Imaging the past: recent applications of multispectral imaging technology to deciphering manuscripts

Douglas M. Chabries, Steven W. Booras[1] & Gregory H. Bearman[2]

Multi-spectral imaging (MSI), which was developed to explore the surface of the earth and other planets from space, has been adapted to read and record faded or burnt manuscripts. The authors show how MSI achieved new readings from carbonised and damaged fragments of papyrus scrolls from Herculaneum, Petra and the Judean Desert. The method has potential for investigating the degraded ornamental surfaces of other artefacts.

Keywords: multispectral imaging, ancient-text imaging, scrolls

Intriguing new digital imaging technology is unveiling previously illegible and even unseen text on ancient manuscripts recovered from caves near the Dead Sea, the ashes of Vesuvius, and the ruins of Petra. Known as multispectral imaging (MSI), the technology has outperformed conventional photographic techniques in many applications, capturing images that are shedding new light on history. This initial success at producing superior textual images of fragile, deteriorating antiquities – and electronically preserving those images for future study and appreciation – has attracted widespread interest and bodes well for the continued use of MSI technology in archaeological fieldwork.

This article outlines the development of MSI, describes its advantages over both black-and-white and infrared photography, and reviews the exciting results of its recent applications to fragments of the Dead Sea Scrolls and to the carbonised scrolls of Petra and Herculaneum.

Development of multispectral imaging

Space exploration has been a rich source of spin-off technologies for terrestrial applications as diverse as robotics, biomedicine, and material science. So it may come as no surprise that MSI, though inspired by techniques developed and first used for remote exploration of the solar system, has begun to significantly affect the study of the past and its artefacts.

Multispectral imaging was first applied in the LANDSAT series of satellites, whose imaging hardware used four or five spectral bands to capture images in either the visible or near-infrared ranges of the light spectrum (Elachi 1987: 104–10). Most of that instrumentation was designed for use on moving platforms such as spacecraft, satellites, and aircraft. In the early 1990s, a shift in NASA's planetary missions from large science payloads (thousands of

[1]*ISPART, Brigham Young University, USA*
[2]*ANE Image, Pasadena, California, USA*

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kilograms) to small ones (up to 100 kilograms) required the development of smaller instruments that retained the same science capability as before.

One result was that new imaging spectrometers (sophisticated multispectral imagers) were developed that did not require motion for image acquisition. This advance allowed MSI technology to be used in other areas; for example, multispectral image detectors can now be mounted on a microscope for biological study or on a fundus camera for medical examination or, in our case, taken into the field or a museum for archaeological imaging.

In contrast to remote sensing from space at hundreds of kilometres, archaeological MSI is typically performed at close range (measured in tens and hundreds of centimetres) in makeshift laboratories in settings that vary from humid jungles and caves to museums and conservatories in faraway lands.

Advantages over conventional photography

By responding to ultraviolet and infrared light, the image detectors in multispectral cameras reveal information that is concealed from the human eye. Multispectral imaging[1] (see technical note at the end) divides that portion of the light spectrum into a number of frequency bands and records each of the images separately, typically as a set of monochrome images. Multiple images of the same scene, each viewed at different wavelengths, form a multispectral image cube. This data cube can then be processed to extract information related to spectral differences of the images within the cube (see Figure 1).

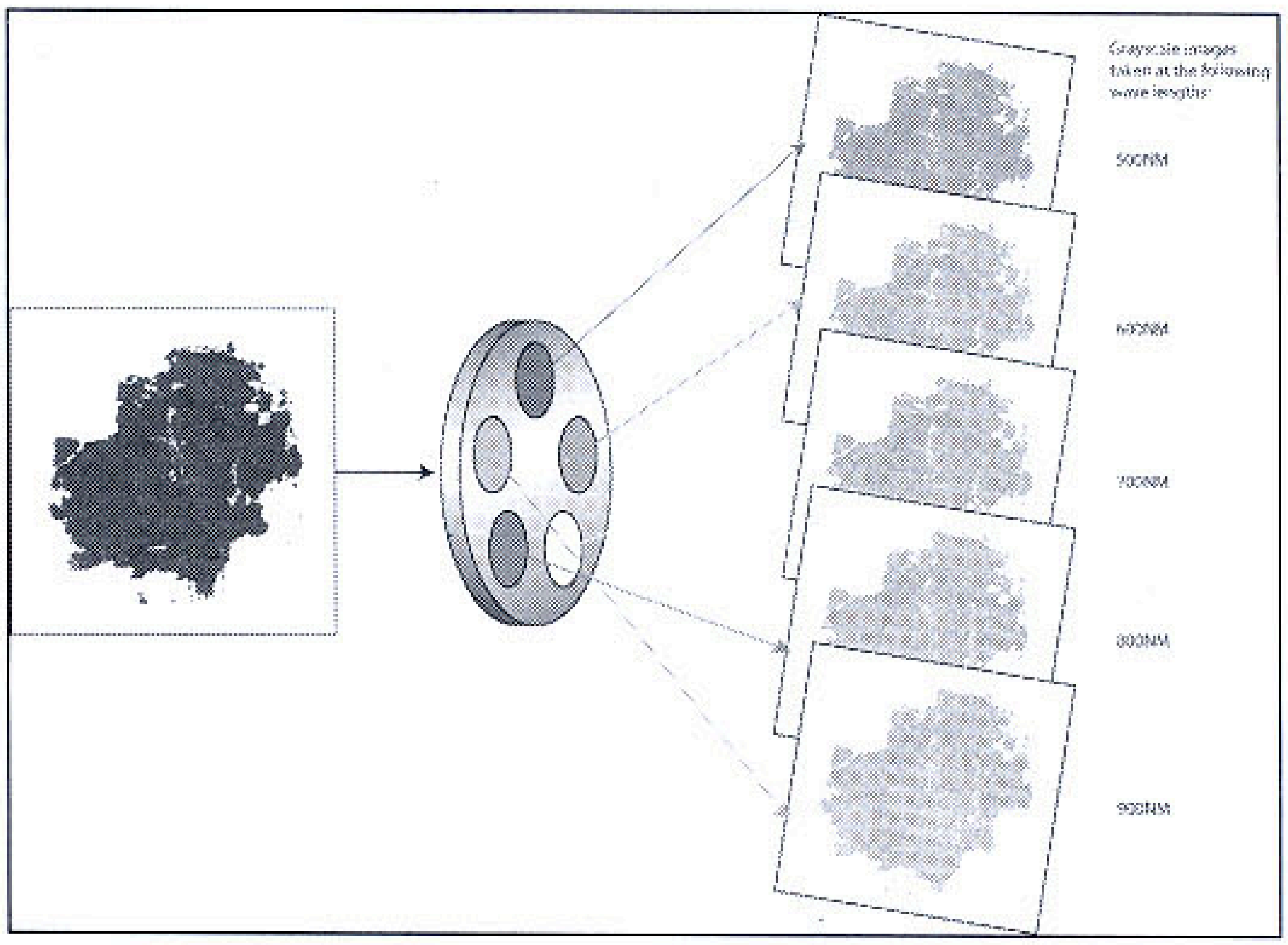

Figure 1 The formation of an image cube by filtering an original image through selective bandpass optical filters. These filters typically range from the infrared through the ultraviolet light bands. For simplicity, this example shows only visible-light filters. (© The Institute for the Study and Preservation of Ancient Religious Texts/ BYU)

By contrast, colour pictures use a very reduced set of frequency bands operating over the spectrum of visible light to produce an image from cyan, magenta, and yellow image planes as shown in Figure 2. Multispectral imaging divides the same spectrum into multiple finer-image data sets and adds images from outside the visible light range. As a result, multispectral imaging produces a set of images with much more information than a single black-and-white or colour photograph. Examining these additional images, one can often see faint details emerge from the background at spectral locations where clutter disappears, ink becomes dark and the background light, or pigments appear. The quality of the response of a single point in an image (a picture cell, or pixel) is a function of the illuminating light frequency. Digitally recording of the image cubes as a

