IMAGE RESTORATION OF DAMAGED OR ERASED MANUSCRIPTS

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ABSTRACT

Modern imaging techniques have been applied to ancient manuscripts to recover writings that are not visible to the naked eye. Over the years, many of these manuscripts have been damaged by the elements or even intentionally erased and re-used to record other information. To successfully recover text from such documents, it is important to understand the nature of the writings and the materials on which they are written. Different imaging and processing techniques are needed, depending on the type of ink used and the condition of the manuscript. In this paper, we describe several imaging techniques and how they are applied.

1. INTRODUCTION

Most of the authors' experience has been with restoration of parchment manuscripts. Parchment is the skin of a sheep or goat that can be very durable. If stored under very dry conditions, parchment can last for thousands of years.

Early inks were made with carbon black suspended in water. This ink provided, and continues to provide, well-defined and high-contrast writing. Later manuscripts were written with iron gall ink, which was easier to make and harder to remove from the surface. The two types of ink have very different spectral properties, so knowing which ink was used is important to recovering the damaged writing.

The condition of the parchment will also influence the techniques needed to recover the text. Parchment in very good condition is light in colour and offers good contrast to the text written on its surface. Damaged parchment is often very dark, making any surviving text characters hard to read.

In this paper, we will illustrate these different conditions of text and parchment and describe the techniques that can be used to recover the missing text.

2. COLOR PHOTOGRAPHS

One does not always have access to original manuscripts. Sometimes, only a photograph is available. Even so, image processing techniques may still reveal hidden characters.

The images shown in Figure 1 are derived from colour photographs of the Dead Sea Scrolls, taken by Bruce and Kenneth Zuckerman of West Semitic Research. The photographs were acquired by the late Dr. Robert Johnston of the

Figure 1 – Photograph of a section of the Temple Scroll, one of the Dead Sea Scrolls. The right side of the bottom image shows characters that are written on a piece of the scroll stuck to the back surface.

Center for Imaging Science at the Rochester Institute of Technology, who converted them to 8-bit digital, colour images using a transparency scanner.

The Dead Sea Scrolls were discovered in 1947, in caves at Qumran near the Dead Sea. Figure 1 is a section of the so-called "Temple Scroll," which was in very good condition when it was first found, but it was later damaged by exposure to humidity. It was hidden under floor boards to prevent its discovery by the authorities.

In the top image, in Figure 1, the right-hand side of the parchment is darkened from exposure to water, making the text characters hard to read. We found that a simple image processing algorithm applied to a scan of the photograph revealed additional characters that can be seen in the lower image in that figure.

The processing method used was to highly stretch the contrast of the difference between the red and green separations of the colour image. The difference image had a lower dynamic range than either of the two individual images and was centred roughly around zero. A Gaussian function was fit to the histogram by measuring the mean and standard deviation of the image. The difference data was then linearly stretched to black and white from ±3 standard deviations around the mean, clipping any values outside of that region. A blue-yellow colour map was used display the final result.

A subsequent analysis of the characters and the shape of the scroll [1] showed this processing had revealed characters on a piece of the parchment from a neighbouring region of the scroll that is stuck to the back surface. This simple image processing technique made these characters visible through the front side of the parchment where they could be read for the first time [2].

Although taking the difference of the red and green separations worked well for this example, the mechanism behind the method is still not clear to the authors. The best explanation that we can determine is that the red separation may have recorded some infrared information, which as described in the next section, would make characters more visible in a damaged region of the parchment.

3. DAMAGED PARCHMENT

When one has access to the original damaged parchment, then characters may be recovered by direct optical imaging techniques. For example, the small fragment of the Dead Sea Scrolls, shown in Figure 2, has been significantly darkened by exposure to moisture. The text characters are written with carbon-based ink, making them very black, and they cannot be read against the background of the darkened scroll.

When this scroll fragment is imaged in infrared light, the hidden text characters become visible and are easily read. The bottom image of Figure 2 shows an image of the scroll fragment taken under incandescent light through a near infrared filter with a pass-band of width $\Delta\lambda \sim 200$nm, centred around $\lambda \sim 800$nm. The darkened parchment reflects light at this wavelength and appears much lighter than the carbon-based letters. The resulting contrast makes the letters easy to read. The greyscale image was then linearly stretched by 3 standard deviations around the mean.

