Archeological Applications of Advanced imaging Techniques

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Photography has long been a recording medium for archeological objects. However, for some objects, photography provides a visual record but does not capture all the information available New technologies, especially electronic imaging, present new opportunities for scholars.

This article presents results of new approaches to imaging, specifically those utilizing techniques developed by NASA for planetary spacecraft missions to other solar system bodies. Results from an Ancient Biblical Manuscript Center month long field project in Jerusalem in the summer of 1994 demonstrate the usefulness of the new techniques on soft media documents and ostraca. This imaging approach is also useful on frescoes, mosaics, ink inscriptions on plaster, colored textiles, illuminated manuscripts and inscribed ostraca. Most of the examples will be drawn from text material, as these are the objects to which we have had the most access. We will present other suggested applications of this approach and provide sufficient detail to allow others to apply these techniques.

The Problem of Reading, Ancient "Soft Media" Documents

One of the major barriers inhibiting research into the historical, religious and cultural background of the Ancient Near East is the inability to retrieve data from ancient documents of the period, This is especially true of "soft-media" documents; i.e., those written on soft, perishable materials such as untreated animal skin, leather, vellum and papyrus, Such documents are particularly prone to deterioration and the consequent degradation of data -- much more so than those written on hard media, such as clay tablets, stone and pottery sherds. Note, for example, the case of the Dead Sea Scrolls (DSS). Not only are such documents typically in shreds and tatters, but the carbon-black inks in which they are written are often faded beyond recognition or indistinguishable from the blackened or dark brown, aged writing surfaces, Thus a significant portion of the Dead Sea material is unreadable in visible light.

Infrared Photography - And Its Limitations

From the first, scholars and technicians working with the DSS recognized that the problem could be addressed by looking for information beyond the visible light spectrum (~700 nm) -- especially in the infrared (IR). imaging DSS with photographic films sensitive to wavelengths in the infrared spectrum yielded highly remarkable, even dramatic, results, Indeed in a number of cases only IR could uncover information from the scrolls. Similar success has also been achieved with other soft media texts, especially those written in carbon black inks (e.g., the Elephantine papyri from the 5th Century BCE). The vast majority of Dead Sea Scroll photographic images available today were shot in large format using Kodak IR film.

Although the application of infrared photography has been one of the great success stories in ancient biblical manuscript research, this success has not been unmitigated. In numerous instances, (mostly unreadable) text becomes discernible when photographed in the IR, but additional readings seem just beyond the edge of legibility. Infrared film is not sensitive beyond 900 nm (0.9 pm) and begins to lose sensitivity well before that. Experiments by B. and K. Zuckerman have for some time hinted that considerable information lies beyond film's cut-off point. The work of G. Bearman and other physicists at NASA's Jet Propulsion Laboratory has clarified the "whys" of IR photography, pointing the way to "pushing" IR film to even better results and developing completely new approaches to imaging.

A Digital Image Primer

The following concepts of image processing will clarify the steps performed on the images to be presented later.

Digital images are mosaics of ***pixels*** (picture elements), composed of clots, much like a newspaper halftone, each corresponding to a sensor element (= pixel) on a C(D (charge-coupled device) camera used to take the images. Each pixel has an associated ***data number (DN)***. The most common, ***8 bit*** (2^8) or 2.$6 ***gray scale***, ranges from O-256: Black is represented by O, white by 256, and shades of gray by intermediate DN values, The 8 bit gray scale is used by all monitors and video cards, primarily because the human eye cannot distinguish that many shades of gray. Gray scales larger than 8 bits, which capture greater dynamic range, are extremely useful in image analysis, but one must carefully select which 8 bits are to be part of the subsequent display (that is the approach taken in this work, in which 16 bit images were captured and analyzed), Image manipulation is done by performing arithmetic or logical operations on the image pixel by pixel; the DNs of the corresponding pixels in the two images are subtracted, divided or whatever, and the resulting DN creates a new image.

A power-fl]l means for analyzing an image and making choices for manipulation is to examine its ***histogram***. This is an XY plot of the number of pixels with each DN. This graphical representation of the image data provides significant clues as to image quality and how to enhance an image. Manipulating the histogram can improve the image, as will be demonstrated later, Figure 1 shows a typical DSS histogram of an 8 bit image.

