https://doi.org/10.2352/issn.2168-3204.2020.1.0.33

Integrating Advanced Imaging of Ancient Manuscripts

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Abstract

Archives, libraries, and commercial firms are utilizing new advanced imaging methods for research into cultural heritage objects. New technical systems, including the latest multispectral (MSI) and x-ray fluorescence (XRF) imaging systems and higher resolution cameras raise major challenges for not only the integration of new technologies, but also the ability to store, manage and access large amounts of data in archives and libraries. Recent advanced imaging of ancient Syriac palimpsests (parchment manuscripts with hidden texts embedded within them) demonstrated an approach that utilized multiple imaging techniques and integration and analysis of data from multiple sources. Three palimpsest imaging projects (Archimedes Palimpsest, Syriac Galen Palimpsest, HMML Palimpsest) supported research with a range of advanced imaging techniques with MSI and XRF, requiring implementation and standardization of new digitization and data management practices for the integration, preservation and sharing of advanced image data.

Manuscripts and Imaging Methods

Palimpsests are parchment manuscripts that contain original undertexts that were removed but remain embedded within the book's sheet material. Scribes recycled earlier parchment pages by mechanically scraping or "chemically" scrubbing off undertext ink to create sheets that could be reused for scribing new manuscripts. These ancient parchments were sometimes used more than once, creating two layers of undertext or a double palimpsest. The challenge to scholars and scientists has always been how to reveal these texts, hidden beneath the surface. Just as challenging is how to archive the complex sets of advanced digital imaging data so they can be accessed and preserved – a decision that must be addressed in the early stages of such projects.

Scientists and scholars have been working collaboratively on advanced imaging techniques using multiple energy levels to read scraped and scrubbed-off palimpsest underwriting. The pioneering imaging and data management for such projects began twenty years ago with the Archimedes Palimpsest project [1] and continues today. Two separate projects involving palimpsests with Syriac underwriting/s have recently advanced this work. These include Saint John's University SJU Ms Frag 32 at the Hill Museum and Manuscript Library (the HMML Palimpsest) - a single leaf in medieval Georgian written over two scrubbed-off ancient Syriac undertexts - and the privately-owned Syriac Galen Palimpsest (SGP), a codex containing medieval prayers in Syriac over scrubbed-off early medical Syriac texts by Galen. Identifying and reading the contents in each palimpsest has required the application of ever more advanced imaging technologies using different energy levels, in conjunction with integrated methods and standards for data management, storage and access.[2]

Each of these two palimpsests represents similar textual traditions with complementary technical challenges. Even when the undertext/s are not visible to the naked eye, traces of the ink can remain in the parchment sheet, bonded to the collagen and proteins in the skin.[3] The surface of each of these manuscripts appears to have been treated with a coating high in calcium, which interfered with optical imaging of the underwriting. When the limits of multispectral imaging (MSI) were reached, higher energy levels proved productive with x-ray fluorescence (XRF) imaging to provide researchers with more information about the underwriting.

The HMML Palimpsest is a "double palimpsest," containing two layers of early writing–both in Syriac–dating to the sixth and the seventh/eighth centuries. Both undertexts are parallel to the tenth-century Georgian overtext written on top–not perpendicular as with many other palimpsests–adding complexity to the imaging and digital processing. Traces of the seventh/eighth-century Syriac undertext are visible to the naked eye (Fig. 1).

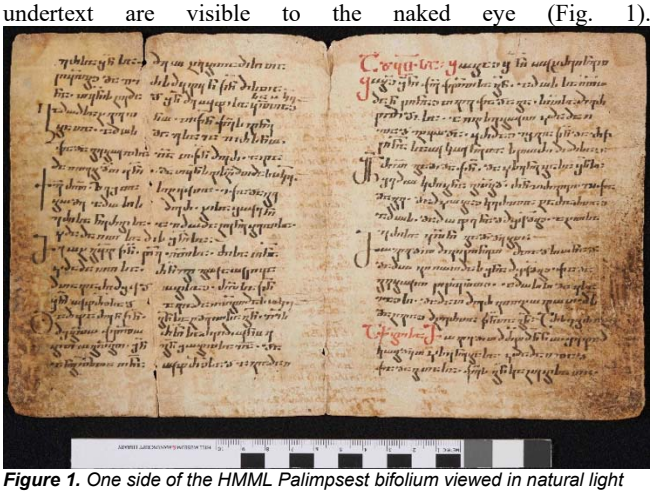

Figure 1. *One side of the HMML Palimpsest bifolium viewed in natural light*

Narrowband multispectral imaging of the fragment, carried out by R.B. Toth Associates in September 2018, revealed significant portions of the later Syriac undertext, as well as the first indications of the even older sixth-century undertext (Fig. 2).