This technique also works with manuscripts that have been burned. Researchers from Brigham Young University [3] have used this technique to reveal characters on burned papyrus manuscripts from the ancient city of Herculaneum. Although these manuscripts have been carbonized, the organic materials of the burned substrate still appear much brighter than the carbon-based ink, thereby revealing the text.

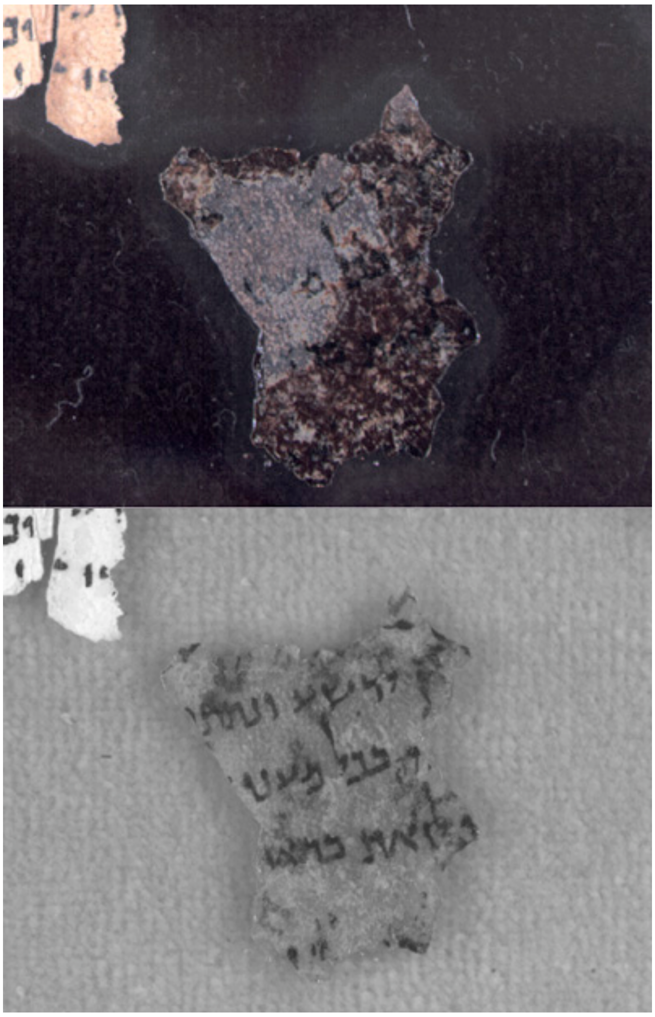

Figure 2 – Near infrared light reveals text characters that are hidden on the damaged surface of this Dead Sea Scroll.

4. ERASED TEXT

A palimpsest is a manuscript that has been erased and overwritten. The word comes from two Greek roots and means "scraped again". The parchment is rubbed smooth to remove the ink and prepare the surface to accept new writing.

The Archimedes Palimpsest [4] includes parts of seven works of Archimedes that were copied a thousand years ago. Approximately two hundred years later, a monastery disbound the book, erased the pages and wrote a Euchologion prayer book over it.

The palimpsest was sold at auction in 1998 to a private collector. The Walters Art Museum of Baltimore, Maryland was contracted by the owner to conserve the manuscript and to arrange for the Archimedes text to be recovered and transcribed. The authors of this paper are responsible for imaging the manuscript and revealing the erased writings.

A sample page of the Archimedes Palimpsest is shown in the top half of Figure 3. The Archimedes and the Euchologion texts, were both written in cursive Greek using iron gall ink. Fortunately, the Euchologion text was written at right angles to the original text. In Figure 3, traces of the erased Archimedes text can be seen as faint vertical lines of text. The readily visible horizontal lines are the Euchologion text.

Although it is still possible to make out the stains in the parchment left behind by the erased characters, it is very difficult for the scholars to read much of the original text.

For faint traces of ink that remain in the parchment, scholars have long known [5] that ultraviolet illumination is helpful for reading the erased text. This can be seen in the bottom half of Figure 3. The ultraviolet illumination causes the parchment to fluoresce, emitting blue light, thereby increasing the contrast of the erased characters.