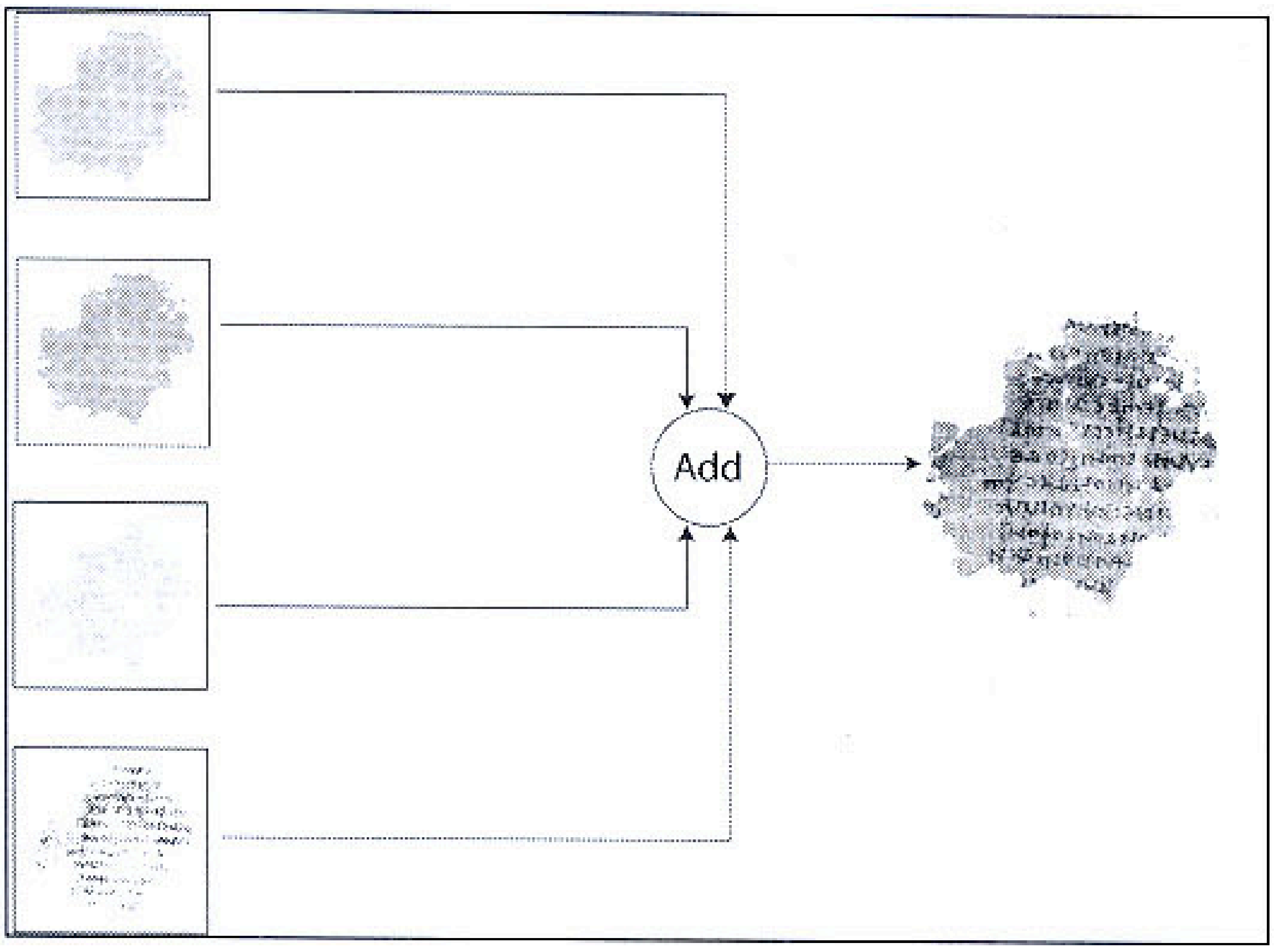

Figure 2 Reconstruction of a colour image from the cyan, magenta, and yellow image planes. (© The Institute for the Study and Preservation of Ancient Religious Texts/BYU)

collection of pixels provides data sets for comparison and later digital processing (for information on remote-sensing algorithms, see Jensen 1999) that yields pictures with significantly improved contrast.[2]

One might think that infrared photographic emulsions can eliminate the need for multispectral imaging in many applications. However, digital infrared imagery has four significant advantages over infrared photography. These advantages were critical in the applications outlined in this paper and can be summarised as follows:

1 MSI requires that image slices in the light spectrum be separately collected. This would suggest that, in the case of infrared film, several infrared images of the same scene would need to be gathered using different infrared bandpass filters. Using infrared film requires almost immediate processing to preserve the optimal image and to determine if the images are in focus. That involved procedure may be feasible when photographing a single object, but for a large collection, the logistics of imaging, developing, and reshooting bad images becomes an insurmountable hurdle.

2 High-fidelity imagery requires that each monochrome image of the multispectral image cube be refocused. For the infrared region this is especially critical. Conventional film does not allow direct observation of the fidelity of the focused image until the film is developed. As a result, traditional photographic techniques typically select a point in the midrange of the infrared film response to set a focus. This compromises the focus outside that region and the ability to make fine adjustments to the depth of field by adjusting the f-stop and exposure. The result is degraded imagery when using film.

3 The dynamic range of digital image sensors exceeds the dynamic range of infrared film, thereby allowing a single image to include more precise information, especially in the fog and saturation regions that correspond to film. Further, the ability to view digital infrared images instantaneously allows one to adjust the sensor response and ensure that the image falls within the expanded dynamic range of the sensor.

4 The spectral range of infrared film is limited to wavelengths below about 900 nm (at around 850 nm, the film's sensitivity to light begins to decrease significantly), while digital sensors extend beyond this limit to wavelengths of about 1100 nm.

Because of these advantages, digital MSI has been applied to some of the world's treasured artefacts with exciting results.

The Dead Sea Scrolls

The first time that imaging spectroscopy was applied to archaeological documents was on the Dead Sea Scrolls. Early work in 1993 and 1994 (Bearman *et al.* 1993, 1996: 56–66) demonstrated its usefulness and led to the development of an inexpensive near-infrared electronic imager (now in regular use at the Rockefeller Archaeological Museum in Jerusalem). That work also helped explain why infrared photography, which was routinely used for imaging ancient texts, was sometimes not effective in those applications. The practical success of imaging the Dead Sea Scrolls paved the way for imaging a variety of other ancient texts and objects.

Both infrared and ultraviolet photography were applied to imaging old and damaged documents almost as soon as illumination sources and films became available (Smith & Norman 1938: 179–207). Early experience with these methods showed that really old manuscripts (before the third century AD) generally responded well (i.e., became more legible) to infrared imaging, while documents of later date responded better to ultraviolet imaging. Thus it was natural to photograph the Dead Sea Scrolls (1947–56) with infrared film. In fact, the majority of the images that Scroll scholars use came from large-format (4 x 5") infrared negatives. What details are known of the original infrared photographing of the scrolls are summarised in Bearman, Pfann, and Spiro (1998: 473–9).

In the late 1980s West Semitic Research (owned and operated by Bruce and Ken Zuckerman) began experimenting with infrared photography in an attempt to improve its capability. Experiments involving a variety of filters yielded mixed results, underscoring the need for new techniques or technology. Progress was made in that direction with Greg Bearman's work of applying imaging spectroscopy to the Dead Sea Scrolls. A physicist at the Jet Propulsion Laboratory (operated by the California Institute of Technology for NASA), Bearman contacted the Ancient Biblical Manuscript Center (ABMC) in 1992 and suggested that imaging spectroscopy could not only increase understanding of the limits of infrared photography but also point the way to a sophisticated electronic imaging system.

Bearman proposed to use an all-electronic imaging system that could tune to any wavelength between 400 and 1100 nm, thus covering the visible and near-infrared part of the spectrum and going considerably beyond the sensitive wavelength of film. This system was developed in his laboratory as part of a program to create small and capable imaging systems for

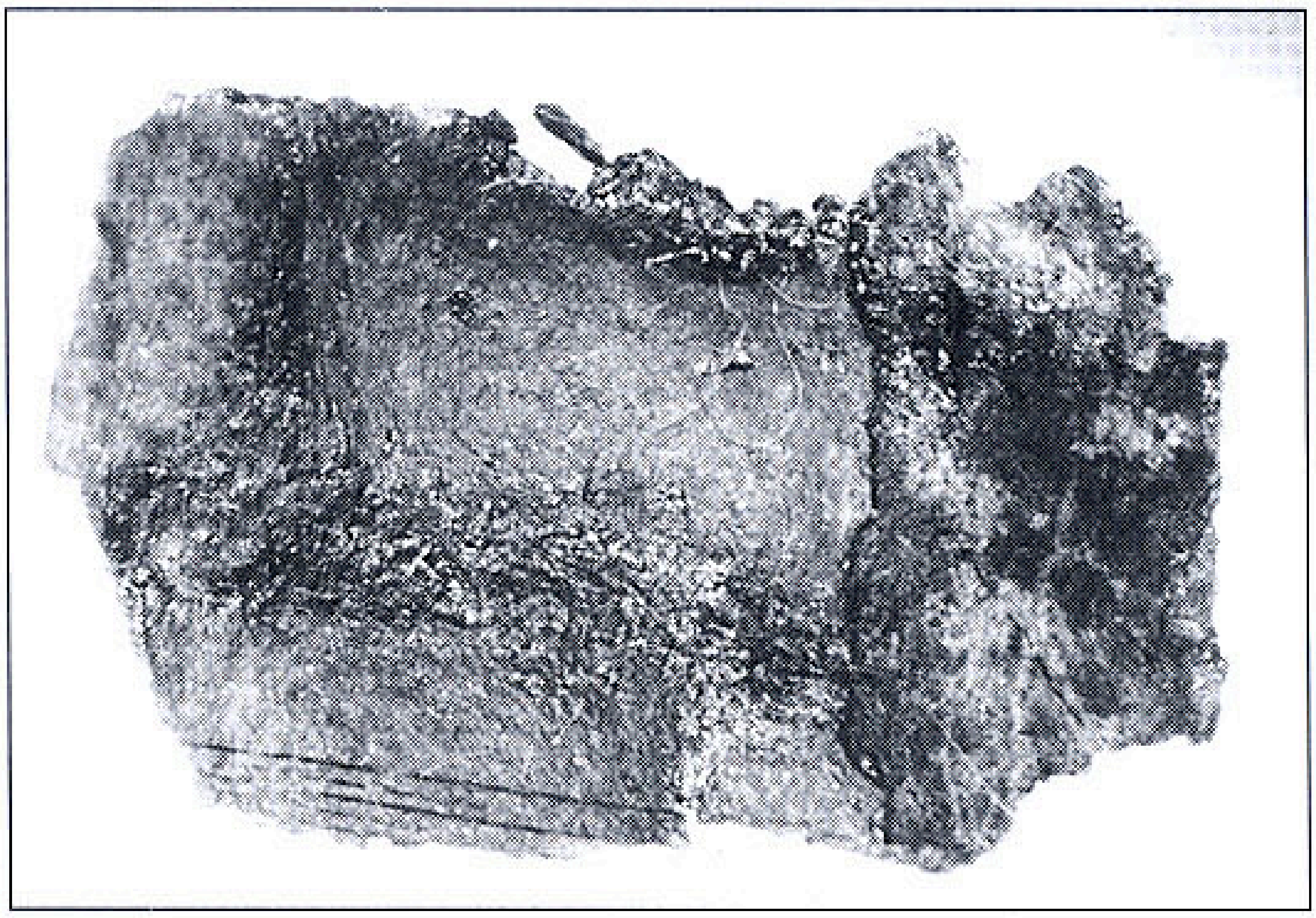

Figure 3a A conventional black-and-white photographic image of a fragment of the Dead Sea Scrolls text known as Genesis Apocryphon. This image used light in the visible part of the spectrum that the human eye can see. (By permission Gregory H. Bearman and The Ancient Biblical Manuscript Center)

planetary exploration. The imaging system featured an electro-optical device, specifically a liquid-crystal tunable filter (LCTF) (Faust, Bearman & Chrien 1995: 412–13) positioned in front of an imaging lens and electronic CCD camera. An LCTF can be thought of as a tunable bandpass filter that can be electronically commanded from a computer to any wavelength in its tuning range. In this case, the bandwidth was selected to be 15 nm.