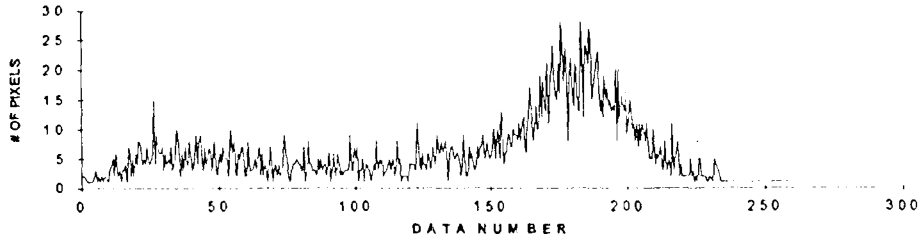


Figure 1. Histogram of part of an image of4Q107 Cant[b]

NIulti-Spectral Imaging (NISI)

MS] is a technique for image acquisition and analysis that relies upon the unique spectral signature of each target pixel (in the case of ancient scrolls, e.g., the ink versus the writing surface). When the respective spectral signatures ofvarious parts ofa given target vary, MS] can be used to enhance this difference by means of computer imaging and analysis techniques, Even reflective differences as small as 2-3°/0 can be successfully exploited to increase differentiation and, hence, legibility.

How MSI works

An imaging spectrometer acquires images of the same scene simultaneously in many contiguous spectral bands over a given spectral range (one might think of this as equivalent to a contiguous set of multi-color images). By adding wavelength to the image as a third dimension, the spectrum of any pixel in the scene can be calculated. MSI allows the investigator to isolate any part of the target based upon its reflectance spectral signature. Once properly calibrated, these images can be used to obtain the reflectance spectrum for each image pixel, which can then be used to identify components in the target, For the geologist, MS] yields compositional maps of geologic sites, showing *which* minerals are *where*. For the ecologist studying the rain forest, MS] helps understand the large scale composition of the forest canopy. For the biologist, MS] yields functional maps, showing *which* biological molecules arc *where* within a structure. For the text scholar, MS] locates those image pixels that have ink, i.e., text, no matter how faint. The powerful combination of imaging and spectroscopy, easily visualized with software, is what makes MS] so useful,

Figure 2 graphically illustrates the approach to image acquisition and analysis, showing four image slices of the same scene, a single image taken in a narrow spectral band, at different wavelengths (An actual instrument may take 100 such images over the visible to near lR, -400 to -1000 nm, or --0,4 -1,0 μm, the spectral range spanned during this work), The visible part of the spectrum is '0.4-,75 μm, while the region out to 1 μm is the infrared,

The images are then stacked in a computer, from the lowest wavelength to the highest, to create an "image cube," The spectrum of a selected pixel is obtained by skewering it in its third dimension, wavelength. Spectral analysis can then be performed in any of several ways. One is to identify the measured spectrum by comparing it with a library of known laboratory spectra. A variation is to conduct principal component analysis, i.e., model spectra from a variety of possible target components to obtain a spectrum that matches the one measured. In either case, spectral tagging is then applied in which all pixels with one specific spectrum are located and visualized by giving all those pixels the same color. A color image then locates composition (through spectra) in the scene.

The key to successful use of MSI is to image in selected, narrow wavelength bands. Broad band imagery loses spectral data as minute spectral differences become mixed with those of neighboring spectra and contrast is lost. This may be compared to trying to find a blue-green jellybean among a million blue ones; if one's camera saw *only* blue-green, that jellybean would stand out. By taking two images, onc in the blue and one in the blue-green, and subtracting the blue image from the blue-green one, one is left with an image showing only the blue-green jellybean

The imaging Spectrometer

An imaging spectrometer consists of a device for spectral selection, imaging optics, a sensor and a data acquisition system. The major criterion for the project was to utilize only technologies that could be reduced to a compact, simple, table-top instrument suitable for field campaigns. Figure 3 shows how the technology was implemented, and the components of the system are described below. Liquid crystal tunable filters (LCTF) were used for wavelength selection; standard photographic lenses for optics; and an astronomical slow-scan cooled silicon CCD camera with Macintosh based data system for image acquisition and storage, image acquisition and storage.