To extract the most information possible, the entire Archimedes Palimpsest has been imaged in 12 wavelength bands from the ultraviolet, through the visible and into the near infrared, i.e. in bands of width $\Delta\lambda \sim 25$nm from 365nm through 910nm. All images were created by illuminating the manuscript with narrow-band light, from a series of LEDs that spanned that wavelength range, and photographing with a Sinar 54H sensor. Although the camera sensor has a 2-by-2, Bayer colour filter, a piezoelectric transducer on the sensor allows it to be moved precisely in single- and half-pixel steps. From a series of 16 images, full-colour, 8160x10880 pixel images were obtained.

The resulting multispectral data cubes are being processed using algorithms developed for environmental remote sensing [6] to extract the Archimedes text. To make the erased text easier for the scholars to read, a pseudocolour enhancement technique [7] was developed and has been applied to all of the processed images provided to the scholars.

The pseudocolour technique being used is reasonably straightforward. An image taken in visible light, in the red wavelength region, shows the Euchologion text well, but the erased Archimedes text is very faint, close to the same grey value as the surrounding parchment. That separation is placed in the red colour separation of the pseudocolour image. An image of the same leaf taken in ultraviolet light is used in the green and blue separations of the pseudocolour image. In the ultraviolet image, both sets of text are visible and they both have high contrast.

By putting both images into different colour separations, a visual comparison is being made between the two images. In order to make a reasonable comparison that emphasizes the text and not the parchment, the average grey levels need to be adjusted so that they have similar values. This is done with a spatially varying linear stretch, similar to the one described earlier, but applied over a small window that slides over the image.

The sliding window is accomplished by considering a region of pixels around every pixel, for example a window of 400 pixels, or 200 pixels in both directions. Within that window, the mean and standard deviation are calculated and the pixel in the centre of the window is linearly stretched so that 3 standard deviations on either side of the mean value would stretch the pixels in the total window to black and white. Of course, only the centre pixel is changed before the window is moved to be centred on the adjacent pixel. Both images are adjusted in this manner, resulting in a uniform variation of background and text across the leaf.

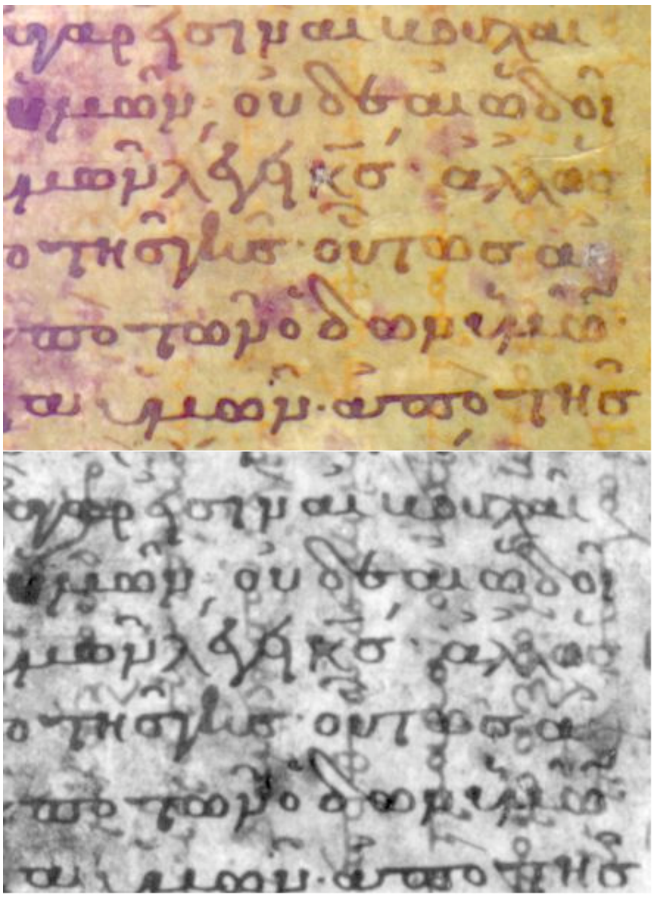

Figure 3 – A piece of the Archimedes Palimpsest as seen in visible light (top) and under ultraviolet illumination (bottom). The erased characters are revealed by the ultraviolet illumination.