Serendipitously, a small Dead Sea Scroll fragment from the Genesis Apocryphon was at the Getty Conservation Institute for study as to why it was deteriorating so rapidly. The institute loaned the fragment to the imaging team, and an image was digitally captured (see Figures 3a–c). Figure 3a is a visible-light monochrome photograph of the fragment, while Figure 3b shows the same fragment imaged with a simple CCD monochrome camera with the LCTF set to 970 nm. Note in Figure 3b the hint of another letter under a flap of parchment (from the inner roll of the scroll) that stuck to the fragment when the scroll was unrolled. At longer wavelengths there are no chromophores to absorb light and the scattering length

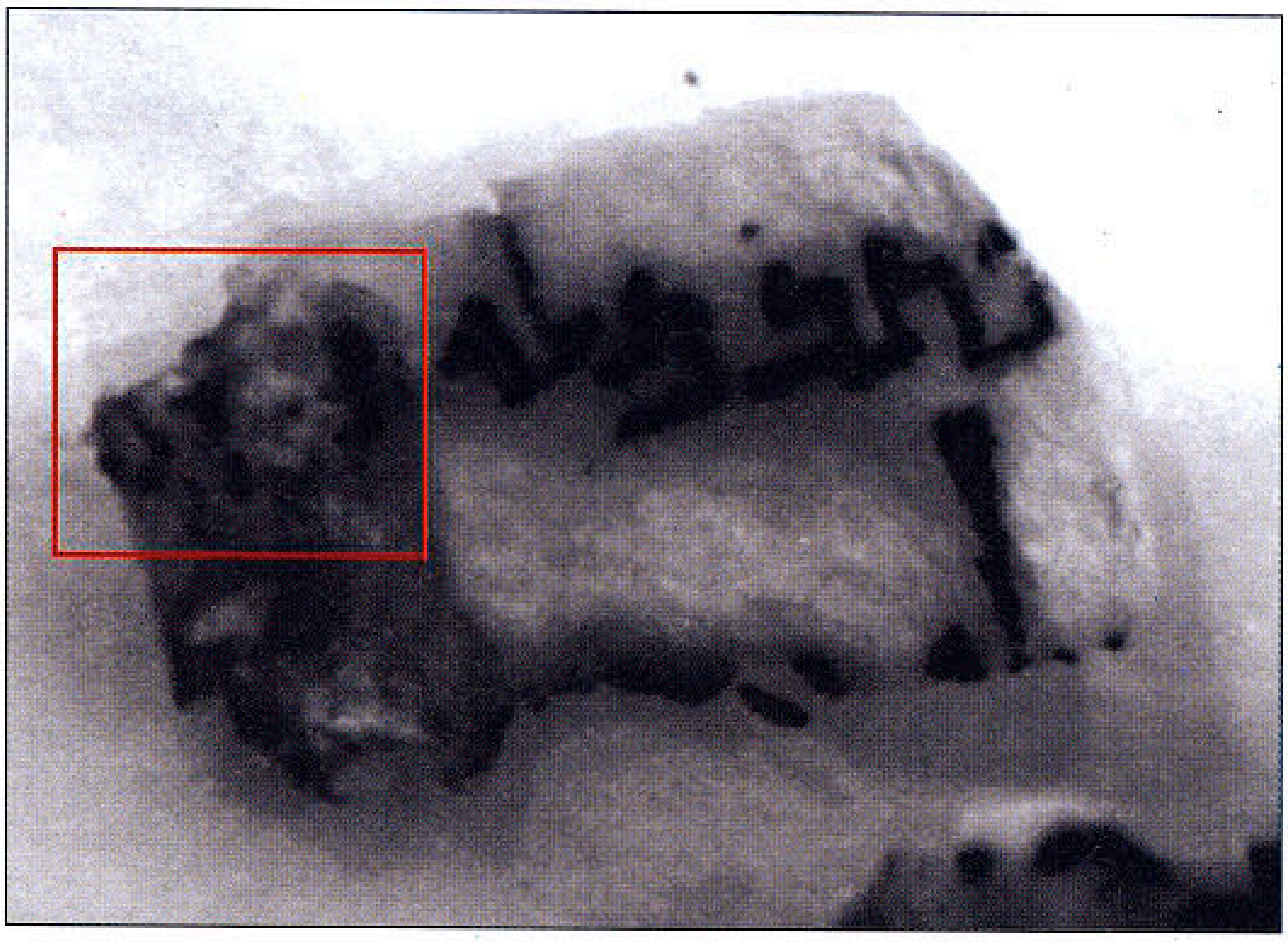

Figure 3b A digital image of the same fragment illuminated only with light between 890 nm (nanometers) and 1000 nm, far beyond the visual range of the human eye. The text clearly shows two words: כתב מלי. Although the script is Hebrew, the language is actually Aramaic, the lingua franca of the times. Inside the box on the left-hand side are hints of a third word that is covered by a piece of parchment that stuck to this fragment when the document was unrolled. (By permission Greg Bearman and The Ancient Biblical Manuscript Center)

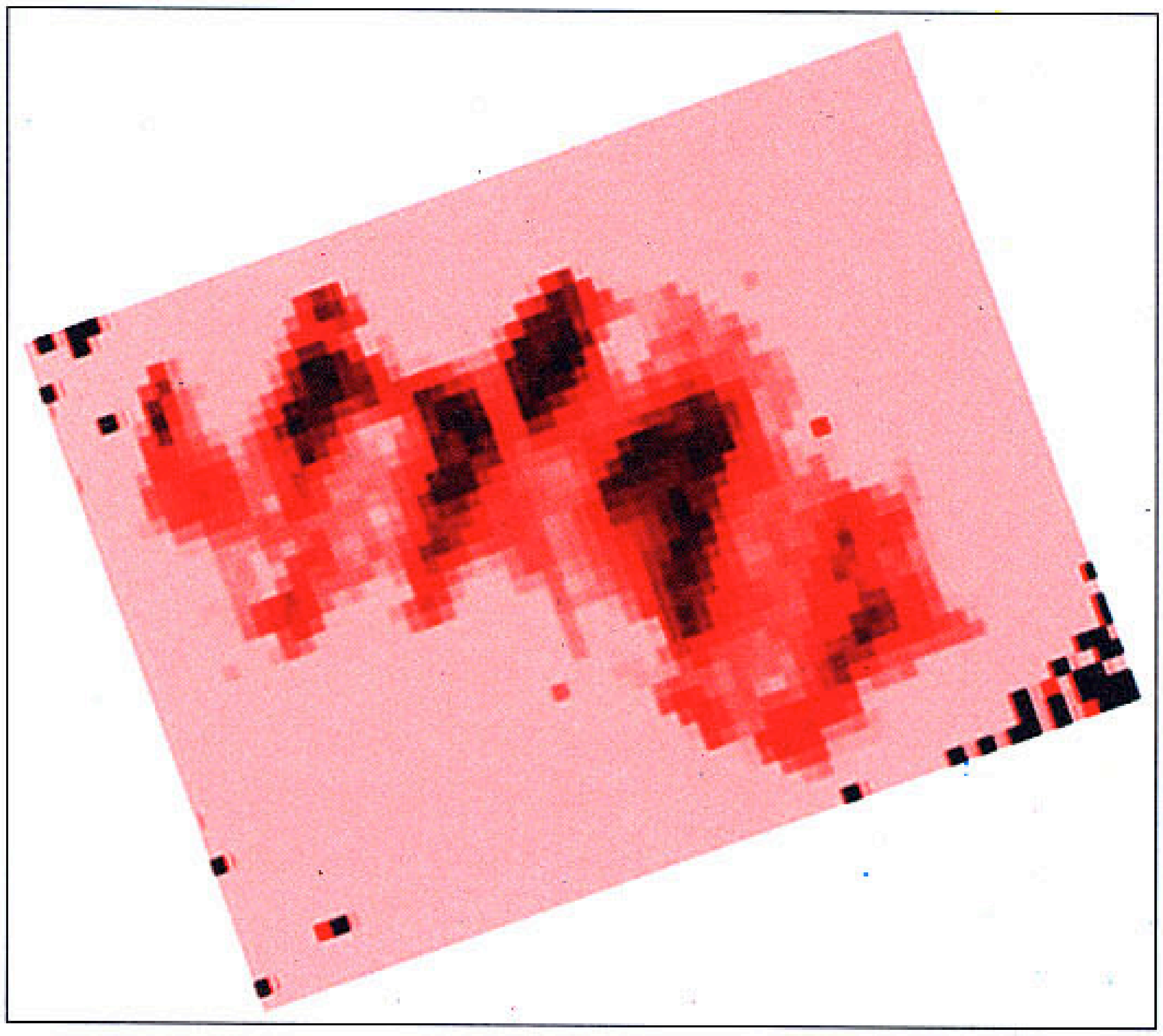

Figure 3c This is an image of the boxed area in figure 3b taken with an indium antimonide infrared camera. Because this camera is sensitive at longer wavelengths in the infrared range (1–3 microns), it can 'see' through the parchment flap to the letters underneath. The three letters, ןב, spell Noah, so depending on how one reads it, the complete text could be 'he wrote the words of Noah' or 'the writings of the words of Noah.' (By permission Greg Bearman and The Ancient Biblical Manuscript Center)

increases, so skin (human and animal) tends to become more transparent in the infrared. To exploit that fact, another infrared camera was used to image the parchment flap. This camera, sensitive to 1–3 µm (much further into the infrared spectrum than a CCD), revealed three more letters under the flap to complete the text, as shown in Figure 3c. The text now reads כתב מלי נו̬ ('he wrote the words of Noah' or 'the writings of the words of Noah'). The Qumran community used full spellings, so there is a ו in the name Noah.