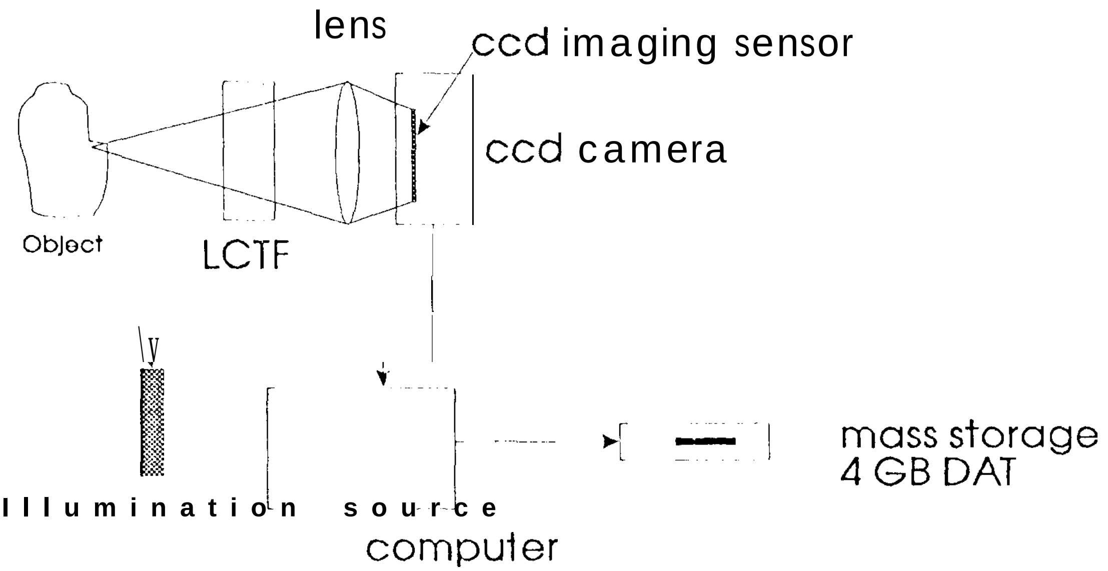


Figure 3. A schematic diagram of the imaging spectrometer used during the field trip.

An LCTF is inserted into the optical path and tuned to provide images in any wavelength. Only recently available commercially, this ncw technology can be thought of as a variable bandpass filter that can be tuned electronically to any wavelength over its range, The filters are spectrally agile and can be tuned to wavelengths in any order; they can be fabricate.cl to order with bandwidths from 1- 200 nm. For the work reported here, two filters were used, onc that spanned 0.4-0.72 μm (visible) and onc 0.6-1.05 μm (infrared).

A silicon CCD camera is sensitive out to 1.05 μm, which is well beyond the failing sensitivity of IR film. In general, image signal intensity is insufficient to allow operation of a camera at standard video framing rates (30 frames/second). This is particularly true when using a 5-10 nm bandwidth LCTF, which considerably reduces the image signal intensity since a smaller bandpass decreases the amount of light passed by the filter for illumination. For this work, exposure times ranged from 1 to tens of seconds over the spectral range of 0.4-1.05 μm. Thus, the selected camera must have a settable exposure time, which can be accomplished by frame transfer or a mechanical shutter, Because of the long exposure times, a cooled camera is needed, Without cooling the sensor, dark current would quickly swamp the data signal in any acquired image. A (CD, by its nature, is always generating an image signal, even without illumination; that is the dark current or dark image. It is a strong function of temperature and can be reduced by orders of magnitude by cooling,

Preliminary tests with a video camera and frame grabber (an analog system) suggested that an all digital system would yield better results, A frame grabber takes the camera video signal and digitizes it for the computer. Video analog signals are noisy and after digitization with a frame grabber yield at most 6 bits, resulting in a gray scale range of only 64. In addition to reducing contrast, this limits the processing that can be done after images are acquired. "l'his can be solved by using a CCD camera that digitizes the data stream with a 12 or 16 bit digitizer immediately behind the signal electronics. This not only reduces noise but also increases the dynamic range and gray scale of the image to 4096 (12 bit) or 65,535 (16 bit). Further, a digital camera is not limited to the typical frame grabber video screen size of 540 x 480 pixels, allowing use of much larger image formats for better spatial resolution. A thermo-electrically cooled 16 bit digital camera with a mechanical shutter was used for the work reported here.

Analysis of the image data shows that a 12 or 14 bit camera would yield equivalent images to a 16 bit camera, When the system was designed, available cameras were either 8 bits or 16 bits, with nothing in-between, There is no disadvantage to a 16 bit camera (except perhaps cost). Aside from the dynamic range, another reason for a camera that digitizes to more than 8 bits is to retain image shading. A coarser digitizing grid will lump pixels together into the same DN that should actually be separate, reducing spatial details,

Data acquisition was computerized and controlled by a Macintosh 840. Custom software for controlling the camera and LCTF was assembled with LABVIEW, a software product developed for generic instrument control, A graphical control panel was designed to allow the user to take either single, fixed wavelength images or to set up and acquire image cubes,

illumination was provided by a standard photoflood lamp, which has a color temperature -3000 K, so the. peak of the spectral output is ~1 pm. Since the spectral output is that of a blackbody, the intensity is steadily decreasing into the shorter, or visible part of the spectrum, but there is more than adequate light for imaging. Special "infrared" lamps are not necessary and, in fact, arc useless in this context. Infrared lamps, designed to provide IR radiation in the -8-14 pm region, generate almost no radiation in the region covered by the imager.

