNCHROTRON BASED X-RAY BEAM

The first successful XRF experiments with fast element mapping at a synchrotron-based X-ray beam to recover erased scripts hidden in a palimpsest were applied in 2006, on the famous Archimedes palimpsest. The XRF methods were developed for this particular manuscript by Uwe Bergmann of the Stanford Synchrotron Radiation Laboratory (SSRL) at the suggestion of William A. Christens-Barry who, together with Roger L. Easton, Jr and Keith T. Knox, was in charge of imaging and image processing of that palimpsest in order to recover its undertexts.[26] Since then, the synchrotron radiation XRF element mapping method has yielded successful results also on some other palimpsests. Already in 2008 Leif Glaser started to experiment with fast scanning XRF element mapping of erased writings at DESY[27] in Hamburg in cooperation with Daniel Deckers from the “Teuchos: Zentrum für Handschriften- und Textforschung” of the University Hamburg.[28]

Motivated by these developments and encouraged by the positive results of the above-described experiment with the laboratory XRF device M6 JetStream, the team of the Vienna project “Scythica Vinodbonensia” decided to explore such possibilities also for the Dexippus palimpsest. They invited Leif Glaser to cooperate in the experiment as the principal investigator, and the image scientists of EMEL Roger L. Easton, Jr., Keith T. Knox and David Kelbe to undertake the image processing of the synchrotron data aimed at maximizing the legibility of the erased script. A proposal “Fast scanning X-ray Fluorescence mapping of the Dexippus Palimpsest” was prepared and submitted to DESY in Hamburg by Jana Grusková

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[25] See *Insights* 2020, 948.

[26] See BERGMANN 2011.

[27] See http://www.desy.de.

[28] See GLASER – DECKERS 2014.

(ÖAW) as the project leader and Leif Glaser (DESY) as the principal investigator.[29] Katharina Kaska (ANL) and Ira Rabin (BAM/CSMC) acted as co-proposers. After a successful evaluation, DESY assigned to the experiment a beamtime period of seven days (see the Acknowledgements).

Being a part of the Austrian cultural heritage, the palimpsest had to be borrowed from the Austrian National Library by Jana Grusková on behalf of the FWF project "Scythica Vindobonensia" and under special conditions transported to DESY in Hamburg. The considerable expenses connected with these activities[30] were covered from the "Holzhausen-Legat" of the Austrian Academy of Sciences after a proposal submitted by Fritz Mitthof, the leader of the project "Scythica Vindobonensia". The ANL generously decided to grant special permission for scanning the Dexippus palimpsest at DESY, taking into consideration Kresten's significant contribution to the cataloguing of the Greek manuscripts of the ANL, Grusková's highly respected research on the Greek palimpsests of the ANL (carried out since 2003), and the worldwide appreciation of the preliminary results of her and Gunther Martin's work on the *Scythica Vindobonensia*. In order to protect the rest of the codex, the two bifolios, which were placed at the very end of the volume (fols. 192–195), were detached from the early modern binding. They were separated from each other and opened to form flat sheets (Fig. 5). The ANL exceptionally permitted the manuscript to be treated in this way for the purpose of further supporting the work of Grusková and Martin on the critical edition of the important ancient text.[31] This conservatory treatment was undertaken by Christa Hofmann and Wolfgang Kreuzer from the Conservation Department of the ANL.

Fig. 5: The two bifolios 192+193 and 194+195 separated from each other

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[29] The Project I-20170505 EC of DESY. We would like to thank the P06 Beamline manager Gerald Falkenberg for the support.

[30] Since the research by Grusková and Martin had revealed the importance of the *Scythica Vindobonensia*, the worth of the bifolios grew, which increased the fees connected with the trip of the manuscript to Hamburg (courier, insurance, special transport etc.).

[31] See more under https://www.onb.ac.at/sammlungen/sammlung-von-handschriften-und-alten-drucken/aktuelle-forschung.

Prior to the experiment at DESY, Jana Grusková and Gunther Martin carefully identified all problematic areas of the palimpsest, and classified them according to their philological priority. The main focus was laid on the two almost illegible pages: fols. 192r and 193v.

The fast-scanning X-ray fluorescence mapping of the Dexippus Palimpsest was carried out at DESY at the PETRA III P06 Hard X-Ray Micro Probe Beamline (Fig. 6a–6c)[32] from 5–12 December 2017. Leif Glaser prepared and directed the experiment. Invaluable assistance and support were provided by Jan Garrevoet, a scientist at the beamline P06. Jana Grusková supervised the session on behalf of the editors and the Vienna project "Scythica Vindobonensia". Katharina Kaska was in charge of overseeing the experiment on behalf of the ANL. Kaska's combined expertise in both manuscript studies and physics was a great benefit for the entire session.[33] To support the demanding session, Glaser invited Ivan Shevchuk (CSMC), Jens Buck (DESY), Stephan Klumpp (DESY), and Daniel Deckers (University of Hamburg) who provided invaluable help. The image scientists Roger L. Easton, Jr., Keith T. Knox, and David Kelbe participated off-site.