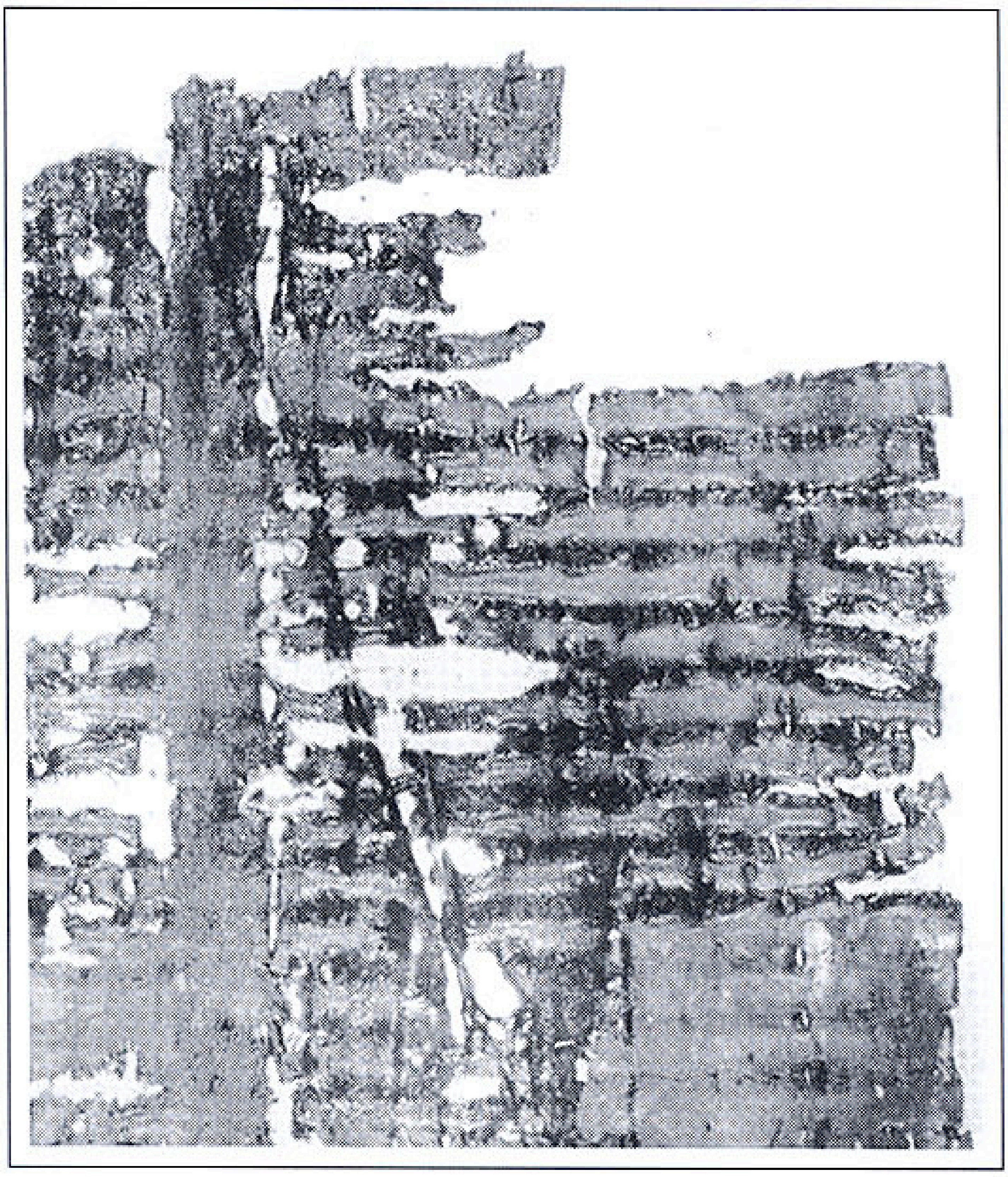

Figure 4a A visible-light monochrome photograph of the top of column 12 of the Genesis Apocryphon. (By permission Gregory H. Bearman and The Ancient Biblical Manuscript Center)

In summer 1994 an ABMC team spent a month in Jerusalem to image the entire *Genesis Apocryphon* and other documents (see Figures 4a–5b). The resulting digital infrared images – acquired entirely at 970 nm – were used in the recently published transcription and translation of the *Genesis Apocryphon* by Moshe Morgenstern and Elisha Qimron (1995: 30–54). These editors of the *Genesis Apocryphon* estimated that these images generated about 20 percent more text than what was available when we began the project. An important result of this project was the realisation that a full spectral cube of the Dead Sea Scrolls was not needed in order to obtain improved readings. Consequently, the ABMC designed and assembled an electronic digital imaging system that used a fixed 970 nm interference filter mounted directly above the camera sensor.

Figure 6 demonstrates how infrared imaging improves the text contrast – and thus the legibility – of the Dead Sea Scrolls. In the visible part of the light spectrum, the reflectivity of the ink is about the same as that of the parchment, so there is no image contrast. The situation is the same as the proverbial black cat at midnight – without contrast there is no image. As the wavelength increases, the parchment begins to reflect more than the ink does and the text contrast increases. The key is using the right filter to bring out that contrast. Imaging over the entire spectral range (as is done with a colour or black-and-white photo), however, washes out the desirable contrast because part of the signal comes from the spectral range where the ink and parchment have the same reflectivity. The chemistry behind the changes in the parchment reflectivity is not understood, but that does not prevent us from exploiting those changes.

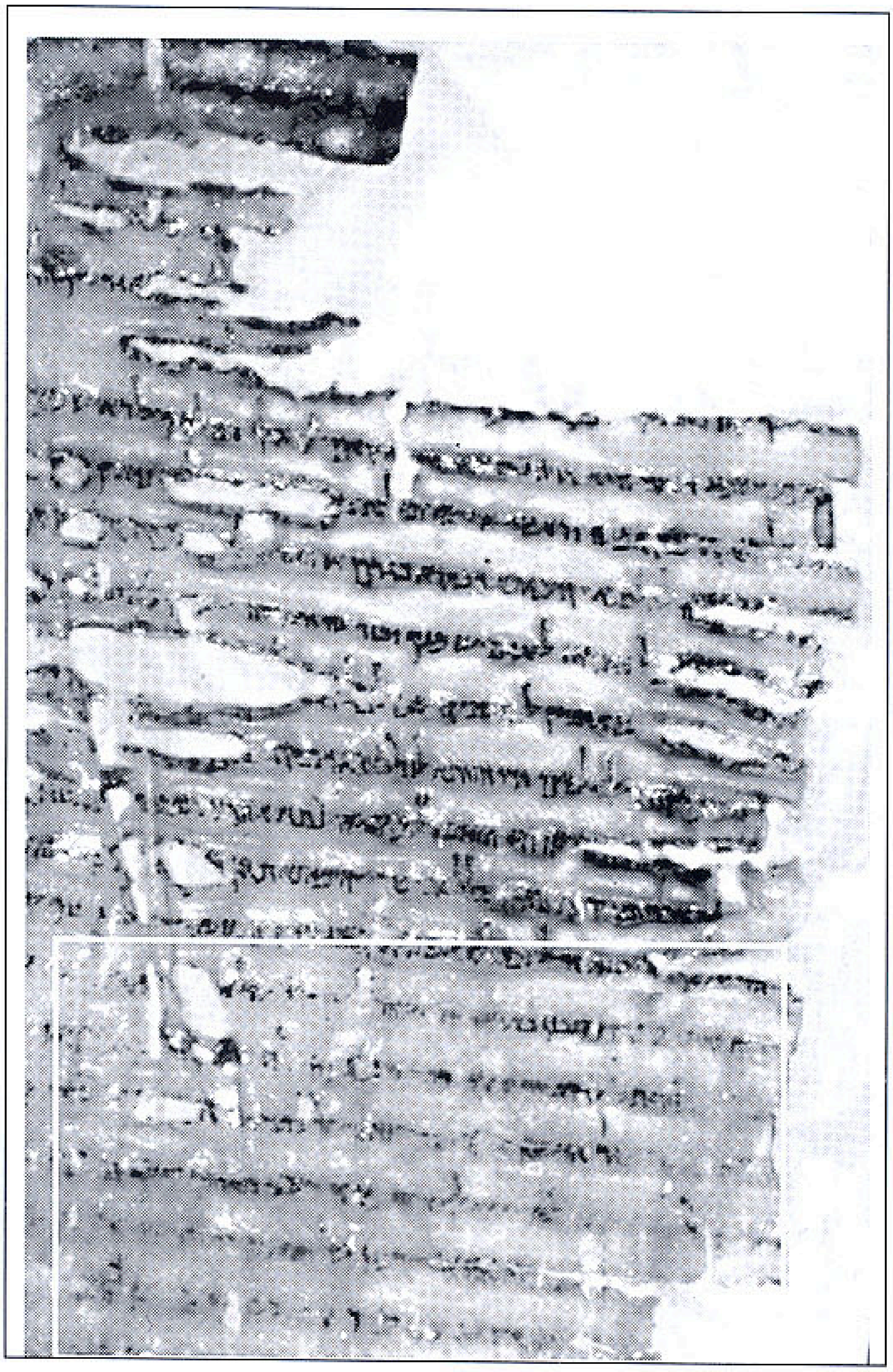

Figure 4b The same column imaged with a bandpass filter centered at 970 nm and with a bandwidth of 15 nm. The boxed area indicates where the editors located new text in this image. (By permission Gregory H. Bearman and The Ancient Biblical Manuscript Center)

One additional finding was that infrared imaging generally yields better results with carbon-based inks than with gallo-tannin inks. For the Dead Sea Scrolls, the ink is carbon black (from soot) originally suspended in some sort of liquid medium for writing. X-ray fluorescence has shown that the ink used on the Dead Sea Scrolls contains carbon almost exclusively and no iron, indicating that it is not a gallo-tannin ink (Ginnell 1993; Plenderleith 1950: 146; Nir-El & Broshi 1996: 157–67).