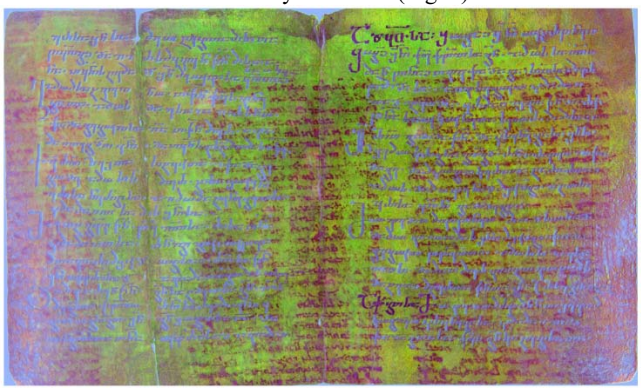

Figure 2. *HMML Palimpsest bifolium side with MSI-processed pseudocolor*

Even after multispectral imaging with the latest generation of lights and 100 Megapixel (MP) camera, the illegible regions were still large enough that establishing a string of connected text proved impossible. This situation made XRF imaging a promising option and it was XRF raster scanned in January 2020 in an x-ray synchrotron by a team of scholars and imaging scientists, assembled by Mike Toth of R.B. Toth Associates and Uwe Bergmann at Stanford University.

For the past decade, another palimpsest–the Syriac Galen Palimpsest–has been the subject of interdisciplinary collaboration between scholars and technical experts since its initial MSI imaging in 2009. The initial multispectral imaging of the disbound SGP in 2010 with a lower-resolution system allowed scholars to identify the Syriac text as Galen's medical treatise *On Simple Drugs* and read many passages of text. The subsequent discovery and multispectral imaging with portable imaging systems of additional folios dispersed in other institutions offered more insights into the original manuscript. Further imaging was required to uncover more of the undertext to allow scholars to identify and read this important medical treatise. This included re-imaging the SGP at Stanford with more advanced MSI systems by R.B. Toth Associates and scanning using XRF. To reveal the Galen underwriting for online study, folios of interest to scholars were imaged with an enhanced multispectral imaging system in 2016 and 2018, as well as XRF imaging on an x-ray synchrotron in 2018 and 2019.

With these complementary tools, narrowband MSI and XRF imaging combined with digital processing contributed quality images of the undertext in both palimpsests. This is supported by data administration and management to ensure the preservation and sharing of the advanced image data online. This advanced imaging and digital image processing highlighted advances in technologies available for manuscript research and provided scholars with additional data needed to identify and read the Syriac undertext. Data management and administration are supporting the addition of new image data to the existing SGP online data set at digitalgalen.net and to the HMML Palimpsest project.

Imaging Technology: Multispectral Imaging

With narrowband multispectral imaging, the imaging team illuminated the unbound and matted palimpsested manuscript folios using multiple narrow wavelengths of light, from ultraviolet through the visible and into the infrared spectra (Fig. 3).