Additional images are required prior to acquisition of an image cube, in order- to insure that acquired data is properly calibrated and suitable for analysis, It is critical to know both illumination intensity as a function of wavelength and spatial variation of illumination intensity across the target. For example, the spectrum of the illumination source used for this work peaks at -1 pm and continually falls in intensity towards the shorter (blue or visible) wavelengths. An image cube acquired with the same exposure time at each slice would seem to indicate that the reflectance spectrum declines at shorter wavelengths. However, that is an artifact of the fact that there is also *less* light at those wavelengths, The correct reflectance spectrum is obtained by *dividing* the image spectrum by the illumination spectrum obtained from the reflectance target.

The calibration data needed to divide out the spectral illumination changes was obtained by acquiring an image cube of a reflectance target over the same spectral range as that of the text image cube. The target, made of a proprietary compressed plastic similar to Teflon (Spectral on), reflects all wavelength radiation uniformly over the visible and infrared image.

Spatial changes in intensity are similarly corrected with data from the Spectralon target. The documents were usually illuminated from the side and there was a distribution in intensity from one edge to the other. Dividing the text image by that of SpectraIon target corrects this problem.

In anticipation of the results, presented later, it is important to note that a full image cube is not always needed. In the case of texts, we discovered that single wavelength images at the appropriate wavelength give excellent results, To be sure, there still is a need for at least *one* image cube, though, to locate that wavelength. Other objects require the full power of an image cube for analysis.

Earlier Work on Texts

Prior to this project, IR cameras of various sorts have been used to investigate ancient soft media documents. The Getty Conservation Institute attempted unsuccessfully to recover legible text from DSS samples employing a broad band camera that covers the 8-14 μm "thermal" region, but their results indicated no contrast between the ink and the parchment for several possible reasons. A thermal camera works by detecting the *emitted* radiation from objects and one reason for the lack of success in this spectral region may be that the ink and parchment have the same average emissivity over this wavelength region, i.e., they radiate thermal energy equally, and there is no contrast. A second reason has been previously discussed -- broad-band imaging washes out narrow spectral details, Even if there are spectral regions where the emissivity of the ink and parchment differ, those differences would be washed out by imaging over the entire 8-14 μm region.

Inks

The type of ink used in the text has considerable impact on the imaging approach selected. Two types of inks were used in ancient texts. The earlier, carbon black, was superseded by iron-gall ink, beginning sometime around the 3rd Century CE. Carbon black inks arc primarily graphite or soot particles suspended in an organic binder and applied with a stylus. The inks do not penetrate or stain the parchment well and basically rest on top, which is why they flake off in spots. Due to the particulate nature of the carbon, however, it adheres to the micro-structure of the parchment (or papyrus reed or ostracon).

Iron-gall inks, also known as gallo-tannin inks, are more like what we think of as an ink. Iron-gall inks contain considerable amounts of iron and can be identified by elemental analysis with x-ray fluorescence, Prepared with organic material that acts as dye, the ink penetrates the substrate more and dyes it black, producing text. With some parchments, though, iron-gall inks may also basically sit on top and be susceptible to flaking.

As mentioned previously, infrared film photography has been used for some time to improve legibility of carbon ink documents. Iron-gall inks fluoresce under UV illumination, so broad-band color photography of the fluorescence has been used to improve legibility of such documents. There may be a better approach to iron-gall ink documents, that would combine imaging spectrometry with laser induced fluorescence, already widely used in biology to sort out cells based upon spectra. The approach is two-fold: (1) Replace broad-band photography with an image cube to measure the fluorescence spectrum. As previously discussed, narrow-band imaging retains spectral features; (2) Excitation-response measurements.