The Scrolls of Petra

The Petra scrolls – one of the largest papyrus finds in recent years – were found in December 1993 during excavation of an opulent Byzantine church in Petra, Jordan. The American Center of Oriental Research (ACOR),[3] in conjunction with the Department of Antiquities of Jordan, conducted the excavation. According to conservators, 152 of a total of approximately 180 scrolls have been unrolled. The scrolls range in date from about AD 513 to 582 and constitute a collection of legal papers from two or more large families that intermarried. Older documents in the collection were passed from one generation to the next until becoming part of the papers of Theodoros, son of Obodianus, an archdeacon presumably of the church where the papyri were found.

The Petra scrolls are all documentary, consisting mostly of legal instruments and registrations concerning changes in ownership of real estate and resulting taxes affecting two branches of a large family. These changes resulted from sales, inheritances, donations, dowries, and postnuptial gifts. The properties involved were largely vineyards and grain land in the countryside and structures on those fields, houses and parts of houses in Petra and in nearby communities, and slaves. The property interests of the main branch of the family reach as far as Eleutheropolis, 93 straight-line miles north-west of Petra. By local standards, this is an upper-crust provincial family with close-knit interests in church and community.

The documents yield unique information. Before their discovery, almost nothing was known about sixth-century Petra from actual documentary evidence (it was even assumed that the city had been destroyed by an earthquake in AD 551).

The challenge of the Petra papyri was that they had been carbonised in a fire that destroyed the Petra church around AD 600 (Figure 8). In some cases the carbonisation was extensive enough to make reading difficult or impossible for the unaided eye. Photographing black ink against a fire-blackened background presented serious difficulties for conventional photography. Once unrolled, the fragile texts were mounted between glass plates measuring 40 x 40 cm. Attempts to photograph them without the glass failed because the fragments immediately curled.

Following usual procedure, a team of scientists from FARMS and CPART[4] performed a diagnostic trial on samples of the Petra scroll

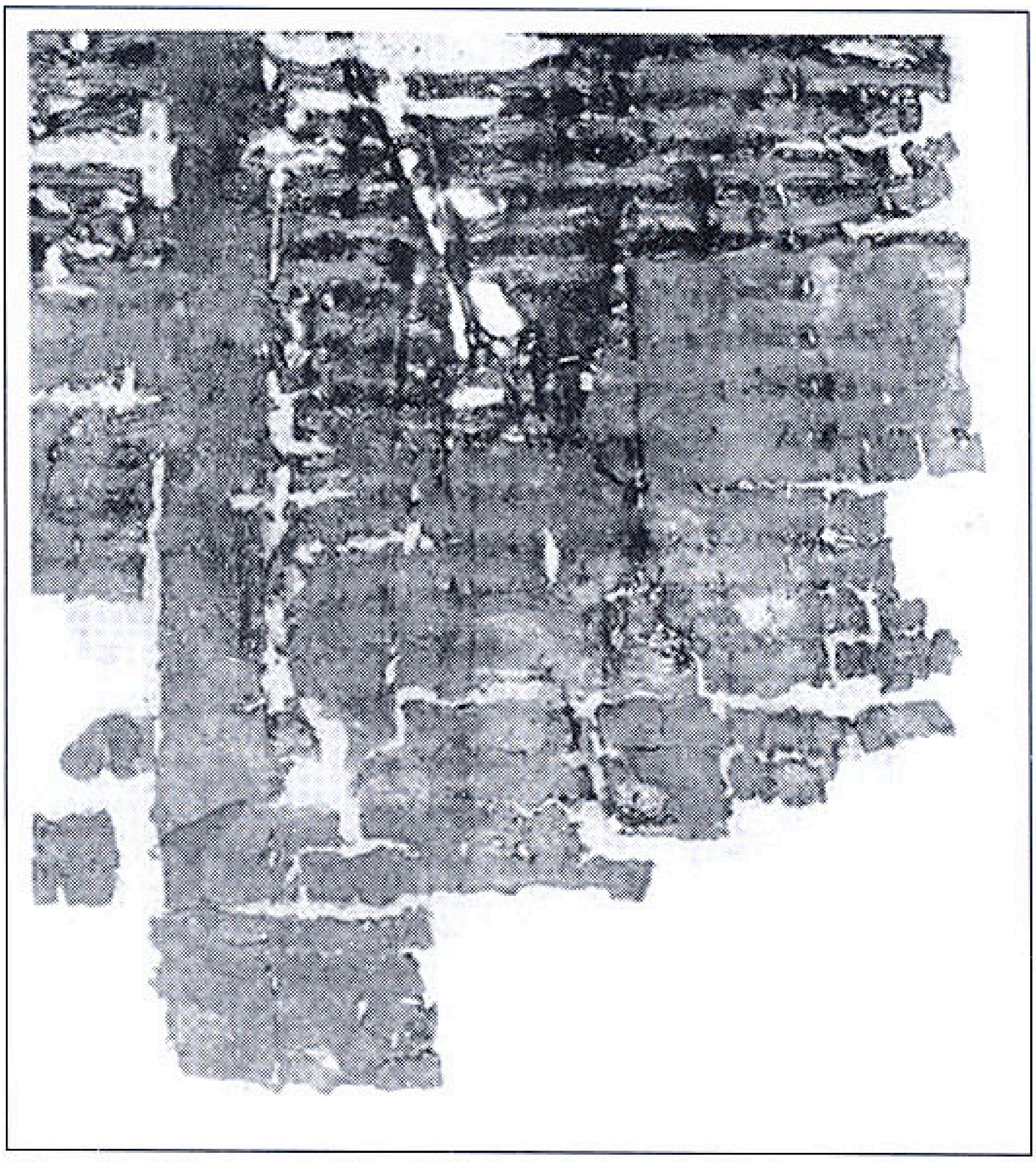

Figure 5a A black-and-white visible-light photograph of the bottom of column 12 of the Genesis Apocryphon, continuing the column of figures 4a–b. (By permission Gregory H. Bearman and The Ancient Biblical Manuscript Center)