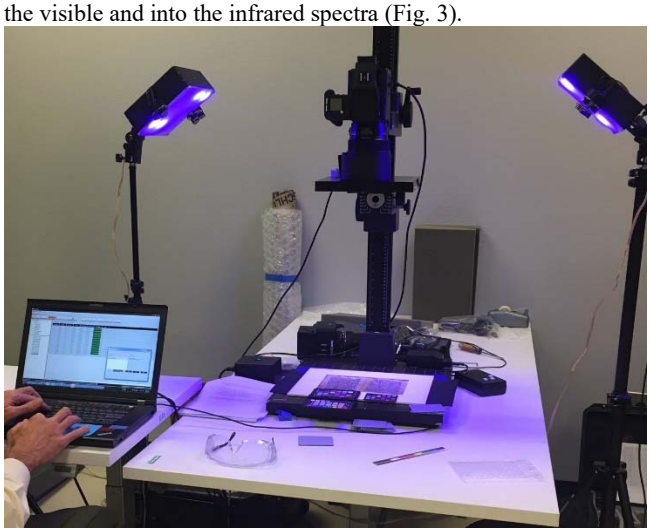

Figure 3. *Narrowband Multispectral Imaging the SGP at Stanford University*

With narrowband multispectral imaging, each wavelength of light interacts differently with the manuscript surface, revealing a range of details that can enhance visibility of parchment, inks, pigments and stains. The imaging team for these palimpsests captured "stacks" of registered images with a Phase One 100 achromatic 100MP camera system (Fig 4). In addition to imaging with narrowband reflected light and no filters, the system also captured a series of images with filters to capture only the weak fluorescence from the parchment. The advanced CMOS sensor with higher 100MP resolution significantly increased efficiency with higher light sensitivity up to ISO 800, allowing shorter exposures for these images with minimal loss of quality.

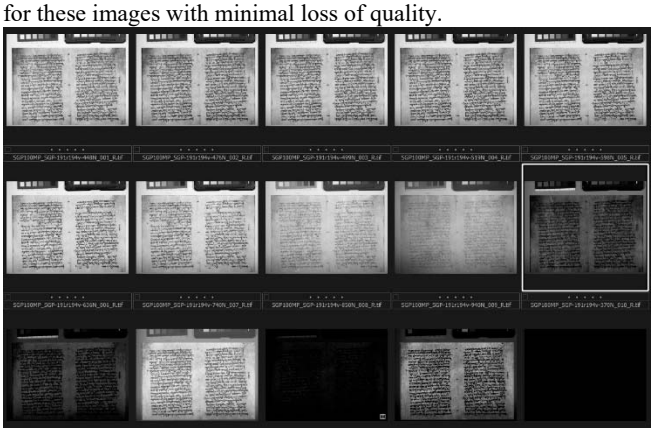

Figure 4. *"Stack" of narrowband multispectral monochrome images of the SGP*

The captured image cube of monochrome images was then digitally processed with tailored open source imaging software to form processed and pseudocolor images to reveal details not visible to the naked eye. The resulting image data were saved as TIFF files for processing and research. Efficient post-processing of the image stacks proved critical to fully exploiting the full potential of the integrated stacks of multispectral images from each of the palimpsests. This processing allowed researchers to visualize text and residues that could not be seen in individual images (Fig. 5).

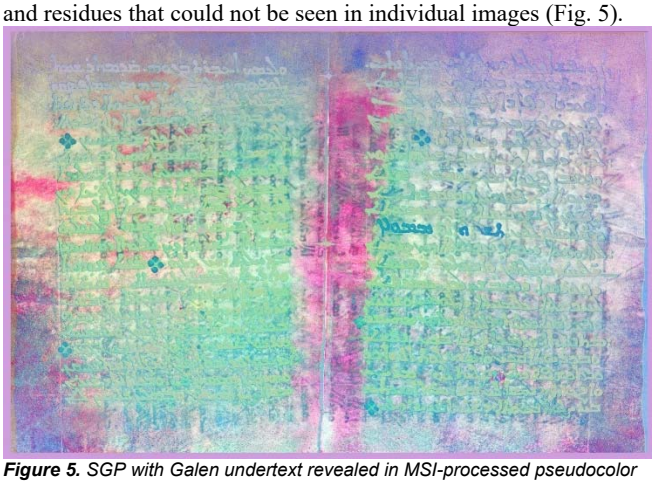

Figure 5. *SGP with Galen undertext revealed in MSI-processed pseudocolor*

Both technical and non-technical personnel could accomplish this image processing with open-source software built on ImageJ, a Java-based open source image processing software developed by the US National Institutes of Health. This efficient multispectral image processing with automated tools was dependent on a standardized

file structure and naming conventions for the captured images. Use of this automated spectral imaging toolkit created for cultural heritage imaging provided researchers with the ability to immediately process images, as well as later processing as part of their research. This includes push-button application of various image processing mathematical analyses, without requiring knowledge of the statistical routines. Researchers could combine and enhance spectral responses from the stacks of images, and then produce images in greyscale or pseudocolor for better visualization.

For both the Syriac Galen and HMML palimpsests, calcium carbonate on the surface of the parchment sheet obscured the imaging results, necessitating further imaging using XRF.

