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Dispersed Palimpsest Offers Digital Insight into St. Catherine's Library

INTRODUCTION

On 26 February 2013, Grigory Kessel visited the library of the owner of the Syriac Galen and Archimedes Palimpsests in the United States with Michael B. Toth. As Kessel sat at a large table in the centre of the private library, he held the bound Syriac Galen Palimpsest for the first time. After quietly handling the manuscript and inspecting the parchment leaves that showed traces of erased text in Syriac, he pulled up on his laptop screen an image of a Syriac manuscript folio with faintly visible undertext he had seen the week before in Harvard University's Houghton Research Library in Boston. He soon noted that the single folio MS Syriac 172 at the Houghton Research Library had the same overtext and the undertext also contained Syriac translations of the Galen text, most likely from the same original source of the erased undertext. This began what became known as 'The Hunt for the Missing Leaves'. Following up on initial multispectral imaging of the unbound Syriac Galen Palimpsest in 2009 and 2010, this launched a loose-knit technical and scholarly program by independent scholars, managers, scientific institutions, and universities for the multispectral imaging of all the folios that had originally been part of the same codex to make them available with free access for further study.

MULTISPECTRAL IMAGING AND DIGITAL REUNIFICATION

Under the leadership of the Walters Art Museum and R.B. Toth Associates, from 2009 to 2010 a multidisciplinary team conducted multispectral imaging of the Syriac Galen Palimpsest (SGP). This manuscript, disbound for the purpose, contains Galen's influential text *On the Mixtures and Powers of Simple Drugs*, which was translated from the original Greek into Syriac during the 6th century. The multispectral imaging project built on advances during the decade-long pioneering project to reveal the scrubbed-off text in the Archimedes Palimpsest.¹ This SGP Multispectral Imaging Project capitalized on more mature imaging and data management technologies and processes developed during and since the Archimedes Palimpsest Project, with the support and funding of the owner of both manuscripts. Following completion of imaging and digital image processing, the SGP Project hosted 300 GB of captured and processed SGP image data online for free, global access under a Creative Commons licence to advance the owner's goals of free access and data preservation.² In July 2010, all 231 folios of the Syriac Galen Palimpsest codex were hosted on <http://digitalgalen.net/> by the University of Pennsylvania Libraries. In the meantime, the digital data continued to serve scholars developing new understanding of the transmission of Greek Medicine in manuscripts of different language traditions.³ Following this imaging, the Syriac Galen Palimpsest was rebound by conservators and returned to the owner's library—but not for the last time.

The open access availability of all the SGP images from the 2009–2010 project permitted continued remote research by various scholars of Syriac, ancient medicine, and the transmission of Western knowledge, including Grigory Kessel. Several years after completion of the SGP Multispectral Imaging Project, Grigory Kessel and Michael B. Toth visited the SGP owner's private library in 2013 for a hands-on review of the actual palimpsest codex. Kessel realized that a folio he had examined at the Harvard University's Houghton Library matched the form and content of folio 223 of the bound Syriac Galen Palimpsest in the owner's private library (Fig. 1). This led Kessel to review Sebastian Brock's catalogue of Syriac manuscripts in St. Catherine's Mon-

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¹ Noel, Introduction.

² Noel, Revealing Lost Codex of Archimedes.

³ Bhayro and Brock, Syriac Galen Palimpsest and Transmission.

astery in the Sinai.⁴ Kessel noted that one entry cited a medical undertext that appeared to be a folio from the Syriac Galen Palimpsest. After multispectral imaging of both the Harvard and Sinai folios, a continued catalogue search by Kessel led to the discovery of three more SGP folios in the Biblioteca Apostolica Vaticana (BAV)⁵ and one in the Bibliothèque nationale de France (BnF).⁶ With support from the owner, the six additional folios that belonged to the SGP discovered by Grigory Kessel were imaged with multispectral imaging systems in the following institutions:

Houghton Library	Syriac 172
St. Catherine's Monastery Library	Syr. NF Fragment 65
Biblioteca Apostolica Vaticana	sir. 647, ff. 38 and 39; sir. 623, f. 227
Bibliothèque nationale de France	syr. 382

In addition to the captured sequences of multispectral images and digitally-processed images, standard metadata was captured for each folio, based on the Archimedes Palimpsest Metadata Standard. The Holy Monastery of St. Catherine in the Sinai, the Biblioteca Apostolica Vaticana, the Bibliothèque nationale de France (Fig. 2), and Harvard University Houghton Library provided not only access to their manuscripts for multispectral imaging, but also, along with the anonymous owner of the codex, generously granted Creative Commons licences to share the captured and processed digital data online for free access on www.digitalgalen.net (Fig. 3).⁷ Thus, in September 2016, with the addition of all the digital images from the newly-identified folios at St. Catherine's Monastery, the Bibliothèque nationale de France, the Biblioteca Apostolica Vaticana, and the Houghton Library at Harvard, the Syriac Galen Palimpsest was digitally reunited for the first time since the folios had been dispersed in the 19th century from St. Catherine's Monastery in the Sinai Desert.⁸