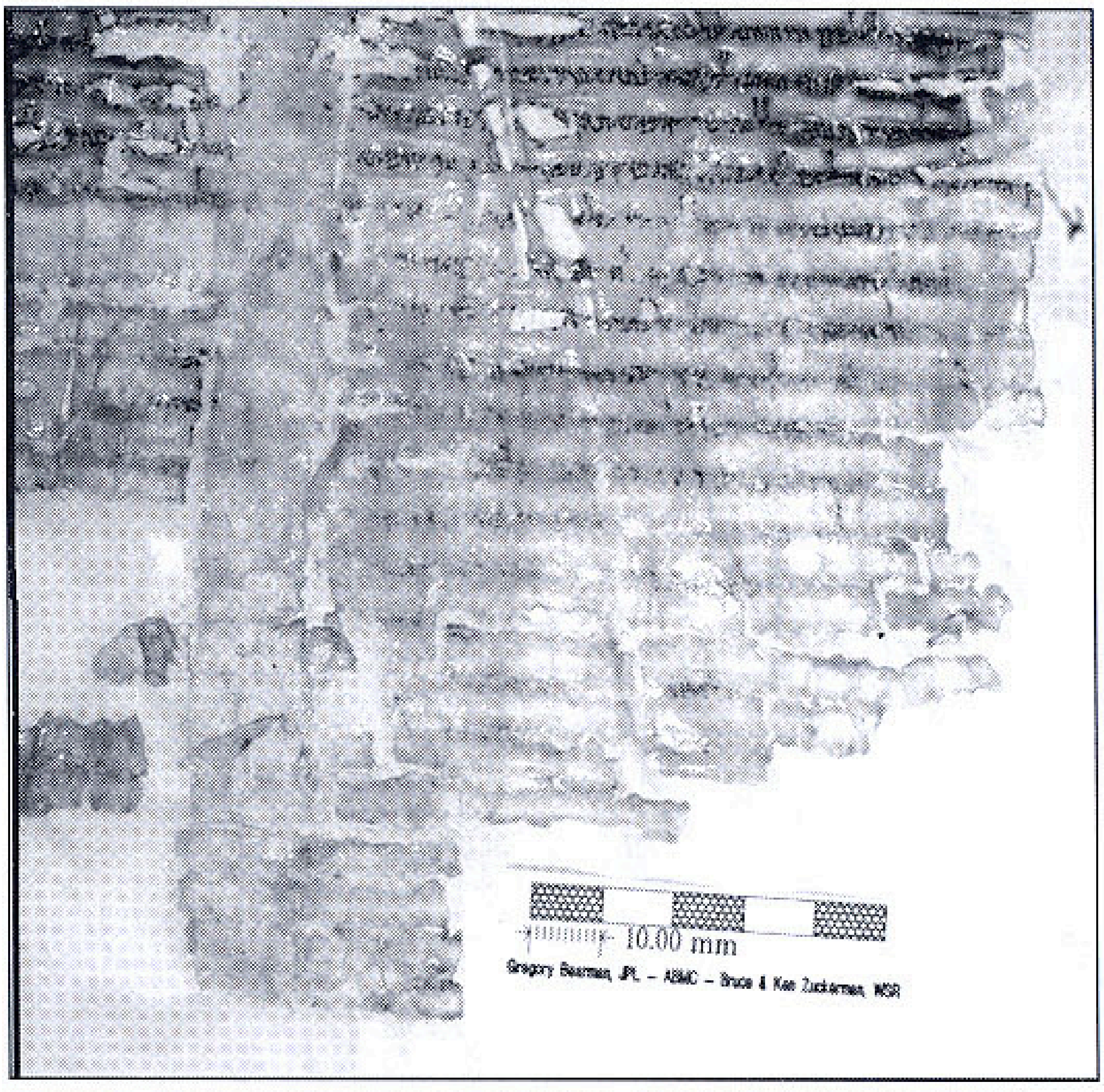

Figure 5b The same column imaged at 970 nm. (By permission Gregory H. Bearman and The Ancient Biblical Manuscript Center)

fragments in January 1999 at the ACOR facility in Amman, Jordan. During these tests, an LCTF filter with 7 nm resolution was used to provide multispectral image cubes of the spectrum from 650 nm through 1050 nm. The images varied significantly in the contrast between ink and papyrus both within a fragment and from fragment to fragment over the full spectrum. This result differed markedly from that of imaging the Dead Sea Scrolls (in which case the significant part of the desired text could be restored using a single fixed filter), and it meant that the massive preservation process of the Petra scrolls would be further complicated because extremely high spatial-resolution images would be required at each of a number of wavelengths.

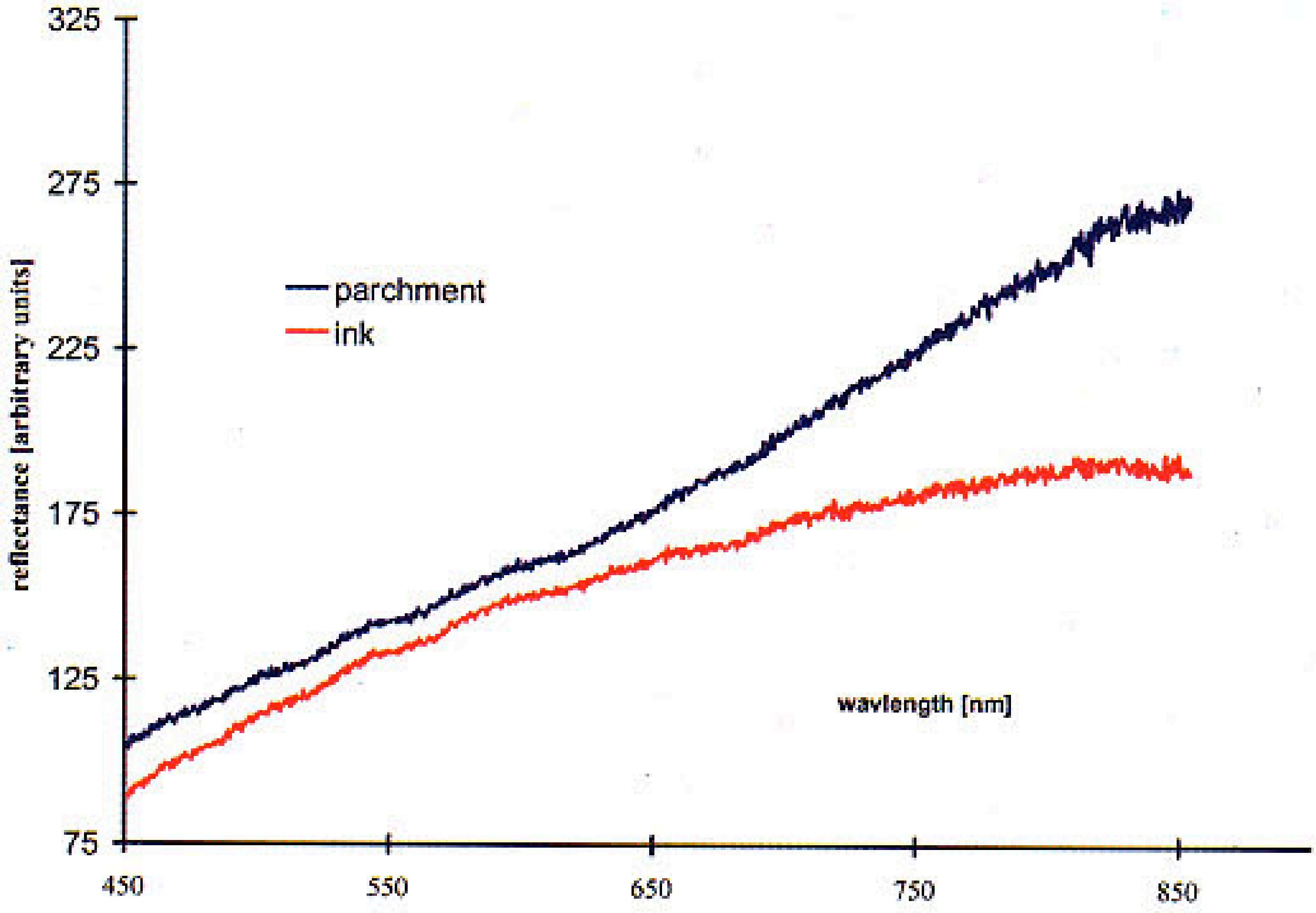

Figure 6 Reflectance spectra of ink and parchment of a Dead Sea Scrolls text. The data are for a nearly illegible scroll, one with a dark parchment background and dark ink. The ink is naturally dark, as it is mostly carbon (soot). In the infrared, the reflectance of the parchment begins to increase over that of the ink, providing visual contrast for imaging. (by permission The Institute for the Study and Preservation of Ancient Religious Texts/BYU)

It was clear that additional testing was needed. This was done in late 1999 using optical interference, or fixed filters mounted in a filter wheel so that an image cube could be formed from only five wavelengths (Kamal *et al.* 1998; Chabries & Booras 2001: 195–8). After analyzing the diagnostic data, scientists had determined that those wavelengths were optimal for recording the scroll data accurately and minimising the amount of image data to be collected. Because the entire Petra scroll collection is charred, the image resolution for all of the scrolls needed to be very high (at least as clear as that observed under a microscope). This was the first time that MSI was applied on such a large scale.

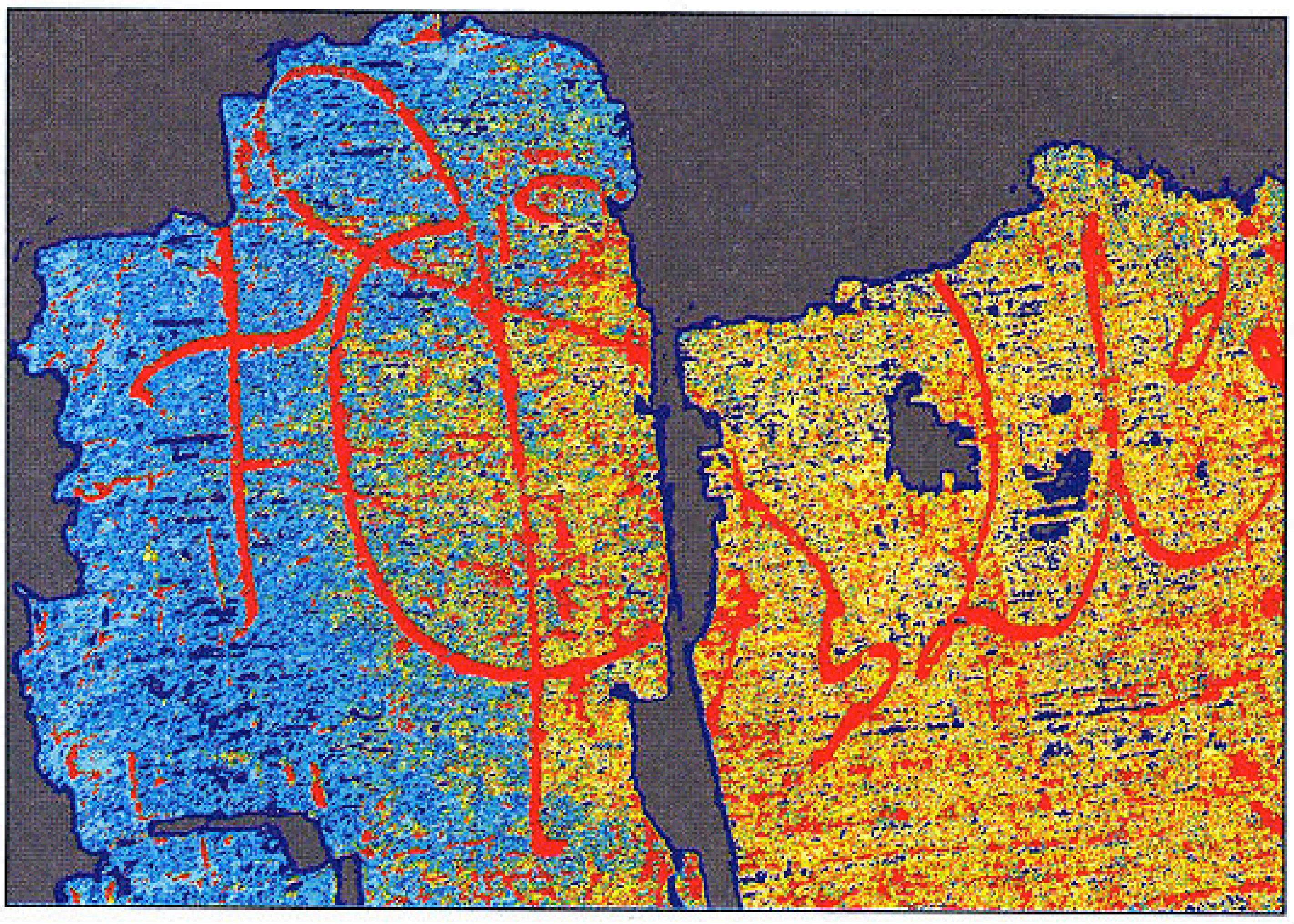

Figure 7 A pseudo-colour image obtained from Petra scroll fragment 310, roll 110. Areas of different colour indicate variations in spectral reflectivity and suggest that the degree of burning or carbonisation varied in this fragment. (by permission The Institute for the Study and Preservation of Ancient Religious Texts/BYU)