During the first days, Glaser prepared the beamline setup and calibrated the four detectors, three on the front and one on the back side of the parchment. The experimental hutch of the beamline was moisturized and moisture stabilized to 50% humidity for the entire time of the experiment. A specifically designed stage at a travelling range of 80 × 100 cm^2 to map scripts in written artefacts (manuscripts etc.) was added temporarily to the beamline (see Fig. 6a–6b). A frame holding the bifolio during the scanning was built specifically for this measurement by Glaser and Shevchuk. Two thin aluminium plates, base and lid with 1 mm thickness, with carefully handcrafted cut-outs were prepared on site before the beamtime. Great care was taken to smoothen all sharp edges. Two Kapton foils (acid-free material) were glued to each plate. Once the lid plate was opened, the bifolio was placed on top of the Kapton foil of the base plate and closed. The bifolio was gently held in place by the tension of the Kapton foil. The base plate was mounted on the rigid aluminium frame. The frame itself was detachable and connected to the XY movable stage. Handles attached to the frame ensured the ergonomic and safe handling of frame and bifolio within. Kaska was in charge of transporting the bifolios from the storage safe of DESY, where they were kept during the session, to the beamline and placing them carefully into the frame. All necessary measures were taken to ensure the safety of the manuscript.

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[32] Schroer – Boye – Feldkamp – Patommel – Samberg – Schropp – Schwab – Stephan – Falkenberg – Wellenreuther – Reimers 2010.

[33] See her report on the XRF session at the BAM: See www.iter-austriacum.at/kodikologie/abgewaschen-und-abgeschabt-neue-messungen-an-den-scythica-vindobonensia/.

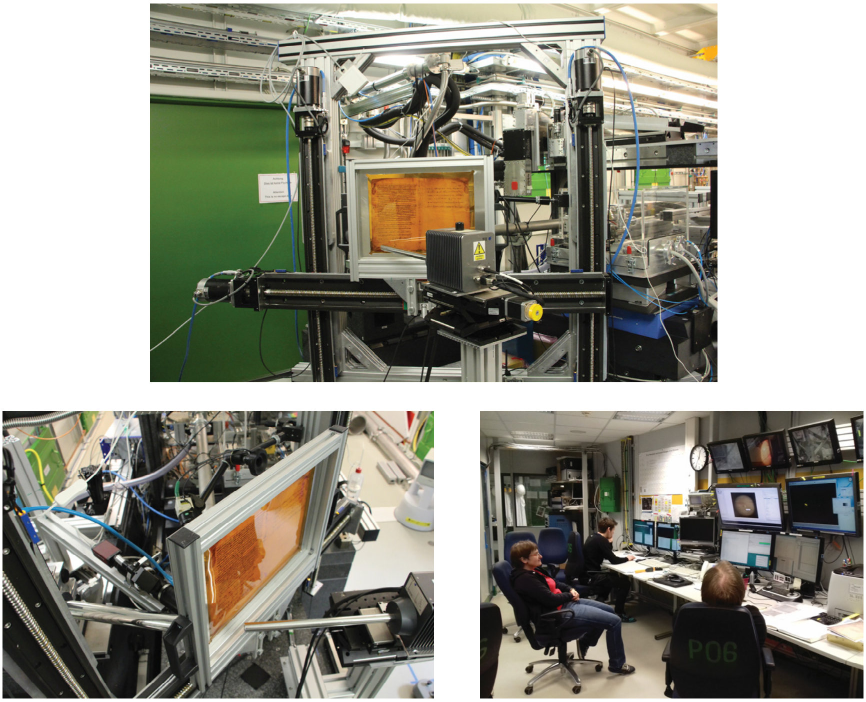

Fig. 6a–6c: Fast scanning XRF element mapping at the P06 Beamline of the Deutsches Elektronen-Synchrotron (DESY) in Hamburg (2017).
Fig. 6a–6b: A frame is holding the bifolio during the scanning. Detectors are on both sides of the parchment in the imaged region.

Subsequently, Grusková indicated on the screen the exact area to be scanned. The processing routine of the beamline worked superbly in extracting the maps in nearly real time using “regions of interest”, so-called ROIs. Elements as calcium (Ca), iron (Fe), copper (Cu), lead (Pb), and some others were expected to be within the scanned areas of the manuscript. After a section of the palimpsest was imaged, the captured data was converted into TIFF files of individual elements and an overview was prepared for Grusková who examined them and identified those which were “useful”, i.e. seemed to contain additional information on the undertext. It turned out that the original ink was quite thoroughly washed off and its remnants were dislocated over the parchment. The only element in which the erased script was visible so far as to recognize individual characters, was again calcium (Ca) (Fig. 7–9).[34] A crucial question arose, how to optimize the beamline setup for calcium. An in-depth discussion followed, which concluded that the optimal setting for mapping calcium could cause damage to the palimpsest—because the calcium

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[34] See above, p. 200. See also *Insights* 2020, 964.

interacts better with softer X-rays (about 4–5 keV), but the lower energetic X-rays are absorbed much better by the parchment, which could lead to potentially irreversible alterations—, therefore we firmly refused to take this path. The priority was to keep the experiment under all necessary limitations needed to secure the safety of the manuscript.[35] As soon as the setting was optimised—so far as allowed—and the time needed for scanning a specific area identified, Grusková adjusted the list of the problematic areas that were to be scanned, accounting for the philological priorities and the total remaining beam time available. After a longer testing session that took more than two days, the imaging of the selected areas followed. There were several beam losses,[36] which had an impact on the scheduled plan, that had to be adjusted every time anew.