INDEPENDENT SCHOLARLY RESEARCH PROGRAM

A number of other scholars had capitalized on the open access to the SGP data for independent research into the Syriac Galen Palimpsest, beginning in 2012. This included two collaborative teams with Siam Bhayro, Grigory Kessel, Robert Hawley, Peter Pormann, and others.⁹ The multispectral images hosted online enabled the researchers from the Universities of Manchester and Exeter to identify more undertext in the Syriac Galen Palimpsest and to reconstruct the structure of the original manuscript. At the same time, scholars in Paris used the images in their research into the use of herbals in ancient medicine, and hosted a 2013 conference that included discussions of the recently-reunited palimpsest.¹⁰ One outcome of their research into ancient medicine was the realization that 'the Syriac text of ... the SGP can be of considerable importance not only for Syriac studies, but also and even especially for specialists of Greek medical texts, since it sometimes allows one to propose or corroborate corrections to the Greek text of Galen's treatise *On Simple Drugs*'.¹¹

Building on this research that scholars had until then undertaken independently and in loose communication with each other, in 2015 an international team received a grant from the Arts and Humanities Research Council of Great Britain for the Syriac Galen Palimpsest Project. Their goal was to identify the Galen undertext in the SGP and enhance its readability with advanced digital processing so they could produce a scholarly edition of the now digitally-reunited original Syriac Galen Palimpsest.¹² After significant progress in the development of advanced computational methods and their use for additional digital processing of the existing images, the team realized the laws of physics prevented them from gleaning any more information from the images that had been produced in 2009 and 2010 with earlier multispectral imaging systems. This included three bifolios that had remained completely illegible after the previous multispectral imaging: the recto and verso sides of

⁴ Brock, *Catalogue of Syriac Fragments (New Finds)*, 63–64, 265–266.

⁵ Rilliet, *Nouveaux fragments syriaques à la Bibliothèque Vaticane*.

⁶ Briquel-Chatonnet, *Manuscrits syriaques de la Bibliothèque nationale de France*, 81–83.

⁷ University of Pennsylvania Libraries, *Openn, The Galen Syriac Palimpsest*.

⁸ Kessel, *Membra disjecta sinaitica I*.

⁹ Bhayro *et al.*, *Collaborative Research on the Digital Syriac Galen Palimpsest*.

¹⁰ The conference, 'From Babylon to Baghdad: Toward a History of the "Herbal" in the Near East', was hosted by the Institut catholique de Paris from 12th–14th November 2013, as part of the ERC project FLORIENTAL.

¹¹ Calà *et al.*, *Textual Interest of Syriac Versions*.

¹² University of Manchester, *Recovery of Lost Text*.

bifolios 31+38, 143+146, and 191+194. A collaborative team from R.B. Toth Associates LLC, Equipoise Imaging LLC, Stanford University Library, and the Stanford Synchrotron Radiation Lightsource (SSRL) at the US Department of Energy's SLAC National Accelerator Laboratory developed a dynamic advanced imaging program to try to reveal more of the thoroughly-erased Galen undertext in the SGP manuscript.

ADVANCED IMAGING PROGRAM

In 2015, initial multispectral imaging with the latest generation system of key folios of the rebound manuscript in the owner's library provided the scholars with additional information. This helped them characterize both the bound codex and the dispersed folios with increased visibility of more undertext and understanding of the treatment of the parchment that made the undertext so difficult to read. It also demonstrated the potential offered by a larger-format Phase One achromatic camera, additional filtering of fluorescent images, new Equipoise LLC illumination panels, and longer exposures—all significant advances from the 2008 and 2009 imaging sessions.

In conjunction with this multispectral imaging test, the team also developed plans to conduct x-ray fluorescence (XRF) imaging of the Syriac Galen Palimpsest at SLAC SSRL, capitalizing on additional power and new higher-speed scanning techniques implemented since the initial XRF scanning of the Archimedes Palimpsest. Uwe Bergmann and Michael B. Toth conducted elemental XRF analysis in the owner's library of key regions of interest in the Syriac Galen Palimpsest, to determine the feasibility of and technical parameters for XRF imaging. They found the Syriac Galen Palimpsest posed a significant challenge for XRF imaging—especially compared to the Archimedes Palimpsest—since it had a significant calcium response and very low iron response in regions of undertext. Their initial XRF analysis revealed the ink in the religious overtext and the residual ink from the scrubbed-off undertext responded differently in XRF, with a very low fluorescence response from the undertext. This would make XRF and follow-on multispectral imaging much more difficult than it had been for the Archimedes Palimpsest.

The SSRL XRF scientific experimental proposal was prioritized for x-ray synchrotron beamtime after it had been scientifically peer reviewed and rated by the SSRL Proposal Review Panel. The team had, however, to address one major problem: the codex had been rebound since the prior multispectral imaging. This would prevent imaging of the gutter regions and XRF imaging by mounting bifolios in an apparatus that would accurately move each one back and forth in front of a 100-micron x-ray beam. The owner agreed to have the SGP codex disbound yet again.