In Figure 6 the reflectance of the carbonised ink appears to be relatively uniform among the fragments, with respect to both spatial and spectral changes. Moredetailed spectroscopic analysis revealed that the primary variations in contrast between the ink and the papyrus are apparently caused by contrast variations of the carbonised papyrus itself. Evidence for this is shown in Figure 7, which displays a pseudo-colour image of plate 316, roll 10, of the Petra scrolls. This image was processed from a multispectral image cube with a digital-image-processing algorithm (Ware *et al.* 2000a: 2486–8) to show the reflectance of various portions of the specimen coded with colour (portions of equal reflectance are assigned the same colour). The blue outline around the fragment is an artefact of the digital algorithm used to obtain the fragment mask. The ink appears to be uniformly red, an indication of the spectral uniformity of the ink despite the fragment's varying degrees of carbonisation. The rainbow of colour shows the reflectance variation of the papyrus, which is presumably due to thermal hot spots and the possible differences in the length of burning and amount of smoke contamination to which different portions of that papyrus were subjected.

The Scrolls of Herculaneum

The only library preserved from the classical world, the private library at the Villa of the Papyri at Herculaneum is providing an unparalleled look into the classical era. Ironically, the catastrophic eruption of Vesuvius in AD 79 that might have utterly destroyed the 1,800 Herculaneum scrolls, instead preserved them for future generations. As unearthed in 1753, the fragile scrolls are carbonised and largely unreadable (see Figure 8). Using MSI technology, however, scientists from Brigham Young University's Institute for the Study and Preservation of Ancient Religious Texts are gaining access to many portions of these classical texts that have not been read for centuries.

Figure 8 An example of one of the rolled charred scrolls found at Herculaneum. (© Brigham Young University courtesy of The Biblioteca Nazionale, Naples, Italy)

Recent advances in MSI technology and in the method of unrolling the scrolls are renewing interest in the Herculaneum papyri, now housed in the Officina dei Papiri Ercolanesi at the Biblioteca Nazionale in Naples, Italy. Professor Marcello Gigante directed an international effort to publish the texts and to document the archaeology of the villa where the papyri were found (see Figure 9). Scholars under the direction of Professors David Blank of UCLA, Richard Janko of University College London, Knut Kleve of the University of Oslo, and Dirk Obbink of Christ Church, Oxford, are identifying the content of the emerging works of Philodemus (a first-century-BC philosopher) from that collection. The unrolled scrolls fill about 4,400 glass frames, or cornici (see Figure 10), of which more than 3,000 have been imaged using MSI. Still, the contents of many unrolled scrolls and hundreds of carbonised scroll fragments remain unidentified.

Some scholars compare this discovery – an extraordinary amount of new information on ancient philosophy and philosophers from the period 300 BC to AD 79 – to that of the Dead Sea Scrolls in terms of the quantity of historically significant writings. Archaeologists have also discovered that the villa has other levels that have not yet been explored, leaving the intriguing prospect that more classical texts, lost for generations, will emerge in future excavations.

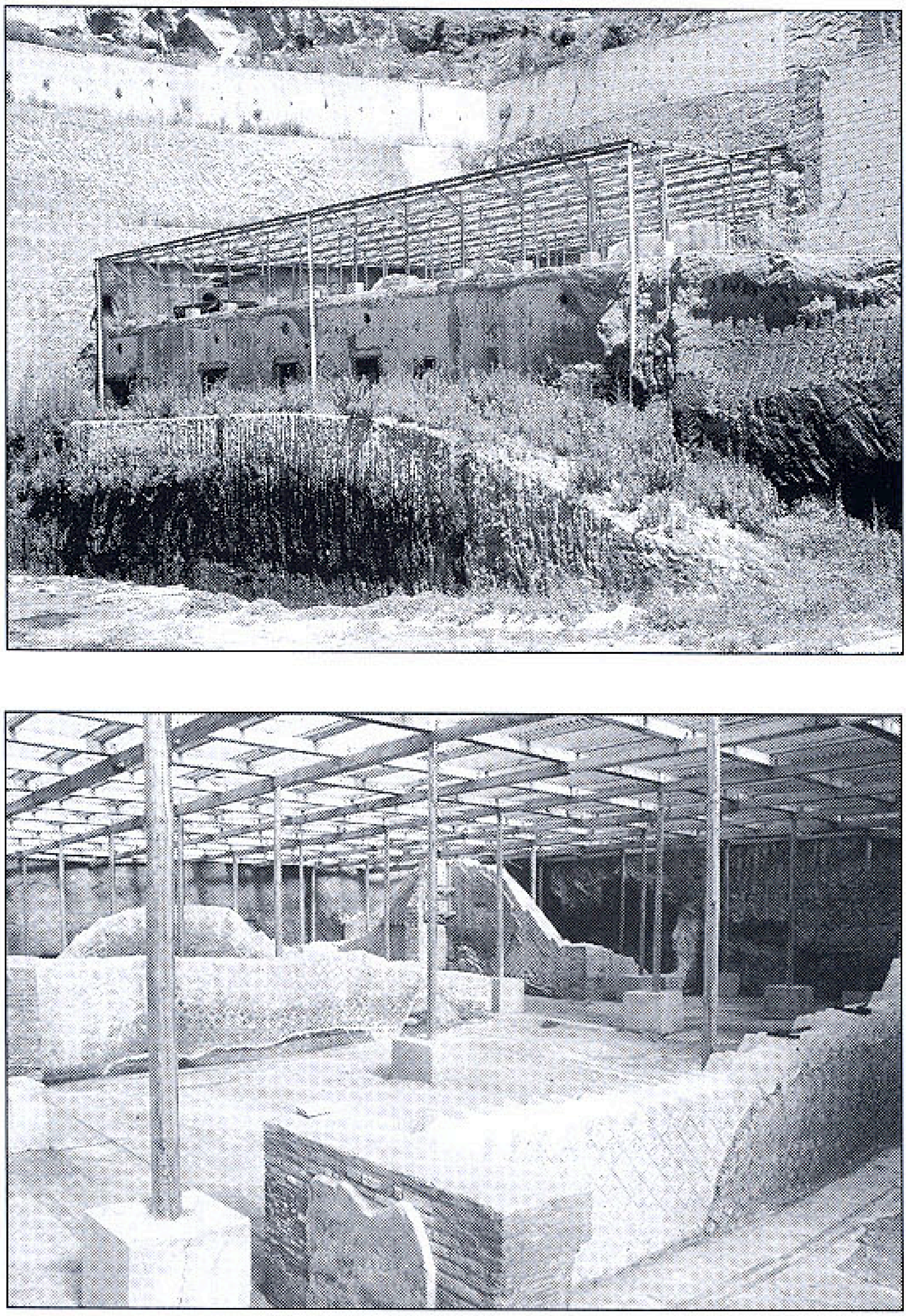

Figure 9a&b Excavation site of the Villa of the Papyri, where the Herculaneum scrolls were discovered. (© Brigham Young University courtesy of The Biblioteca Nazionale, Naples, Italy)

The results of the test images of the Herculaneum papyri have far exceeded expectations. The first images taken with the 450 nm filter were very dark with little contrast realised between the ink and the carbonised papyrus – not much better than what the unaided eye could see. But the images steadily improved as they progressed toward the near-infrared range until, at 950 nm, the ink became very distinct and the texts very readable without computer enhancement (see Figures 11 and 12). The multispectral images preserve enough data so they can be vastly improved with computer enhancement (Booras & Seely 1999: 95–100), though in many cases even the raw, unenhanced images have provided improved readings.

BYU has completed the first phase of imaging the Herculaneum papyri at the Biblioteca Nazionale with the hope of contributing to the international effort to publish the papyri and related scholarship and returning to assist in ongoing work. The resulting images will form a complete, secure electronic archive of the collection that will help further the scholarly enterprise for decades to come.

In conclusion, multispectral imaging is helping unveil the past by allowing access to ancient records not otherwise possible. This technology gives scientists, scholars, and other researchers the freedom to work on-site without the need to chemically process infrared film. High-quality images can be quickly captured, stored, and disseminated. The excitement of this work is its potential to bring to light significant works that have been lost to mankind for centuries.