Imaging Technology: X-ray Fluorescence Imaging

X-ray fluorescence (XRF) imaging uses a high-powered x-ray source to cause elements in an object to emit x-ray energy. Capturing and mapping this x-ray response from elements that make up the ink in manuscripts allows the residues of iron gall ink in the parchment (including iron as well as zinc, copper and others) to be identified and differentiated from the layer of calcium that obscures the optical response in multispectral imaging. XRF imaging of these palimpsests was conducted on the Stanford Synchrotron Radiation Lightsource (SSRL) as part of fundamental research at the SLAC National Accelerator Laboratory, a multi-program national laboratory user facility operated for the US Department of Energy by Stanford University. Both the SPG and HMML Palimpsest projects build on methodologies employed during the Archimedes Palimpsest program, and use some of the same techniques and the metadata extensions developed during the Archimedes Palimpsest XRF imaging at SSRL that have since been refined.[4]

XRF imaging at SLAC national lab took place on Beamlines 6-2 and 10-2, which are wiggler end-stations that are used for hard x-ray imaging on the SSRL SPEAR3 3-GeV, high-brightness third-generation storage ring operating at 500 mA. The individual palimpsest leaves were fitted into standard size, conservation-safe mats. Each leaf in its mat then fit into a holding mount (Fig. 6) positioned at 45° to the 100µm X-ray beam.

Figure 6. *SSRL XRF scanning setup (x-ray beam from right) for the HMML Palimpsest being adjusted by Distinguished Staff Scientist Uwe Bergmann*

The mount with the matted leaf in it was attached to a motorized stage that moved the palimpsest leaf in front of the beam to capture a raster scan of the entire leaf or region of interest. Multiple Vortex detectors each collected the XRF signals of multiple elements in the palimpsests, including from the inks.

The XRF image data from the SGP and HMML Palimpsest projects were collected and stored at SSRL as Hierarchical Data Format version 5 (HDF5) data files. The interdisciplinary team collected multiple channels of data, with the metadata elements defined in documents from each of the imaging sessions. For the Syriac Galen Palimpsest project, the University of Manchester converted the HDF5 data into TIFF images for each element map for archival storage and preservation, and the HMML HDF5 data was converted to TIFF on site. These TIFF images provide the digital XRF image data in the standardized data set for broad access, research, and digital preservation.

The resulting XRF image data was processed using image processing software and specialized XRF analysis tools to build images for scholars to study (Fig. 7). The latter include a data-processing toolkit for x-ray microprobes: Sam [Webb]'s Microprobe Analysis Kit (SMAK). This was used to view and analyze images both for textual analysis and in real time during imaging to improve the imaging methods and techniques. The resulting images are "snapshots" drawn from a specific configuration of the data, meant to enhance certain features of the manuscript (for example, ink) using assigned pseudocolors, and diminish other features that would obscure a clear reading of the text. This means that as long as the data is stable and available, there are an infinite number of possible configurations available for visualization and study.

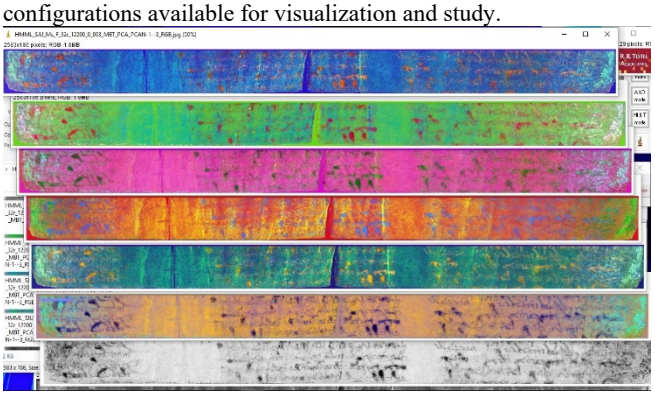

Figure 7. *Pseudocolor images of elemental XRF scans of the HMML Palimpsest at the SSRL Synchrotron*

Imaging Results

Each imaging project presents its own set of challenges. Solving these data and processing challenges further enhances access, sharing and future study of these and similar texts. Twenty years ago, at the start of the Archimedes Palimpsest program, very little was known about the material characteristics of parchment and its fluorescence - its ability to absorb short wavelengths and reflect long wavelengths of light. Little was also understood about the specific characteristics of different inks and parchment preparation from various ancient manuscript traditions. For example, the parchment preparation in the Syriac tradition often left a layer of calcium on the surface, which can obscure modern imaging of the writing. It is understood that Syriac scribes used a "chemical" method of erasing manuscript texts when they wanted to reuse parchment. This involved creating weak acidic liquid preparations

containing milk or lemon juice or conversely an alkaline wash (containing calcium hydroxide). The preparation, which made the iron gall ink soluble, allowed the surface ink to be partially or fully washed away.[5] The parchment sheet could then be recoated with a white calcium carbonate wash, for use in creating a new manuscript. These scrubbing/washing and recoating techniques can obscure MSI images of earlier palimpsest layers in Syriac manuscripts, necessitating more advanced imaging using XRF.