The scholarly team led by Peter Pormann, including Natalia Smelova, Naima Afif, William Sellers, Grigory Kessel, and Siam Bhayro, developed a prioritized list of folios and regions of interest for further imaging to reveal needed undertext that could help them to identify and read additional lines of Galen text. The scholars provided an initial list of twenty of the highest-priority folios that were critical to their understanding of the Syriac Galen Palimpsest and its text across this and the other relevant manuscripts, based on their inability to discern information from the previous multispectral images.¹³ This list was updated throughout the imaging based on their near real-time review of images:

<i>Reconstructed original bifolio</i>	<i>Readability</i>	<i>Book</i>	<i>Sides</i>
31r+38v	unidentified	??	1
31v+38r	unidentified	??	2
143r+146v	unidentified	??	3
143v+146r	unidentified	??	4
191r+194v	unidentified	??	5
191v+194r	unidentified	??	6
33v+36r	unreadable	IX	7
72r+75v col. A	unreadable	VII	8

¹³ Natalia Smelova, *pers. comm.*, 13 February 2018.

<i>Reconstructed original bifolio</i>	<i>Readability</i>	<i>Book</i>	<i>Sides</i>
80r+83v col. B	unreadable	V	9
94r+99v	unreadable	V	10
101r+108v	unreadable	VII	11
167v+170r	unreadable	II	12
173r+180v	unreadable	VIII	13
176v+177r	unreadable	VI	14
198r+203v	unreadable	VII	15
208v+209r	unreadable	VII	16
215v+220r	unreadable	VIII	17
222v	unreadable	III	18
223r+226v	poor/unreadable	IV	19
223v+226r	poor/unreadable	IV	20

While the multispectral imaging systems were brought to the dispersed palimpsest folios for onsite imaging—whether they were in a private library in the United States, libraries in Boston or Paris, or even in Vatican City and the middle of the Sinai Desert—for XRF imaging the SGP had to be transported to the multi-billion dollar, 240 metre in circumference, high energy storage ring and x-ray source in California. The still-bound Syriac Galen Palimpsest was couriered to the Stanford University Library Conservation Department in California in early 2018. There the trained Library Preservation Team carefully removed all the bifolios from the binding and prepared custom flat mounts to position the folios for precise imaging. This was only possible with the prior documentation, preservation, and rebinding by the professional conservation team led by Abigail Quandt at the Walters Art Museum.

ADVANCED MULTISPECTRAL IMAGING

Multispectral imaging of the Syriac Galen Palimpsest in the Stanford University Library Conservation Department took place in March 2018 with a 100 Megapixel (MP) Phase One camera and portable system brought out to Stanford by Toth. The following bifolios of the Syriac Galen Palimpsest were imaged in the Stanford University Library Conservation Lab with the latest multispectral imaging system: 31r+38v, 31v+38r, 33r+36v, 33v+36r, 80r+83v, 80v+83r, 125r+132v, 125v+132r, 143r+146v, 143v+146r, 152r+153v, 152v+153r, 191r+194v, and 191v+194r. These images were added to the Research Contributions folder (<https://digitalgalen.net/ResearchContrib/>) of the digitalgalen.net website by the University of Pennsylvania Libraries.

The narrowband multispectral imaging system used during this program included commercial off-the-shelf hardware and software for digital multispectral image capture and viewing as part of the integrated system. This latest system (Fig. 4) offered greater dynamic range, more illumination wavelengths, and higher resolution than the system used in St. Catherine's Monastery Library and the prior imaging at the Walters Art Museum. It also included customized image processing software for processing and exploitation of the spectral images by the users. The Phase One 100 MP medium-format camera with a 11608 × 8708 pixel sensor took a series of high-quality digital images, each illuminated by a specific wavelength of light. The resulting image set was then digitally processed and combined to reveal residues and features in the object that are not visible to the eye in natural light. These processed images (generated from the captured images) served to clarify the Galen undertext in the SGP, providing more information for scholarly research.

CAMERA SYSTEM

One of the challenges with the application of the latest technical systems for long-term studies is the dynamic nature of technology development, requiring the integration of rapid advances in sensors, digital processing, and data handling to get the best results for researchers.¹⁴ The camera system utilized for the follow-on multispectral imaging of the Syriac Galen Palimpsest incorporated the latest in digital sensor technology, offering the higher signal-to-noise ratio needed to capture very faint fluorescence from the parchment. The Phase One XF Camera System with a 100 MP Achromatic CMOS sensor and a 120 mm macro lens produced images of over 1200 pixels per inch. The higher sensitivity of the sensor with passive thermal management also allowed shorter exposures at higher ISOs—capturing in a single day what used to take several days of imaging with earlier systems. Automatic focusing greatly aided setup and minimized handling of the fragile palimpsest folios.¹⁵

ILLUMINATION SYSTEM

The imaging system provided narrowband illumination with light in specific wavelengths from the low heat and low maintenance, long-lifetime light emitting diodes (LEDs). It included two new integrated Equipoise Imaging illuminators, each with multiple LEDs, providing illumination for imaging in distinct ultraviolet, visible, and infrared wavelengths. This was integrated with the operating software to allow simplified system operation and unified metadata capture. Ten illumination types were used to produce each image:

- 370 nm ultraviolet (UV) LED illumination
- 448 nm visible LED illumination
- 476 nm visible LED illumination
- 499 nm visible LED illumination
- 519 nm visible LED illumination
- 598 nm visible LED illumination
- 636 nm visible LED illumination
- 780 nm LED infrared (IR) illumination
- 870 nm LED IR illumination
- 940 nm LED IR illumination.