The selected areas were analysed with X-ray fluorescence using silicon drift detectors on both sides of the parchment in the imaged regions. The beam was focused to a 100 µm spot with 17 keV primary photon energy (Fig. 6b). The frame with the bifolio was moved by the sample stage at a speed of 10 mm per second. The scanned areas varied from a full written area of an opened bifolio (which was finally cut to three scans due to two beam losses) to small sections of only 3 to 5 characters or individual words. For each scan, a set of 2048 different bands was collected. The resulting resolution was—for the most part of the XRF scans—100 µm per spot measurement which corresponds to a spatial resolution of approximately 250 ppi. The scanning speed was limited by the minimum time necessary per sample to achieve sufficient detector count rates to differentiate the signals.[37]

IMAGE PROCESSING OF THE COLLECTED SYNCHROTRON DATA

The project collected a large quantity of high-quality XRF data at DESY: 115 individual scans were captured; the first scans (1–52) could be classified as "experimental" runs intended for equipment setup or assessment.

The ultimate goal of the experiment at DESY, hence of the related image processing as well, has been to recover new information on the erased and partly concealed script in the problematic areas, i.e., information beyond what the multispectral imaging had provided. The project "Scythica Vindobonensia" entrusted this image processing to the image scientists Roger L. Easton, Jr., Keith T. Knox, and David Kelbe, leading specialists in the field, assembled by EMEL.[38] They

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[35] See *Insights* 2020, 961–962.

[36] Beam losses are an unfortunate phenomenon that can appear at a storage ring. When the electron beam at the storage ring is down (that can happen due to many different reasons) it can take hours to restore and then always takes half an hour for the beamline to reach its operating conditions.

[37] Cf. *Insights* 2020, 961–963.

[38] See *Insights* 2020, 962. In 2018, David Kelbe left the EMEL team of image scientists after he got a job at XERRA, New Zealand.

performed it in close cooperation with the classical scholars Jana Grusková and Gunther Martin, the editors of the *Scythica Vindobonensia*, who were in charge of evaluating the images (see below).

As mentioned above, the undertext was sufficiently visible to recognise individual characters only in Ca element map. In the maps of other elements, such as Fe and Cu, the remnants of the undertext were very fragmentary and strongly dislocated, so that no identifiable parts of letters were visible.

The methods applied on the DESY data of the Vienna Dexippus palimpsest have been mainly statistical, instead of focusing alone on concentration maps of individual elements, as was done in the very first phase of XRF mapping evaluation. Due to the fact that inks and support material all contain very similar elements and only vary in their relative contributions, the application of mathematical and statistical means (to separate the information by correlation between different measured positions) was assumed by the image scientists to be a superior method to achieve readable undertext. Since the ink of the undertext was almost completely removed (its elements may have also been partly diffused over the parchment), there was almost no contrast in the maps of individual elements except in that of calcium, though also this signal was very weak. Therefore, the statistical approach (more common in MSI analysis) proved to be more useful.

Two processing software programmes were used. Roger L. Easton, Jr., Dave Kelbe and Ivan Shevchuk (see below) used the ENVI® software package from L3Harris Corporation, while Keith Knox used Hoku, a Java-based software package that he designed to process multispectral image data sets to recover writings that have been damaged or erased.[39]

The first XRF data analysis and some first processing methods were applied during the beam time session at DESY. Since it was not possible for Easton, Knox and Kelbe to attend the session, Ivan Shevchuk from the CSMC Hamburg, who was present on-site, supported the project by preliminary processing of a selection of captured data. For this purpose, Grusková selected four small problematic (i.e. illegible) areas which had major philological value. These tests showed that image processing of the XRF data can improve the legibility of the undertext.[40]

Ivan Shevchuk created a MATLAB script during the first days of the beamtime to enable initial analysis of the captured XRF data. He used a HDF5 reader and MATLAB software to translate the instrument specific XRF DESY data to a more neutral and common ENVI-readable format. The beamline control software saved individual scanlines in HDF5 file containers along with all necessary metadata. After the session Keith Knox formatted entire extensive dataset, with the goal to load, reorder, calibrate all the scanlines from the HDF5 files and create so-called

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[39] See http://www.cis.rit.edu/~ktkpci/Hoku.html. The software is distributed free-of-charge, without warranty.

[40] Cf. *Insights* 2020, 960–961 with n. 50.

hyperspectral cubes with 2048 bands. This three-dimensional cube was saved in a format in which image processing programs such as ENVI or Hoku could work with and perform statistical image processing and feature extraction. In such a cube, the X and Y coordinates determine the location of a pixel/measurement and the third dimension is the counts at each of the 2048 bins. Each bin corresponds to an energy in eV. It was possible to select between individual available detectors or average their signal.

In image processing, it turned out to be useful to apply statistical routines such as principal component analysis (PCA), independent component analysis (ICA), and minimum noise fraction analysis (MNF). These routines are widely used to achieve better contrast and legibility with multispectral data, where they extract or visualize features of text and subtle differences between the ink and writing support layers. The methods generally are based on the statistics of the ensemble of bands in each region, which may be considered in the following way. In the case the XRF data of the Vienna Dexippus palimpsest collected at DESY, the dataset consists of a measured number of photons (counts) at each picture element ("pixel") for each of the 2048 energy levels. At a pixel where there is an erased character with no ink covering it, we expect that large numbers of photons will be measured at energy levels characteristic of calcium. At a pixel with ink over an erased character and parchment, large numbers of photons will be counted at energies characteristic of both calcium and iron. By evaluating the statistical measures of numbers of photons at each energy and at each pixel, it is possible to construct metrics of the likelihood that each pixel contains ink; these metrics are displayed as grayscale imagery.