Advanced imaging at different energy levels, including light and x-ray, has increased understanding of the material properties of various parchments, residues and inks, allowing researchers to be better informed about palimpsest imaging and better manipulate and refine the visualization of embedded texts. In particular, open source machine learning tools developed by Equipoise Imaging and the University of Manchester produce images that better identify and display the underwriting. The former is a plug-in to the medical ImageJ digital processing tool used for Principal Component Analysis of the spectral responses in stacks of narrowband multispectral images. The latter is a Machine Learning tool developed to conduct Canonical Variates Analysis with scholarly system training and supervision.[6] Both tools digitally process the TIFF images from multispectral and/or XRF imaging. The combination of MSI and XRF imaging have allowed independent teams of researchers to identify and read more of Galen's medical text and the texts in the HMML Palimpsest. This imaging of the Syriac Galen Palimpsest offers new information about not only ancient medicine, such as the use of herbals, but also the role of Syriac in the transmission of Western thought to the Islamic world. MSI and XRF images have been used to support multiple workshops and conferences, in which scholars have worked together and presented their findings on the Syriac underwriting of Galen's *On Simple Drugs*.[7] The more recent advanced imaging of the HMML Palimpsest offers similar potential for new insights into the multiple texts.

It is instructive to compare the results of the multispectral and XRF imaging of the HMML Palimpsest. The processed MSI images revealed much more of the later Syriac undertext than had previously been visible when viewing it with the naked eye. Legible portions of the processed MSI images typically consisted of from one to three words, and no more than five words, per line. The initial reading permitted an approximate dating of the text to between the sixth and eighth centuries based on paleographic analysis of the Estrangela script. This is quite early, making the fragment among only approximately 70 dated Syriac manuscripts known to exist from between the sixth and eighth centuries.[8] The multispectral images of the back of the leaf also revealed traces of an even earlier undertext, which could not be detected with the naked eye, in the lower half of the center (gutter) portion. Preliminary paleographic analysis of these traces suggested a date between the fifth and sixth centuries, a period from which only 47 dated Syriac manuscripts survive.[9] However, due to the layer of calcium on both sides of the parchment, as well as dirt deposits on the lower outside corners and interference from the parallel overwriting, it was still impossible to identify a complete sentence or to secure a positive match with a known Syriac text using MSI. In addition, the extent of the earlier undertext remained unknown.

The XRF imaging revealed portions of the later Syriac undertext beneath the dirt deposits on the lower outside corners. This permitted the reading of connected text in the lower right portion of the front of the sheet. Also, the earlier undertext was evident on the entire surface on both sides of the parchment, in some cases as shadowing against the fluorescence of the calcium on the sheet. The more extensive view of the earlier undertext allowed a more precise paleographic dating to the late sixth century, which in turn narrows the dating of the later undertext to the seventh century at the earliest.[10] The analysis of the XRF images to identify both Syriac undertexts in the HMML Palimpsest is still underway.

In the same way, the multispectral imaging of the SGP enabled researchers to identify the undertext on most of the leaves. After the advanced 100MP MSI, the Galen undertext in three leaves still could not be identified, and others were still difficult to read. The MSI and XRF processed images allowed the international team of scholars to identify and read additional leaves with online collaboration. Their research continues to draw new conclusions from the text and its relationship with other know Galenic texts.

Data Management and Open Access

Advanced imaging, whether multispectral or XRF, generates large amounts of data. This poses challenges in the storage, transfer and conversion of data and metadata for research, especially in institutions without robust information management infrastructure and support. Management of the data from this advanced digital imaging builds on work processes and standards utilized for prior multispectral and XRF imaging, starting with the Archimedes Palimpsest program.[11] The multispectral imaging data management pioneered on that program has been refined with the integration of mature camera systems, operating software, and processing and management tools to provide TIFF images in a standard file format. The XRF data management has been optimized by SSRL to provide both elemental HDF5 data sets as well as TIFF images of each data set. Both multispectral and XRF imaging continue to produce numerous, large image files, requiring sufficient storage and data transfer throughput.