FILTER SYSTEM

To capture fluorescence from an object, a six-position motorized filter wheel containing two-inch square optical glass filters, with control software and a computer interface, inserted a filter into the optical path during additional images captured at short wavelength illuminations. Filtered images increase the range of captured information to include fluorescence emissions. This allows the characteristic spectra of substrates, colourants, and contaminants to be revealed from the faint light they emit. The filter wheel is driven by computer control with a removable carousel containing a selection of filters (UV bandpass; visible bandpass and longpass filters). The following filters were used in follow-on multispectral imaging of the Syriac Galen Palimpsest:

- N = CLEAR (no filter)
- U = BP365 (UV bandpass filter)
- V = LP400 (long pass filter that passes wavelengths longer than 400 nm – blue and above)
- G = LP515 (long pass filter that passes wavelengths longer than 515 nm – green and above)
- R = LP590 (long pass filter that passes wavelengths longer than 590 nm – red and above)
- I = LP715 (long pass filter that passes wavelengths longer than 715 nm – IR and above)

¹⁴ Christens-Barry *et al.*, *Camera System for Multispectral Imaging*, vol. 724908.

¹⁵ Phase One A/S, *XF IQ3 100MP Camera*.

IMAGE CAPTURE INTEGRATION

Another challenge in efficient multispectral imaging of manuscripts is the ability to integrate all imaging functions into a single automated process. To accomplish this, the Spectral XV image capture operating software provided integrated control of the digital camera back, filters, and illumination as a single system. This mature software—developed by Equipoise Imaging LLC based on the CaptureCore application engine used by Phase One A/S to control camera capture operations and processing workflow—allowed streamlined operation and metadata capture from a single interface with simple and efficient setup and imaging.

SPECTRAL IMAGE PROCESSING

The efficiency of multispectral imaging is dependent on the speed not only of image capture, but also image processing by the end users. Captured images are processed with image processing software in the customized Paleo Toolbox—a spectral imaging toolkit created by Equipoise Imaging, LLC, for applications in cultural heritage imaging. The Paleo toolkit comprises plugin modules that integrate into ImageJ, an open source image processing tool originally developed at the US National Institutes of Health. ImageJ has been widely adopted and extended by scientists working in remote sensing, biological science, and cultural heritage world-wide. It offers a wide range of digital operations for the enhancement and reproduction of non-visible features from the objects based on their spectral response in images captured with the full set of illumination wavelengths and emission bands. The Paleo Toolbox allows researchers to capitalize on these powerful tools with just a few clicks of a mouse.

X-RAY FLUORESCENCE IMAGING

High-powered x-rays easily penetrate the collagen of parchment, but energize metallic inks and other elements heavier than aluminum on the surface to emit fluorescence radiation. The strength of this fluorescence radiation is recorded with sensitive detectors. By moving the manuscript folio back and forth in microscopically small steps in a very fine x-ray beam about the width of a human hair, raster scanning the palimpsest folio can yield elemental XRF maps that reveal text that is not visible with optical imaging. This was used to reveal undertext and text that had been painted over with forged illuminations in key leaves of the Archimedes Palimpsest. The US Department of Energy-funded SSRL SPEAR3 3-GeV, high-brightness third-generation storage ring was upgraded in 2004, after the Archimedes Palimpsest XRF imaging.¹⁶ These extremely bright x-rays were used to image the Syriac Galen Palimpsest in 2018 and 2019. For Syriac Galen Palimpsest imaging, it operated at 500 mA in top-off mode with energy added every five minutes, so that the imaging did not have to stop every eight hours to top-off the beam with more energy—as occurred during Archimedes Palimpsest imaging. The upgraded XRF imaging systems developed by SLAC SSRL produced five megapixel elemental maps in a half to a third of the time it took to scan the Archimedes Palimpsest, and with high reliability and low emittance. Based on the strength of the XRF imaging proposal and peer review feedback, SLAC SSRL made two beam lines available for the initial imaging session at Stanford in 2018: Beamlines 6–2 and 10–2, both of which were equipped with climate control systems to regulate temperature and humidity for the parchment.

XRF imaging was conducted around the clock since beamtime is always in high-demand from more than 1,600 scientists from around the world who conduct experiments at SSRL. Each designated bifolio was mounted on a translation stage that moved it in front of the beam for scanning, and the lead-lined hutch was locked before the x-ray beam was opened (Fig. 5). After the scan was completed eight to 12 hours later, the bifolio would be swapped out for another and the next scan would begin.¹⁷ The scanning hardware and software at SSRL only allowed scanning in one direction, but a future bidirectional upgrade should minimize overhead time required to return the manuscript to the beginning of the next scan line.