Though designed for the application to environmental remote sensing, the methods available in ENVI® are quite useful for spectral imaging of cultural heritage. This should not be surprising, as this application is really just a specific form of "remote sensing". Among the useful tools available in ENVI® are PCA, ICA, MNF, and spectral angle mapping (SAM).[41]

The other image processing software package is "Hoku," (the word "star" in the Hawai'ian language) is being actively developed by Keith Knox of the Early Manuscripts Electronic Library and is freely available online. Hoku is a batch processing software package; jobs are defined and parameters are set interactively with a graphical user interface, but jobs are run in batch mode without requiring user supervision. Users can apply any of several image processing methods to enhance image details that otherwise are difficult to see, including PCA, SAM, and now ICA and MNF. Because Hoku is written in the Java language, it may be used on either of the two most common operating systems for personal computers: Windows and Apple macOS.

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[41] ENVI® also includes its "spectral hourglass wizard", which produces images using a variety of these tools.

To briefly outline the action of the most frequently used tools in the image processing:[42]

> Principal Component Analysis (PCA) assumes that all statistics are "Gaussian", which means that the photon counts for each feature follow the well-known "bell curve" of probability. PCA evaluates the correlation properties of an original set of N image bands and constructs an "equivalent" set of N images from weighted sums of the original image bands, where "equivalent" means that the transformation may be "inverted" to reconstruct the original image bands from the principal components. Each output band is obtained by "projecting" the pixels in the N-dimensional histogram of original data onto mutually "orthogonal" (or "perpendicular") axes, which means that all output image bands are "uncorrelated". In PCA, these N output bands also are sequenced in order of image "variance", which means approximately that the output images are ordered from the widest dynamic range for the low-order bands to the narrowest dynamic range for the high orders. The ideal result of PCA would be a set of output bands with each exhibiting a specific individual feature in the scene, with the high-order bands with the smallest dynamic range showing random variations ("noise"). In typical use, the feature of interest usually appears in several PCA bands, and it often is helpful to render those bands in pseudocolor.
>
> Independent Component Analysis (ICA) is conceptually similar to PCA, but uses less-stringent assumptions (e.g., it allows non-Gaussian statistics and it uses higher-order statistical correlations to determine the transformation). ICA is therefore somewhat more capable of segmenting the feature(s) of interest into different output bands. Recall that the output of PCA is a set of "orthogonal" or "uncorrelated" image bands, whereas ICA produces results that are statistically "independent". The bands resulting from ICA may be sequenced in a similar manner to the variance calculation in PCA by evaluating the "spatial coherence" of the image data by comparing ("correlating"), in each spectral band, the pixel before and after each individual pixel. If the correlation is small, then the image is assumed to consist primarily of "noise"; bands with large correlations are assumed to have spatial structure due to useful information. The bands are sequenced in descending order of spatial coherence in similar fashion to sequencing PCA bands in descending order of variance.
>
> The calculation of the "spectral angle map" (SAM) produces a monochrome image whose grey value reflects the "similarity" of the spectrum of each pixel in the image to that of a specified reference object (usually a pixel or group known to belong to the feature of interest. The "similarity" is mapped as the angle between the N-dimensional vectors for the test and reference pixel; the "lightness" of the pixel is not considered. The grey value of the output image pixel is proportional to this angle: a "black" output pixel means that the angles of the reference and test pixel are very similar, while a "white" output

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[42] See KNOX 2023, esp. 398; EASTON – KELBE 2023.

means that the two angles are very different, so that the output pixel likely has a different material composition from the input pixel.

Minimum Noise Fraction (MNF) is similar to a PCA transformation, except that, before applying a PCA transformation, it whitens the input data based on noise statistics derived from the image. The output bands of a normal PCA transformation are arranged in order of decreasing variance of the output. As a result, the higher order bands have little variation, or contrast, and tend to be mostly noise. When the input image bands are whitened in the MNF algorithm, the variance, or contrast, is equalized across the bands. This means that when the PCA algorithm is applied to the whitened input, the decreasing variance in the bands relates to a decreasing amount of image content. Some authors refer to this as ordering the bands by decreasing image quality.

Speaking in general terms, after the results of the different processes are obtained, it is useful to combine those results to create pseudocolor images, which may enhance the visibility of low contrast features by translating to color contrast, which become more visible to the eye. The pseudocolor images are much appreciated by the philologists who evaluate the image data. Using a general purpose imaging package, such as Adobe Photoshop® or GNU "Image Manipulation Program" ("GIMP"), the philologists in charge of deciphering the text can themselves enhance the visibility of the feature of interest relative to the "background", by e.g. dynamically rotating the hue angle, changing the saturation level, changing color renderings etc. The scholars themselves can modify appearances of individual areas to optimize the visibility of every single detail. For this reason, Grusková and Martin have strongly preferred pseudocolor images.