As a result, in the pseudocolour image, the Archimedes text, which is bright in the red separation and is dark in the other two separations, shows up as bright red in the pseudocolour image. The Euchologion text, on the other hand, is dark in all three separations of the pseudocolour image, therefore it appears as a neutral grey, without colour. This difference in colour, along with the greyscale difference between the text and parchment, makes the erased text very visible and easy to distinguish from the upper layer of Euchologion text.

5. SEEING THROUGH PAINT

Sometime in the first half of the twentieth century, four leaves were cut out of the Archimedes Palimpsest, re-erased and painted over with Byzantine icon forgeries, possibly in an attempt to increase the potential value of the manuscript.

The paintings are opaque to optical wavelengths, so the text on these leaves has been unavailable for several years. These pages were taken to the Stanford Linear Accelerator Center (SLAC) to be imaged at the Stanford Synchrotron Radiation Laboratory (SSRL). Uwe Bergmann, a scientist at SSRL, used the X-ray beam of the facility to image the ink through the paintings using X-ray fluorescence (XRF).

When exposed to X-rays, the iron in the iron gall ink emits low-energy photons at wavelengths unique to iron. These photons can be detected even through the paint covering the text. An example XRF image is shown in Figure 4. The vertical writing that appears in the painted image on the top half is the Euchologion text. The horizontal text in the bottom half (XRF) is Archimedes text. Because the X-rays travel through the parchment, writing from both sides is visible in the XRF image.

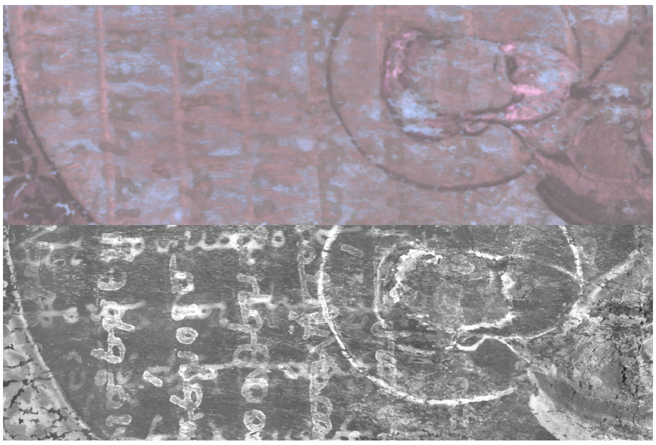

Figure 4 – Comparison of optical and X-ray fluorescence images of a leaf of the Archimedes Palimpsest that was painted over by a forged Byzantine icon. The iron in the ink fluoresces to reveal text hidden under the paint.

The Archimedes Palimpsest project has seen the application of several different scientific techniques, involving many people from around the world. The project has a goal to complete publication of the images and the transcription of the manuscript by the end of 2008.

6. ERASED COLOPHON

The most unusual imaging session in our experience was when Evelyn Cohen of the Jewish Theological Seminary of America brought a Hebrew prayer book to the Rochester Institute of Technology for us to image.

The manuscript was a beautiful 15th century Italian illuminated manuscript, whose colophon was erased. The colophon is the page in a manuscript where the scribe records information about the manuscript, such as the date it was written, the patron's name, the scribe's name etc. Unfortunately, the colophon on this manuscript was completely erased, as can be seen in the top half of Figure 5.

We had dealt with erased writing on parchment before and guessed that ultraviolet fluorescence in the blue would reveal the colophon. We expected that the stains in the parchment from the erased text would respond to the blue fluorescent light from the parchment and enhance the erased characters. However, when we illuminated the leaf with ultraviolet light and photographed the leaf through a blue band-pass filter, no characters were revealed. In fact, none appeared at any visible wavelength.

As a last resort, we tried ultraviolet illumination together with an ultraviolet band-pass filter on the camera. The ultraviolet filter blocks everything except for a bandwidth of $\Delta\lambda \sim$ 75nm centred at $\lambda \sim$ 350nm. The sensor in the camera had been specially treated to respond to ultraviolet illumination and the lens was made of quartz that transmits ultraviolet wavelengths. In other words, this system could be used to record reflected ultraviolet light; most camera systems cannot.