Each page was scanned and the resulting elemental maps captured using SLAC SSRL operating systems were converted from Hierarchical Data Format (HDF) hdf5 data to 16-bit.TIF format and jpegs. HDF is a data model and file format designed by the National Center for Supercomputing Applications for the storage and

¹⁶ SLAC National Accelerator Laboratory, *Stanford Synchrotron Radiation Lightsource*.

¹⁷ Bartels, Greek Medical Text Rediscovered.

manipulation of scientific data across diverse operating systems and machines.¹⁸ The resulting TIFF and jpeg image files for each element were posted online for study by the scholars on the project. Throughout the imaging process, scholars in the UK (some nine hours ahead of the California time zone) would review the images and offer immediate feedback via email and marked up jpeg images. As an example, during the January 2019 imaging session, the scholarly team noted good results, with a 31 January email from Peter Pormann stating: 'For fol. 141v–148r, we were able to read the complete rubric (which was totally invisible beforehand). It is particularly nice, as it contains the title to chapter 3.6 and has an interesting variant reading compared to the Greek ...'¹⁹

DATA INTEGRATION

Supporting not only the current team of independent scholars, but also future research, required good data management and standardization. Borrowing from the Archimedes Palimpsest Program, that program's metadata standards were followed for multispectral imaging, as well as the metadata extensions for XRF imaging. All the images and metadata now being hosted in simple flat files on the University of Pennsylvania Library's OPenn online data repository are accessible directly through digitalgalen.net.

All the SGP data and metadata was stored during the image collection process, including those from the original privately-owned codex, as well as the dispersed folios in other institutions. The multispectral image capture software collected the stacks of multispectral images in separate capture image folders. Each folder includes descriptive metadata in an associated JSON file with details of the image capture that are automatically entered by the Spectral XV software. This includes basic *Archimedes Palimpsest Metadata Standard* metadata.²⁰ For the SGP multispectral images these include:

NAME:	SGP 100MegaPixel Phase One
RIGHTS:	CC 4.0 BY
PUBLISHER:	Owner of the Syriac Galen Palimpsest
PROJECTNICKNAME:	SGP100MP
CREATOR:	MB Toth
CONTRIBUTORS:	R.B. Toth Associates, Stanford University Libraries, Digital Transitions, Phase One A/S, SLAC SSRL
DESCRIPTION:	High Resolution Images of Syriac Galen Palimpsest
LOCATION:	Stanford University Libraries

The XRF metadata was stored in imaging logs and imaging system files throughout the imaging sessions, and then entered into a single metadata document for each of the three imaging sessions in accordance with the *Archimedes Palimpsest Metadata Standards XRF Extensions*.²¹ Since two beam lines were used for the 2018 imaging session, two sets of metadata were documented.

The following bifolios of the Syriac Galen Palimpsest were imaged at two beam lines at SLAC SSRL in the 2018 imaging session, with some bifolios also imaged with multispectral system at the Stanford University Library:

¹⁸ Oak Ridge National Laboratory, HDF5 Overview.

¹⁹ Pormann, *pers. comm.*, 31 January 2019.

²⁰ University of Pennsylvania Libraries, *Archimedes Palimpsest Metadata Standard*.

²¹ University of Pennsylvania Libraries, *Metadata Standard XRF Extensions*, 2008.

Beam Line 6–2

31r+38v	31v+38r	Also 100 MP Multispectral Imaging
33r+36v	33v+36r	Also 100 MP Multispectral Imaging
80r+83v	80v+83r	Also 100 MP Multispectral Imaging
103r+106v	103v+106r	
125r+132v	125v+132r	Also 100 MP Multispectral Imaging
143r+146v	143v+146r	Also 100 MP Multispectral Imaging
152r+153v	152v+153r	Also 100 MP Multispectral Imaging
167r+170v	167v+170r	
176r+177v		
191r+194v	191v+194r	Also 100 MP Multispectral Imaging
216r+219v	216v+219r	

Beam Line 10–2

152r+153v	152v+153r	Also 100 MP Multispectral Imaging
80r+83v	80v+83r	Also 100 MP Multispectral Imaging
190v+195r	190r+195v	
94r+99v		
23r+30v	23v+30r	
199r+202v	199v+202r	
101r+108v		
125r+132v	125v+132r	Also 100 MP Multispectral Imaging

While the x-ray beam penetrated the parchment of the folios to yield an elemental response from both sides at the same time, each side of most folios was imaged to increase the XRF signal needed to reveal the very faint text.

The scholars usually reviewed the multispectral images first, and then turned to the XRF TIFF images created from the elemental maps to glean more details from the undertext. In most cases the scholars reviewed and compared the digital images from both the multispectral imaging and the XRF imaging separately, but for some images the scientists and technical personnel would overlay an XRF image on the multispectral image. Advancing this technique by automatically merging multispectral and XRF images may offer researchers a useful research tool. Correlating XRF elemental data with specific spectral responses in multispectral images may also offer an easier and portable method of deriving more information from objects that cannot be subjected to XRF scanning, potentially benefiting from artificial intelligence as well.