Of necessity, the image processing of the XRF data was an "iterative" process with a workflow very similar to the processing of MSI data. First, the two philologists selected the area of interest in each scan. Then, the image scientists processed the XRF image data of each scan by using the above-mentioned methods, focusing on the selected area. The processing required significant computing time, so that it was often necessary to work on small cropped sections. The scientists delivered assortments of various processed images to the philologists, who assessed the "value" of each image, for each area of interest, by determining whether the image contained additional information about the erased eleventh-century script. During this work, the philologists optimized the legibility of single details changing their visibility relative to the "background" (as described above) using Adobe Photoshop®. They regularly sent their feedback on the examined images to the scientists, highlighting the remaining problematic areas, i.e. those that were still not sufficiently visible and thus needed further processing. The scientists analysed the feedback and identified new processing strategies that could help in recovering the problematic areas. During the re-processing, the scientists used different data bands or tried other processing methods for areas of need. The resulting processed images were sent to the philologists and the work went on in the same way as described above. Note that XRF imaging, i.e. element mapping, has a unique issue in that texts (the upper and the lower one) and other elements (e.g. stains) from both sides of the parchment leaf are usually visible in both the original images and the processed results (which issue does not occur in MSI). This makes the philologists' task to find every single extant piece of information on the undertext in the middle of all this mixed data much more difficult, sometime even impossible (Fig. 10c and 12c).[43]

In general, the spatial resolution of the XRF synchrotron scans is poorer than MSI.[44] In the case of the Vienna Dexippus palimpsest the XRF resulting spatial resolution was—for the most part of the scans—approximately 250 ppi (10 pixels per mm) (Fig. 7b, 8b, 9b),[45] i.e. only 250 spots could be fitted within a single inch. For comparison, in the EMEL multispectral images (MSI 2013), the spatial resolution was 1216 ppi (48 pixels per mm) which made it possible to see clearly fine details (Fig. 1b, 2b, 11a, 12a).[46]

To sum up, the XRF data have been processed by using the same image processing techniques as for MSI data. The effectiveness of specific methods for individual scans varied widely (just as in the case of MSI processing). A great number of various processing algorithms were tried. The statistics varied widely over various areas of the same page, even in adjacent areas. This usually required processing each area individually to find the method which could recover as much text as possible. Hence very often, to reduce the time required for processing, the data was treated in small cropped sections, which, in turn, caused some additional difficulties to the workflow of the philologists.

Among the methods of image processing applied to XRF data of this particular palimpsest, those that proved most capable of providing additional information about the erased script removed the overtext from the areas inaccessible to MSI. Examples are shown in Fig. 7b, 8b, 9b. This removal was accomplished by mixing several individual results of MNF and PCA being run with varying starting conditions. Unfortunately, because of their serendipitous nature, these methods were not consistently successful on all problematic areas (see Fig. 7c). This means that different processing was needed for different—often even adjacent—areas. Up to this point, all efforts to establish a systematic workflow for processing the XRF data of this particular manuscript have proven to be too rigid. Hence flexibility to perform customized image processing for different, and often very small, regions is necessary.

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[43] See *Insights* 2020, 962.

[44] At a synchrotron, the images are produced by scanning a single spot over a specific area.

[45] See above, p. 205, and *Insights* 2020, 961.

[46] For MSI, the spatial resolution depends on the image sensor of the camera, which has much smaller spots. Therefore, the spatial resolution of MSI images is typically 600 ppi or better.

USEFULNESS OF THE SYNCHROTRON DATA FOR RECOVERING THE PROBLEMATIC AREAS

The philologists Jana Grusková and Gunther Martin, i.e. the editors of the *Scythica Vindobonensia*, examined in depth all processed images that the image scientists created from the XRF data. This analysis has shown that despite the above-described limitations, XRF scanning at DESY and related image processing definitely provide new, i.e. additional "legible" information in areas inaccessible through MSI.[47] The method of optimizing the legibility of individual areas and single details of the undertext by modifying their visibility relative to the "background"—that the philologists use to follow while examining the MSI images—has turned out again to be crucial for finding and identifying remnants of the erased script (for this reason, pseudocolor images have been preferred).

In the problematic areas on the hair sides of the parchment leaves, the XRF synchrotron data has proved useful in several ways, though the results were different from case to case. What worked in one area often did not work or not equally well in a very near, even adjacent area of one and the same parchment page. The observations made so far on this particular palimpsest can be summarised as follows (Fig. 7–12): (a) XRF and MSI data complement each other. (b) In some areas XRF images provide missing information about those portions of the undertext that are concealed by the overtext. (c) In some larger areas that had been previously almost completely illegible, XRF data has provided a substantial amount of new information (fol. 192r, lines 13–30);[48] some other areas have remained—until now—completely or almost completely illegible, despite multiple processing attempts (e.g. fol. 192r, lines 1–10), hence new approaches and attempts are needed.

In a few, very small, areas scanned on the flesh sides of the parchment (where the undertext is well legible in the MSI processed images (Fig. 12a), but some parts of letters of major philological significance remain concealed in such a way as to render an exact decipherment impossible) the processed synchrotron XRF images have not yet provided any help (Fig. 12b, 12c).

FURTHER DECIPHERING BASED ON THE PROCESSED XRF SCANS

During the decipherment, the two philologists conducted a thorough palaeographical analysis combined with in-depth philological scrutiny. For each area of interest they examined, letter by letter, all useful XRF processed images (and re-examined also MSI images from the earlier imaging sessions), optimizing in Adobe Photoshop® the legibility of individual details. It has been a challenging and time-consuming effort, requiring countless sessions and many repeated examinations of

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[47] With a different elemental composition of the upper ink, "looking through" the upper ink could be less successful.