Fluorescent materials usually respond to a number of illumination (excitation) wavelengths and generate a different fluorescence spectrum (response) for each wavelength. Excitation-response curves, acquired with an imaging cube, could be used to more easily delineate ink from parchment and perhaps later writing. For example, separate illumination at 2S3.7 nm, 312.6 nm and 435.8 nm, all produced by a mercury UV lamp, may result in different fluorescence spectra. Another source of illumination would be an argon-ion laser, which covers a number of wavelengths in the blue suitable for this application. A collimating optic is used to produce a large area beam with low power density, Fluorescence spectra tend to be weak and thus require longer exposures; so cooled CCD camera would be necessary.

Analysis and Enhancement

Image analysis for h4SI is done in two stages, First the raw data is taken and the images calibrated by correcting for spectral and spatial illumination effects. As explained above, this step is required for meaningful comparison of the spectra of pixels at different locations in the image. The images are then interactively enhanced. MSI image cube data taken as described herein is called "band sequent ial," and several available software packages can handle the spectral nature of the data, For single image slices, any popular image processing software, such as Adobe Photoshop, will allow most image enhancement operations. However, the imaging data system stores images in a custom 16 bit format, which would require preprocessing to make them available to such popular packages..

The inter-active nature of dealing with digital images is part of the power of this approach to imaging. Selected areas of the text can be enhanced or analyzed in different ways, For example, a document with a considerable range of contrast can be improved by segmenting the image and enhancing each part independently. Spectral tagging can be used to locate different parts of the image quickly; simply selecting a different pixel to tag as the target spectrum allows rapid changes in the analyzed image,

Imaged objects

After consulting with E. Tov, Editor in Chief of the DSS Publication Project, the ABMC submitted to the Israel Antiquities Authority (l AA) a list of Rockefeller Museum plates, from which DSS fragments to be imaged were selected, These were seen as typifying a variety of common problems, such as flaking ink, severe fading of ink, darkening of the background, colored inks and the like.

The IAA selected a dozen plates for examination as a 'pilot project" and during its summer 1994 Jerusalem trip the ABMC field project team imaged the IAA documents listed in Table 1. In addition, the entire Genesis Apocryphon was imaged at the Shrine of the Book under the supervision of M. Broshi, and Z. Meshal arranged for sample imaging of ostraca and other materials from Kuntillet Ajrud at the Israel Museum. Other material used for this research include Roman frescoes from the Harvard Museums, several papyri from the School of Theology at Claremont, manuscripts from the Center for Judaic Studies at the University of Pennsylvania and ostraca and pottery from private collections.

Images and Results

Text

The subject fragments were viewed on-screen and briefly observed and evaluated as they were acquired. Software used for this purpose were Adobe Photoshop and NIH image. The former is a popular image-processing software commercially available for both IBM and Mac platforms. The latter, freeware developed by the National Institutes of Health, is limited to use on a Mac. NIH Image lets one look at individual slices from an image cube in 16 bit format, although it neither uses 16 bits for image processing nor allows one to do pixel tagging and some of the calibration steps. Photoshop and similar image software use 8 bit images,

The real power of the approach becomes apparent when the images arc loaded into an interactive image processor and magnified several times,

In visible light, the fragments of Canticles (ROC 11 19; Ed., E. Tov) clearly show the presence of text. (For his work E. Tov is using the early infrared photographs that yield considerably more information than is apparent from the 1994 visible light photograph in Figure 4, Figures 5 and 6 demonstrate the results of using various enhancement techniques on selected sections of the fragments,

Acquiring image cubes, as indicated above, was a lengthy procedure with the camera and software used during the 1994 field trip, During the project it was determined that the optimal wavelength for the ink and parchment of DSS fragments generally is found in the wavelengths of 970 nm to 1000 nm, Thus, in the interest of time and as no new knowledge was to be gained by taking image cubes of every fragment, image cubes were taken of only selected subjects, However, a new CCD camera and data acquisition software now under development at JPL will reduce the time required to obtain a full image cube to only a few minutes, allowing more freedom to acquire. image cubes.

Results from image cubes of several documents illustrate the spectral nature of the document and how the image changes with wavelength, Figure 7 is a collage of image slices of the raw data from an infrared image cube of 4Q365 RP[c] (ROC 800, Eds., Tov, White). Except for the last image, they have not been enhanced, demonstrating that the text contrast improves as the image wavelength moves further into the infrared. The last image is an enhanced version of the 97o nm image.

Using 4Q53Sam[c] (ROC 406, Ed., E. Ulrich), Figure 8 demonstrates how results differ, even without enhancement, when a subject is imaged at various wavelengths. The first image was taken at 700 nm, which is within the range of visible light; the second at 900 nm, the wavelength at which IR film completely cuts out; and the third at 970 nm, judged optimal for the project at hand. The third image was then enhanced and processed.