Given the difficulty in reading the Galen undertext, Dr. William Sellers at the University of Manchester developed an open-source, machine-learning artificial intelligence software tool called GalenQt that significantly increases the readability of the processed undertext images (Fig. 6). The open source program is freely available to enhance visualization of a variety of advanced technical image sets. This tool proved invaluable in detecting and enhancing undertext that could not be seen with statistical procedures and transformations only, such as Principal Component Analysis. This enabled the scholars to work through the various images to identify and read more of the Galen undertext in the SGP.

CONCLUSION

The Syriac Galen Palimpsest Program significantly advanced the methodology and standards for integrating image data from a palimpsested manuscript that had been dispersed from its original location: St. Catherine's Monastery in the Sinai. In the over a decade since the completion of the Archimedes Palimpsest Project, advancements in technology have offered new opportunities for advanced research into palimpsests. In addition to reuniting the original manuscript, the loose-knit and dynamic program advanced knowledge of the palimpsest and its origins and is making a large corpus of data available online. This program benefitted from the three key components of an effective system: 1) *People* who are knowledgeable, 2) *Processes* that are defined and repeatable, and 3) *Technology* that provides useful results in timely fashion.

This program relied on several key aspects of advanced digitization and access to support researchers around the globe as they attempted to get more information from the very difficult-to-read Galen undertext:

1. *Multispectral Imaging*: Advances in imaging technology provided more information of use to scholars that was not available from the initial imaging with earlier-generation systems. Integration of new advanced imaging systems hastened the imaging itself and provided scholars with the needed tools to reach conclusions based on images they could develop themselves. The off-the-shelf camera systems with higher resolution and new light panels with more LEDs in additional spectra of light provided new wavelengths of reflected light, as well as generated additional fluorescence—all in less time.
2. *XRF Imaging*: The XRF imaging revealed text not visible with enough detail in any multispectral imaging. SSRL advances provided a steadier and brighter x-ray beam that greatly eased the setup and imaging of manuscript leaves. The advanced XRF analysis and multispectral imaging in the owner's library provided useful information to maximize the results from the limited beamtime available.
3. *Image Processing and Visualization*: Advanced processing proved critical to differentiating faint undertext from the background noise of the parchment. The integrated Paleo processing tools based on ImageJ provided scholars with the ability to develop images that met their specific needs, while the Galen QT machine-learning tool revealed text that statistical methods failed to show.
4. *Metadata Standards and Access*: The availability of image data for current and future generations of scholars is entirely dependent on the ability to identify not only the images of interest, but also the technical parameters associated with their collection and processing. The Archimedes Palimpsest Metadata Standards developed in the previous decade continued to clearly define the metadata elements required for efficient image access and further research.
5. *Interdisciplinary Development*: Advancing knowledge of the Syriac Galen Palimpsest required collaboration across the humanities and sciences in developing methodologies and technologies to better meet researchers' needs. This demonstrated that it is no longer sufficient to have scientists and scholars working together to just produce good images. Instead, they have to work more broadly on the development of technology and work processes that put useful tools directly into the hands of non-technical researchers.

Automatically merging multispectral and XRF images, building on the manual process used during this project, may offer researchers a useful research tool. Correlating XRF elemental data with specific spectral responses in multispectral images may also offer an easier and portable method of deriving more information from objects that cannot be subjected to XRF scanning, potentially benefiting from artificial intelligence as well.

Building on similar projects that came before, this program is providing new insights into this key manuscript of medical knowledge. While the parchment codex is no longer part of the Library of St. Catherine's Monastery, the codex and all its dispersed leaves are even more freely accessible for research now in digital form, with publication of a scholarly edition planned by 2022 by the University of Manchester, supported by the Arts and Humanities Research Council of Great Britain—if Covid health restrictions permit.

ACKNOWLEDGEMENTS

The successes of imaging programs such as the imaging of and research into the Syriac Galen Palimpsest rely on the expertise and dedication of international teams of professionals. Each of them contributed to this project with their own unique skills: scholars, conservators, interns, scientists, engineers, librarians, curators, data administrators and managers, and many others. All their dedicated work provides valuable data and information for future generations. Of particular note is Grigory Kessel's tenacious hunt for missing leaves of the Syriac Galen Palimpsest. His research enabled the imaging and digital reunification of what is believed to be the entirety of the original erased text.

This program was dependent on the generosity of the owner of the Syriac Galen Palimpsest as he gave permission to disbind his Syriac Galen Palimpsest and image it yet again. Not only has his support allowed significant technical development for other projects, but his focus on efficiencies and scope throughout the project has also advanced cultural heritage digital projects and open data access.

Ultimately it fell to Doug Emery and the team at the University of Pennsylvania Schoenberg Institute of Manuscript Studies to corral all the data and make it available online for free access.