[48] See MARTIN – GRUSKOVÁ 2022.

every single stroke in order to make progress in deciphering the text. The poorer spatial resolution of the XRF synchrotron scans caused the details to be much more difficult to judge than on the high-resolution MSI images.[49] This made the decipherment of characters, ligatures, etc., especially the interpretation of ambiguities, considerably more challenging, sometimes even impossible.[50] Another difficulty arose from the fact that many XRF images contained information on elements also from the other side of the parchment leaf.[51] This information strongly contaminated the relevant data (Fig. 10c, 12c). Furthermore, on the most problematic two pages, fols. 192r and 193v, the scribe wrote the same characters with considerable variations in size and shape, which made the deciphering process even more difficult. Hence, numerous examinations based on a very careful palaeographical and philological scrutiny, combining information from all useful images, both XRF and MSI, have been required to draw conclusions on individual details, characters, subsequently words, word connections, and, based on this, sentences, etc.[52]

So far, thanks to the synchrotron imaging and the related image processing, Grusková and Martin have been able to decipher—besides several very small fragments on fol. 193v—18 new continuous lines of text on fol. 192r (fr. IIIa) (see Fig. 10d–10f); they have already published a preliminary edition of this portion of text, with a translation and a comprehensive philological and historical commentary (including some XRF images).[53] On the other six pages of the Vienna palimpsest, the philologists have clarified several uncertain characters (in their preliminary publications edited with underdots) and deciphered a few new ones (e.g. Fig. 7–9).[54] In those problematic parts where the undertext has remained invisible, further at-tempts of image processing will be undertaken.

CONCLUDING REMARKS

The work on the digital recovery of the *Scythica Vindobonensia* has demonstrated the productivity and necessity of close cooperation among experts in a wide range of diverse fields with a view to revealing this part of our cultural heritage. The experiment at DESY and the subsequent image processing aiming at recovering the problematic areas of the Vienna Dexippus palimpsest required intensive team-

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[49] See *Insights* 2020, 964–965.

[50] See MARTIN – GRUSKOVÁ 2022, 439.

[51] Hence, there were four layers of script, i.e. the overtext and the undertext from both sides.

[52] See *Insights* 2020, 963–964.

[53] See MARTIN – GRUSKOVÁ 2022. Based on these new results, further investigations have already been carried out, focusing on various philological and historical aspects of the new text; see the contributions of Gunther Martin und Herwig Wolfram in this GLO volume.

[54] E.g., on fol. 194r (fr. IIa) lines 17–18 they confirmed an important Gothic name which they could previously only tentatively suggest, since the major part of it was covered by the upper script. For further details see the critical edition MARTIN – GRUSKOVÁ (in preparation).

work by the participating specialists: the physicists, the image scientists, the librarians and conservators, and the classical scholars-editors of the Vienna fragments. The last mentioned and their project colleagues, Fritz Mitthof and Otto Kresten, initiated and organized the experiment.

One of the more intriguing findings has been that in order to make the script of interest in this particular palimpsest visible, we had to focus on measuring not the usual metals of an iron-gall ink, such as iron (Fe) or copper (Cu), but calcium (Ca.). Calcium has turned out to be the only element in the maps for which the erased script was sufficiently visible to enable identification of individual characters (Fig. 7–12).[55] The authors of this article are looking for possible explanations of the presence of the calcium in the locations of the erased characters. Because the original ink was completely removed, we cannot say if the detected calcium came from the ink itself or from the preparation of the parchment. As for visualizing all extant remnants of calcium, the image processing using statistical methods was able to significantly improve the visibility of the undertext compared to a mere calcium map. What the digital recovery in general seems to have recovered here, i.e. in this particular palimpsest, are areas of concentration of calcium in the locations where the erased text was once written. However, these results cannot be generalized, since each palimpsest is different, even various parts of the same palimpsest react differently to the same imaging and processing methods.

The element mapping using XRF analysis at a synchrotron as a method of digital recovery of palimpsests has advantages and disadvantages, as labelled above.[56] The first minor disadvantage lies in the fact that the manuscript under study must be transported to a storage ring facility (synchrotron), which is a complicated process. Secondly, there are time and conservation constraints. In our case, because of these constraints, our multidisciplinary team decided to work with a beam size of 100 microns that further reduced the spatial resolution of the XRF synchrotron images, which is generally markedly poorer compared to MSI images. This has caused difficulties to the work of the philologists. Even so, and despite other disadvantages, additional information has been acquired: some areas of the Vienna Dexippus palimpsest that had not been accessible through MSI[57] have been rendered visible through XRF fast element mapping and related image processing.

This experiment has taken a great deal of effort, but the new text that the classical scholars have been able to decipher and to expose by an in-depth analysis of

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[55] See *Insights* 2020, 964.

[56] One of the logistic disadvantages of the imaging at DESY is that the beam time available runs nonstop, requiring the persons in charge to be present at the storage ring at all times.

[57] One of the major advantages of the MSI is, as mentioned above, the high spatial resolution of the images. As for the disadvantages, the MSI cannot render visible what is covered by the upper text and can reach its limits when the surface of a parchment leaf is very damaged and the remnants of the erased script are very poor.

the content is of great historical and philological value.[58] Hence, the efforts are worth continuing, because every single stroke of this erased ancient text is important. As approximately 15–20 % of the text remains illegible, the classical scholars and the image scientists will continue working on the collected data. Additional image processing, using different approaches, may still enable progress.