All the imaging data and metadata for these manuscripts are or will be hosted on public servers as TIFF images for further review and research. The multispectral and XRF image data from SJU Ms Frag 32, the HMML Palimpsest, will be on vHMML.org as JPEGs, in addition to the current natural light images.[12] Downloadable TIFF images will also be available on a separate HMML site and/or hosted on the University of Pennsylvania Library's OPenn site. All data from the SGP is currently hosted under Creative Commons license on OPenn (Fig. 8).[13] The SGP advanced 100MP MSI and XRF image data and metadata were added after completion of the original multispectral imaging program, so this was included in the *Contributed Research* data folder, not integrated with the core data set.[14]

Figure 8. *SGP data, with XRF and advanced 100MP MSI, in ResearchContrib folder at digitalgalen.net on OPenn*

Making all captured and processed data and metadata from both palimpsests available digitally for free access allows scholars to use increasingly advanced imaging software and tools to process and re-process the images. Open access hosting also enhances the preservation of the data. TIFF image data is preserved as an established and much-used image standard for access as a digital entity not dependent on specific viewers, software, or web applications that could promote obsolescence. Establishing shared digital preservation standards is key to the long-term success of these projects and the future of the field. This involves careful definition and planning of the online storage environment, data formats, standards, data migration and conversion. The digital preservation of these projects builds upon the standards and practices of the Archimedes Palimpsest program, including the Archimedes Palimpsest metadata standard,[15] with defined XRF extensions.[16] These are currently being reviewed and revised by a working group of institutions using multispectral imaging systems. Use of common standards will support broader sharing, access and visibility of the data and metadata from advanced imaging in libraries and archives around the globe. In turn, these will also support interoperability, integration and visualization of the data across institutions and disciplines.

Conclusions

The development of methodologies for implementing and managing advanced imaging, integrating new technologies and data, and supporting advanced digital products has contributed to manuscript and textual studies, engineering and the sciences. They also highlight some of the benefits of public-private partnerships between institutions, government labs and industry in support of the humanities for open access and preservation. The interdisciplinary work of collecting, processing, accessing, archiving and collaborating with digital data from the various imaging technologies (MSI, XRF and others) has enabled better imaging of cultural heritage objects with refined guidelines and standards for best practices in data management, access and storage.

Further development of a suite of computer analysis tools, such as a standard toolbox to process MSI and XRF data, can support researchers as they enhance and refine their imaged data and interpret hidden texts and other features in the manuscripts more effectively on their own. New machine learning tools will enhance this data processing. This allows imaging technology to be available to more scientists and scholars, supporting more research into a larger numbers of hidden texts. With international consensus standards, these and other complex data sets from multispectral, XRF and other advanced imaging can be readily archived to ensure their preservation and sharing for and by future generations.

Acknowledgements

The successes of these imaging projects were only possible with the expertise and dedication of interdisciplinary teams. Each of them contributed to these projects with their own unique skills: scholars, conservators, scientists, engineers, librarians, curators, data administrators, managers and others. Research and open access to the Syriac Galen Palimpsest was only possible with the support of the owner. For the Syriac Galen and HMML Palimpsest projects, multispectral imaging was provided by R.B. Toth Associates with Equipoise Imaging, supported by UCL PhD student Cerys Jones.

XRF imaging at SLAC/SSRL relied on the dedicated around-the-clock support of Uwe Bergmann, Nicholas P. Edwards and Sam M. Webb, Beam Operators and many others, with conservation guidance from Kristen St. John at the Stanford University Libraries. The use of the Stanford Synchrotron Radiation Lightsource, SLAC National Accelerator Laboratory, is supported by the US Department of Energy, Office of Science, Office of Basic Energy Sciences, under contract no. DE-AC02-76SF00515.

For the HMML Palimpsest, Hill Museum & Manuscript Library staff Melissa Moreton, Wayne Torborg and David Calabro provided logistics, data management and scholarly analysis of the Palimpsest's texts. Researchers Natia Dundua and Cici Guledani identified the tenth-century Georgian text in what was originally described as a seventeenth-century Armenian fragment. HMML's Curator of Western Collections/ Rare Books and Manuscripts, Matthew Heintzelman, was the first to recognize the fragment as a palimpsest, then identified as Syriac by HMML Executive Director Columba Stewart.

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Author Biography

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