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Fig. 1: Grigory Kessel studying the SGP (© R.B. Toth Associates)

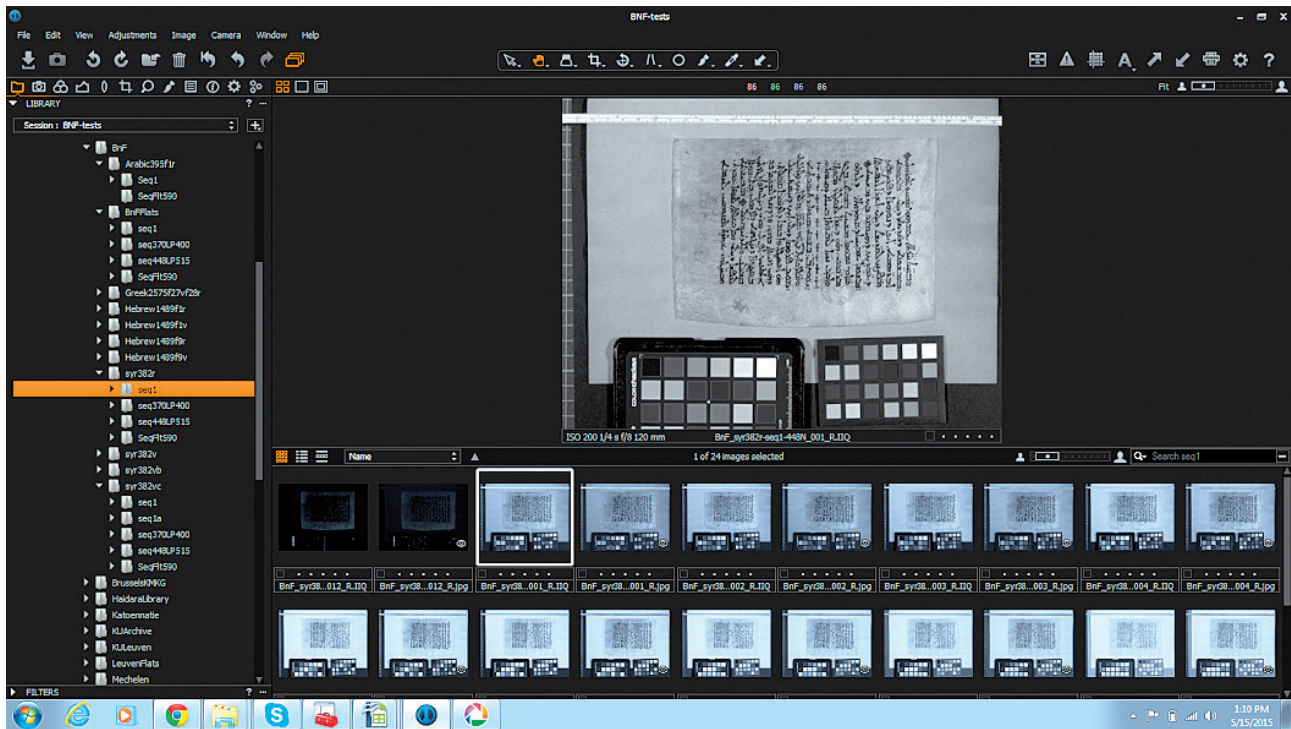


Fig. 2: (B&W) SGP Multispectral image stack captured at BnF (© R.B. Toth Associates & Phase One A/S)



The Syriac Galen Palimpsest

	Name	Last modified	Size
	0_ReadMe.html	2010-07-21 21:31	18K
	0_ReadMe.txt	2010-07-21 21:31	11K
	1_FileList.html	2010-07-21 22:37	2.0M
	1_FileList.txt	2010-07-21 22:34	683K
	Data/	2016-04-29 16:26	-
	Documents/	2010-07-09 11:43	-
	ResearchContrib/	2010-07-19 14:46	-
	Supplemental/	2010-07-08 13:51	-
	Support/	2010-07-09 14:44	-

Fig. 3: (B&W) Digitalgalen.net site on University of Pennsylvania Libraries OPenn (© University of Pennsylvania Libraries)