Despite all the delight at revealing what has been hidden for centuries, it must be considered that the manuscript under examination is a unique, irreplaceable object of our cultural heritage, the safe preservation of which must be secured by every means. Therefore, where a balance has to be struck between the safety of the historical document and achieving the ultimate goals of the experiment—which in our case was to collect all additional information on the erased script of the eleventh-century manuscript of Dexippus—the absolute safety of the object must overrule any other considerations.

As to the work itself, there has been an astonishing similarity with archaeological "excavations". Retrieving information of interest hidden in a historical parchment manuscript amidst data from multiple layers and on various elements of various materials (inks, parchments, stains etc.) bears a striking resemblance to archaeological work in exploring and separating stratigraphically intricate find complexes. The findings that have emerged in the "excavation" of the new fragments by Dexippus have proven no less astonishing and enlightening than those of a new statue, settlement or inscription.

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[58] See MARTIN – GRUSKOVÁ 2022.

PROBLEMATIC AREAS OF THE VIENNA DEXIPPUS PALIMPSEST
(ÖNB, Codex hist. gr. 73)

A. Figures 7–11: Hair sides of the parchment:

Fig. 7a: Processed MSI image, EMEL
Sometimes the undertext is covered by
the overtext and hard to read, image processed
by Roger L. Easton, Jr., EMEL
© FWF Project P 24523-G19

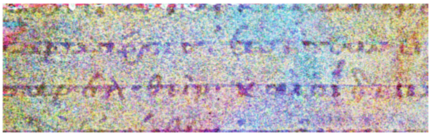

Fig. 7b: Processed DESY XRF element
mapping image: The undertext is visible
because the X-Rays can see through
the overtext, image processed
by Roger L. Easton, Jr., EMEL
© FWF Project P 28112-G25

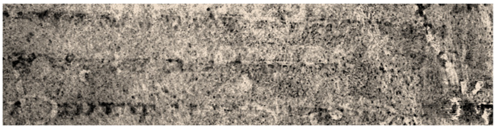

Fig. 7c: Processed DESY XRF image. The same processing method as in Fig. 7b was applied on another area of the same page, but without success: the undertext remained invisible.
© FWF Project P 28112-G25

Fig. 8a: Processed MSI image, EMEL, the undertext is covered by the overtext
image processed by Roger L. Easton, Jr., EMEL
© FWF Project P 24523-G19

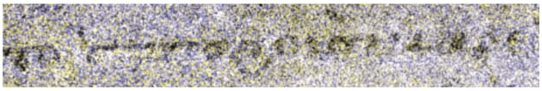

Fig. 8b: Processed DESY XRF element mapping image:
The undertext is visible, the overtext is "removed",
image processed by Roger L. Easton, Jr., EMEL
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Fig. 9a: Processed MSI image, EMEL,
the undertext is covered by the overtext image
processed by Roger L. Easton, Jr., EMEL
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Fig. 9b: Processed DESY XRF element
mapping image: The undertext is visible,
the overtext is "removed", image processed
by Ivan Shevchuk, CSMC
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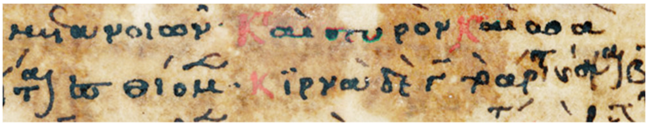

Fig. 10a: Visual appearance image, EMEL
© FWF Project P 24523-G19

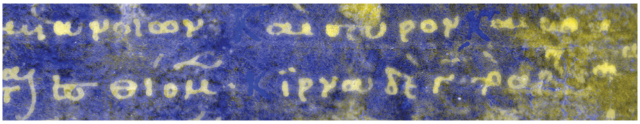

Fig. 10b: Processed MSI image, EMEL, the undertext is invisible,
processed by Roger L. Easton, Jr., EMEL
© FWF Project P 28112-G25

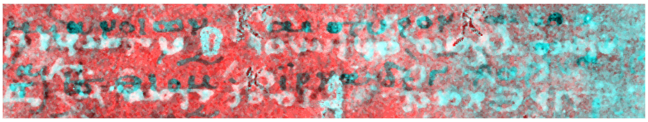

Fig. 10c: DESY XRF element mapping: The overtext from both sides
of the parchment is visible, the undertext is almost invisible,
image processed by Roger L. Easton, Jr., EMEL
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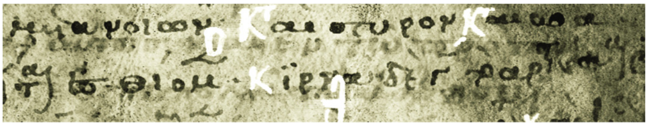

Fig. 10d: DESY XRF element mapping: XRF map of Ca
The undertext is partly visible
© FWF Project P 28112-G25

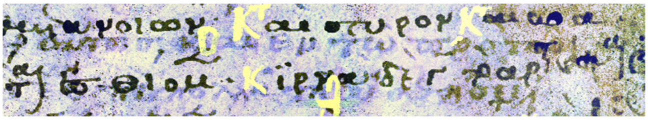

Fig. 10e: Processed DESY XRF element mapping image:
The undertext is visible, image processed by Keith T. Knox, EMEL
© FWF Project P 28112-G25