Figure 10 The unrolled charred scrolls are mounted in glass frames called cornici for further examination. (© Brigham Young University courtesy of The Biblioteca Nazionale, Naples, Italy)

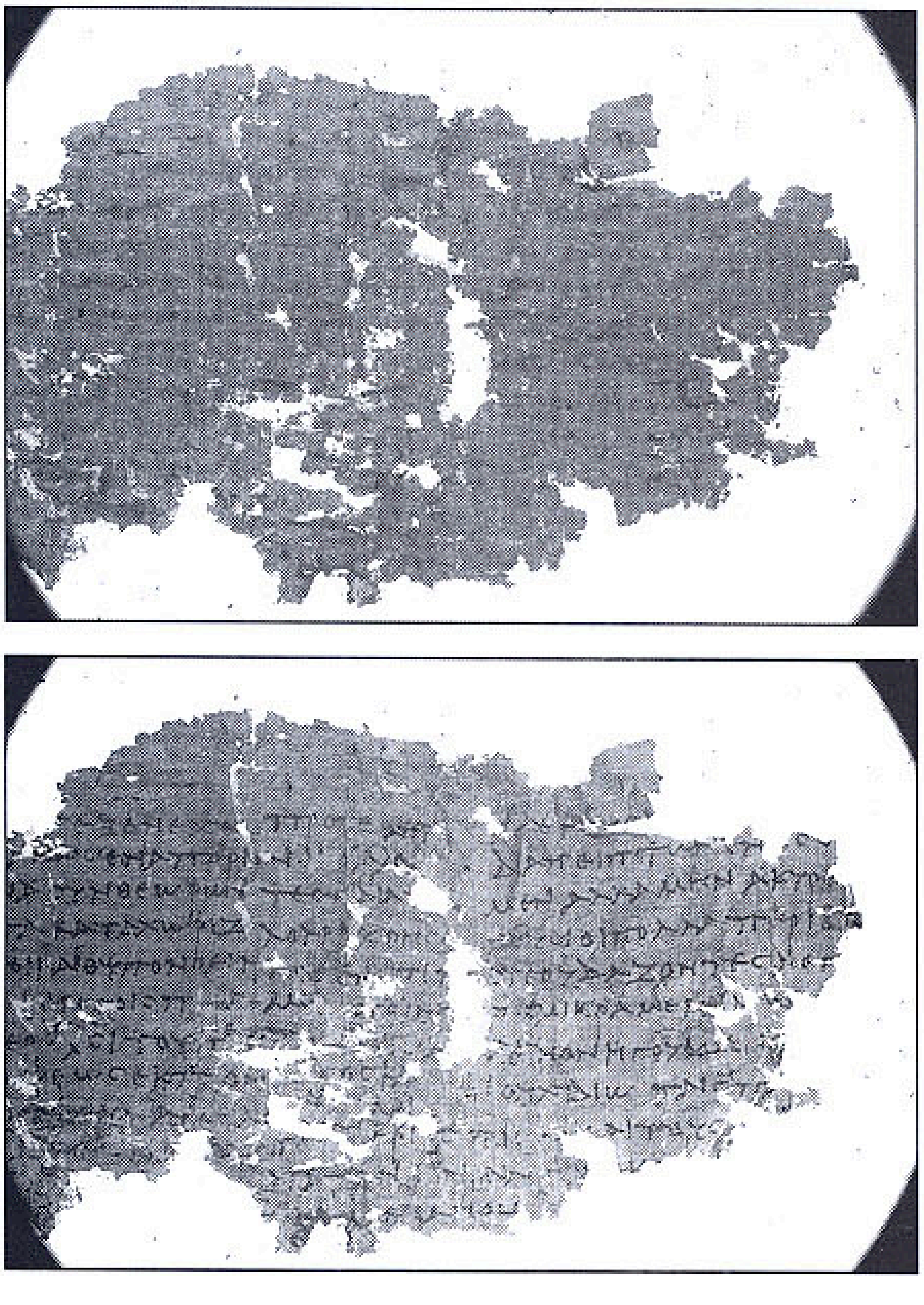

Figure 11 Herculaneum scroll PHerc 1491, imaged with two different spectral filters 450 nm and 1000 nm. (© Brigham Young University courtesy of The Biblioteca Nazionale, Naples, Italy)

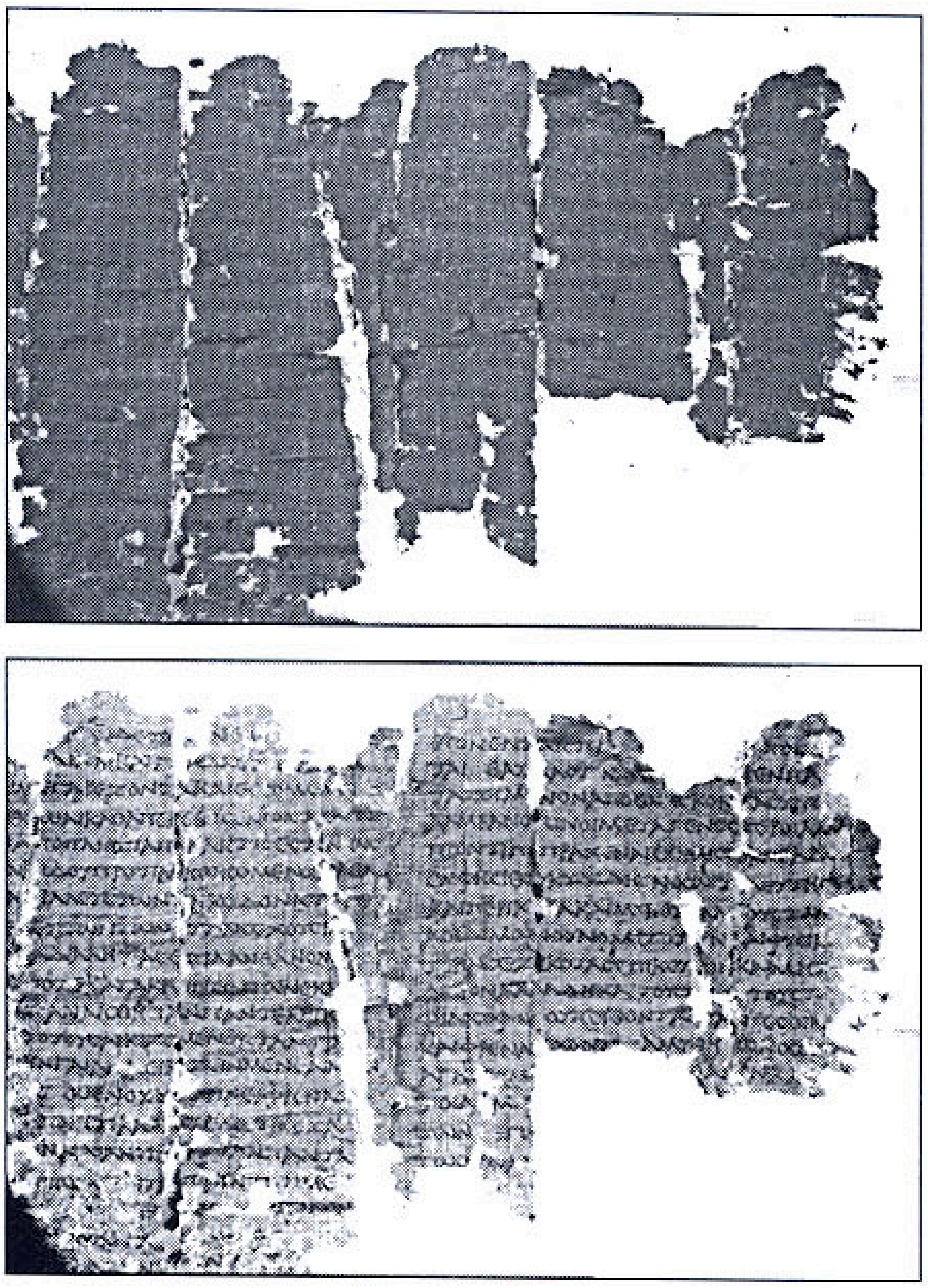

Figure 12 Herculaneum scroll PHerc 1050, imaged with two different spectral filters, one at 500 nm and the other in the near-infrared at 950 nm. (© Brigham Young University courtesy of The Biblioteca Nazionale, Naples, Italy)

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Notes

1 The terms *multispectral, hyperspectral,* and *ultraspectral* are used in the technical literature to categorise images of the same scene captured at different wavelengths. Multispectral data sets include on the order of 10 images, hyperspectral data sets include on the order of 100 images, and ultraspectral data sets include thousands of images. In terms of image spectral bandwidth, multispectral images range from hundreds to thousands of nanometers, while hyperspectral images are in the tens of nanometers and ultraspectral images are in the nanometer and sub-nanometer range. The data presented in this paper are multispectral in the sense that about ten different bands are used, but also hyperspectral because the image bandwidths range from 7 nm through 40 nm. For convenience, the term *multispectral* will be applied to this data set.

2 Direct techniques used to measure the response of an image as a function of the illumination frequency combine imaging technology with spectroscopy to provide a powerful tool for analysis and visualisation. There are many technical means to obtain spectroscopic image data, but in all cases the result is a two-dimensional image containing spectral data for each pixel. This data can then be used to classify and further analyse the image to reveal information not available in monochromatic or traditional film color images.

3 The papyri are presently at ACOR in Amman, Jordan. In accordance with a contract signed by ACOR, the Department of Antiquities of Jordan, and Professors J. Frösén of the University of Helsinki and L. Koenen of the University of Michigan, publication of this archive has been assigned in equal portions to a Finnish team and an American team.

4 FARMS is the Foundation for Ancient Research and Mormon Studies, and CPART is the Center for the Preservation of Ancient Religious Texts. Recently these two organizations at Brigham Young University have merged into the university's Institute for the Study and Preservation of Ancient Religious Texts.

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