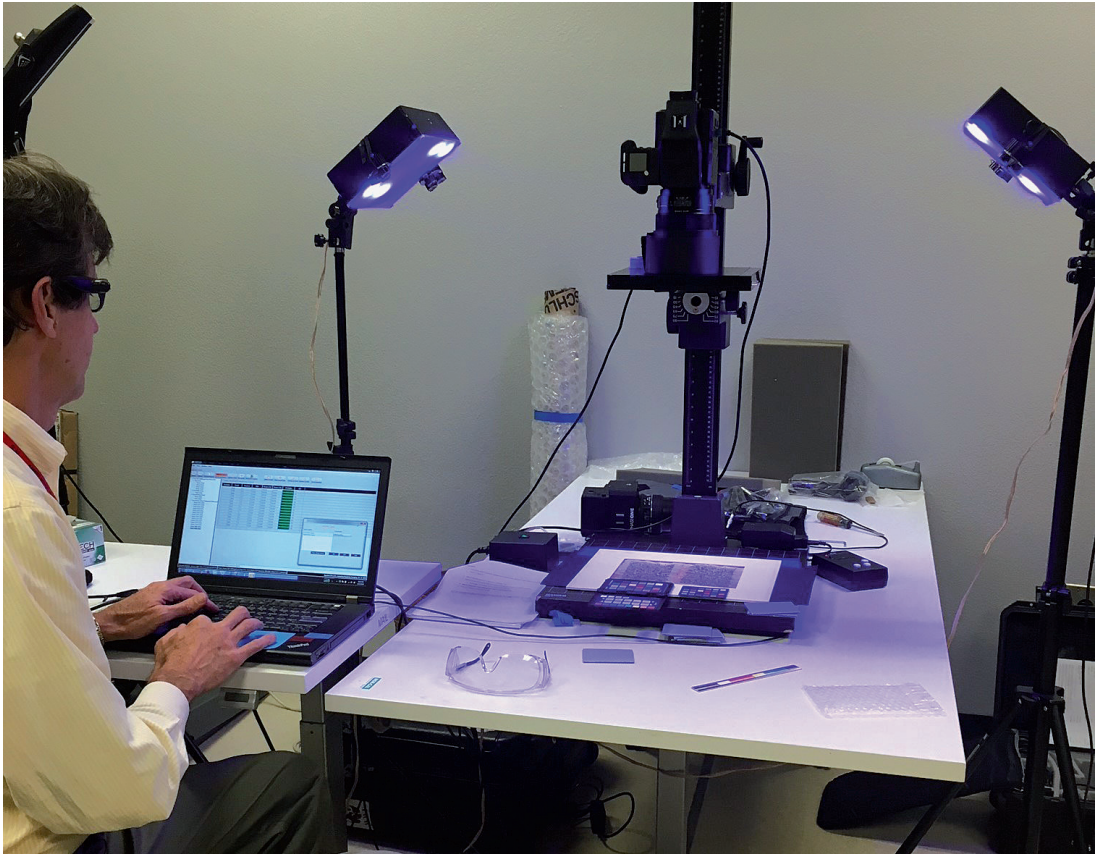


Fig. 4: Multispectral imaging the SGP at Stanford University Library (© R.B. Toth Associates)



Fig. 5: SGP bifolio mounted on translation stage in SLAC SSRL beamline hutch (© R.B. Toth Associates)

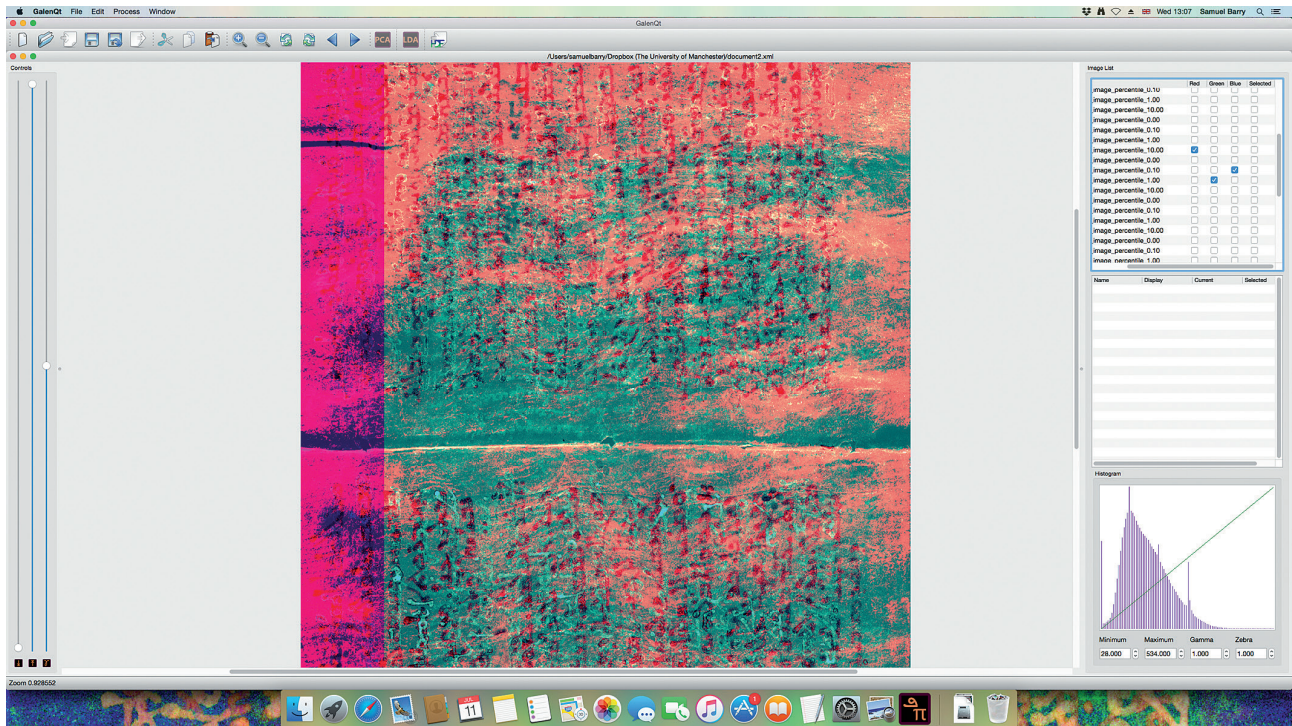


Fig. 6: (B&W) Galen QT software revealing elemental map of SGP undertext (© William Sellers)

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