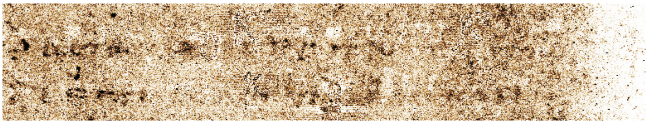

Fig. 10f: DESY XRF element mapping image,
processed by Roger L. Easton, Jr., EMEL: Some remnants of the undertext are visible
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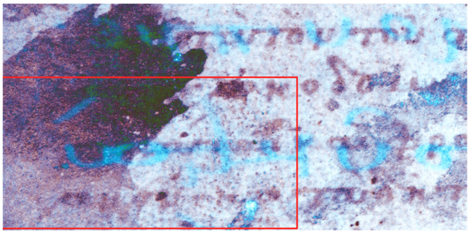

Fig. 11a: EMEL MSI imaging 2017, image processed by Roger L. Easton, Jr.
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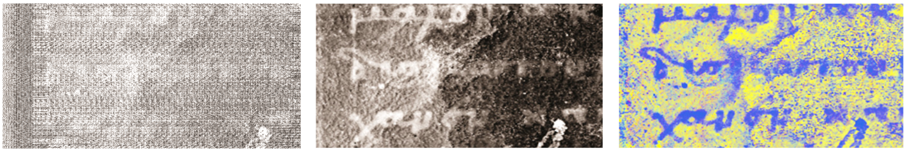

Fig. 11b: XRF testing scan Ca channel (detectors 1–3)

Fig. 11c: XRF useful results Ca channel (detectors 1–3)

Fig. 11d: XRF image of the Ca channel processed by Keith T. Knox, EMEL

Fig. 11b–11d: Synchrotron DESY fast XRF element mapping
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B. Figure 12: A flesh side of the parchment:

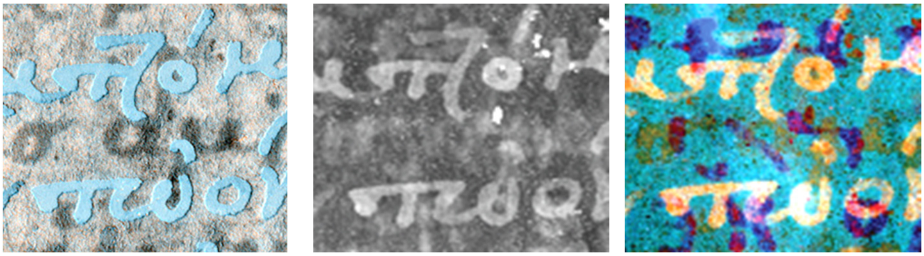

Fig. 12a: MSI image, processed by David Kelbe, EMEL

Fig. 12b: DESY, XRF element mapping, “raw” image, XRF element map of Ca

Fig. 12c: DESY, XRF element mapping, image processed by Roger L. Easton, Jr., EMEL

Fig. 12: An important detail of the text covered by the upper script on a flesh side of the parchment
Fig. 12a: © FWF Project P 24523-G19
Fig. 12b–12c: © FWF Project P 28112-G25

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[59] SCHROER – BOYE – FELDKAMP – PATOMMEL – SAMBERG – SCHROPP – SCHWAB – STEPHAN – FALKENBERG – WELLENREUTHER – REIMERS 2010.

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Abstracts

New Approaches Using Image Processing of Spectral Data from Synchrotron X-ray-Fluorescence Element Mapping to Recover Erased Text from the Vienna Dexippus Palimpsest

Roger L. EASTON, Jr., Leif GLASER, Jana GRUSKOVÁ,
Katharina KASKA, David KELBE, Keith T. KNOX,
Gunther MARTIN, Ivan SHEVCHUK

The article provides insights into the digital recovery of the *Scythica Vindobonensia*, the Vienna Dexippus palimpsest. These new fragments were discovered some years ago in a palimpsest of the Austrian National Library in Vienna and contain lost ancient historical text about Gothic incursions into Roman provinces in the Balkans in the third century AD. In order to render the erased script of the eleventh-century Greek manuscript visible, the classical scholars in charge of deciphering and editing the *Scythica Vindobonensia* cooperate closely with specialists in the field of digital recovery of palimpsests. The article presents new approaches using image processing of spectral data from synchrotron x-ray-fluorescence element maps to recover illegible areas of the erased text. The work on the palimpsest is still in progress.

[Nové prístupy vo využívaní digitálneho spracovania obrázkov aplikované na spektrálne dáta získané mapovaním elementov pomocou röntgenovej fluorescencie na synchrotróne s cieľom zviditeľniť zmazaný text viedenského Dexippovho palimpsestu]

Článok približuje proces špeciálneho digitálneho odkrývania fragmentov známych pod názvom *Scythica Vindobonensia*, tzv. viedenský Dexippov palimpsest. Fragmenty strateného antického diela historika Dexippa boli objavené pred niekoľkými rokmi v štyroch listoch palimpsestu uchovávaného v Rakúskej národnej knižnici vo Viedni. Obsahujú nové informácie o vpádoch Gótov do rímskych provincií na Balkáne v 3. storočí po Kr. Aby sa podarilo zviditeľniť zmazané grécke písmo rukopisu z 11. storočia, spolupracujú klasickí filológovia-editori textu so špecialistami v oblasti digitálneho zviditeľňovania palimpsestov. Článok predstavuje nové prístupy využívajúce spracovanie spektrálnych dát získaných pomocou snímania s použitím RTG synchrotrónového žiarenia s cieľom zviditeľniť nečitateľné časti zmazaného textu. Práce na palimpseste stále prebiehajú.