To our amazement, the ultraviolet reflectance image revealed many characters, as can be seen in the bottom half of Figure 5. We were very surprised at this result and are still unsure of the reason behind this response to ultraviolet reflectance.

Although we could not explain why it worked, from this image, Evelyn Cohen was able to extract the name of the scholar, the name of the patron, the date of creation, and the location where the manuscript was written [8].

As a result of the recovery of the erased colophon, ultraviolet reflectance is one scientific tool that we retain for future use in recovering erased text.

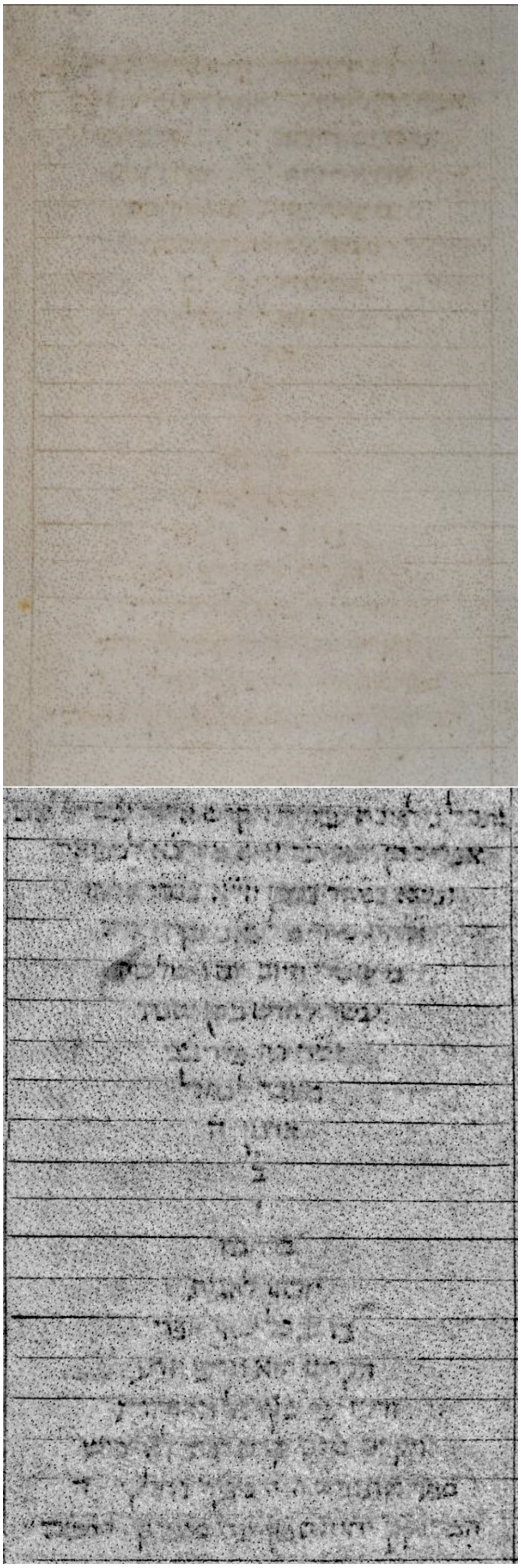

Figure 5 – The colophon of a 15th century Hebrew prayer book. In reflected ultraviolet light, the erased text appears revealing the name of the scribe and the patron for whom he wrote the manuscript.

7. CONCLUSIONS

The nature of the inks and the condition of the parchment will influence what regions of the optical spectrum will reveal characters. From our experience, we have found that infrared illumination is good for revealing carbon-based ink on blackened parchment. Ultraviolet fluorescence (and sometimes reflectance) can enhance erased characters. Contrast stretching of visible wavelengths (such as photographs) can bring very low contrast characters to light in scanned images. Finally, X-ray fluorescence can detect iron gall ink that is completely covered by opaque materials.

Despite the usefulness of the above general rules, sometimes you have to try everything that you can think of to see what works.

8. ACKNOWLEDGMENTS

The authors wish to acknowledge the generosity and vision of the owner of the Archimedes Palimpsest, who has made possible the recovery of these works of Archimedes. Copyright of the images in Figures 3-4 is retained by the owner of the Archimedes Palimpsest.

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