Inexplicably, the Genesis Apocryphon (1 QapGen) has suffered darkening and deterioration unprecedented among the DSS. Thus, the entire scroll was electronically imaged. In this case as well, merely imaging the scroll at 970 nrn produced images that contain all the data of the infrared images of the early 1950s and also *reveal new text*. Further image enhancement operations have yielded dramatic results, Figure 9 is a considerably enhanced electronic image of the top of column XV; primary operations used were unsharp mask and histogram adjustments. The bottom 6 lines are new text that were previously unknown [Greenfield and Qimron].

Frescos/Ostraca

Some results from analysis of an image cube of a Roman fresco is are presented in Figure 10. A color image, made by combining three separate slices from the cube (450 nm, 540 nm and 650 rim), is presented to give an idea of how the object appears to the eye in Figure 10a. The other images were made by subtracting slices taken at different wavelengths, after normalizing the data for the two images, Figure 10b is IMAGE(540)-IMAGE(660) while Figure 10c is IMAGE(600)-IMAGE(700). In the color image, towards the center of the fresco, two green triangles are visible among a lot of background. Part of what may a third triangle' has flaked off and the color or shape is not that clear; in addition, based upon spacing, perhaps there should be a fourth triangle as well. In Figure 10b, the green is accentuated and the triangles are very clearly delineated, confirming the third one (the outer edge of its boundary is visible) and a very small piece of a fourth is visible at the top, near the arrow. The blue area appears dark due to an artifact in the processing algorithm. Figure 10c, the difference between yellow and red, highlights the red spots in the middle of the fresco that are in the background clutter. Note that the processing in Figure 10c completely suppresses the green triangles.

All this processing is based upon the spectral signatures of the different colored areas of the fresco.]n Figure 10d, typical spectra from the fresco are presented; they clearly show how the image cube adds a third dimension to the image data,

~'here is not sufficient space for all images of all the objects examined, but wc will show point spectra of some that demonstrate spectral signatures that an image cube can capitalize on. Figure 11a contains the spectra of a First Temple period ostracon, showing the differences between the ink and clay background. The major difference between the clay background and the ink of the ostraca is relative reflectance rather than sharp spectral features. In Figure 11b are spectra from a papyrus text from the Cairo Genizah. All of these spectra are rather broad without sharp features, However, there are some substantial differences in shape, slope and reflectance that can be used to advantage when imaging. Included also is a spectrum of a fragment from the Genesis Apocryphon, Figure 11c

Other Applications

There are many other areas where multi-spectral imaging or other applications of spectral data should bc helpful in archeology and related fields of study:

1) Reading ostraca. Although ostraca are physically durable, the text on many has faded. Since the earliest material is written with carbon ink or pigmented inks, MSI should be helpful in differentiating the ink from the background. Some material, such as the Kuntillet Ajrud ostraca, arc written in reddish inks, presumably from some sort of iron oxide pigment. As previously mentioned, this sort of material shows very clear changes in contrast and legibility as a function of wavelength As an example, the distribution of iron oxide pigment (red) in an Ice Age painting was mapped with an edge filter [Asmus and Marshack].

2) Sorting ostraca. Spectral signatures maybe useful in classifying ostraca, particularly in the near to middle infrared, Many slips and pottery colors that require differentiation and sorting are very close in color. Using point spectra, rather than spectral imaging may be helpful here. As the name suggests, a point spectrometer measures the spectrum of a small, $\leq 1\,mm^2$, area on a sample. Recently, small, portable point spectrometers that cover the 0.2-1 µm region have become available--there is even a version that plugs into a conventional PC slot. Although it is expected that the clay substrate always has basically the same spectrum, the use of coloring agents in the slip, decoration or the body itself may provide a handle for spectroscopy. In effect, this approach would act like a quantitative Munsell chart. For this application, work in the 1-5 pm part of the spectrum may also be useful, although it is more difficult to work in this region.

3) Monitoring of large monuments, In many areas, such MesoAmerica and the East, large scale archeological sites arc subject to damage from plant overgrowth. Biocides are used to control such growth, and continual monitoring and reapplication is necessary. imaging spectrometry can easily detect recurring plant and fungi growth, and is already being used for agricultural and rain forest studies. MSI would detect chlorophyll from algae and plants and reddish, black, or yellow pigments typical of fungi to provide quantitative data for minimized biocide use.

4) Location of water for conservation purposes. Water vapor is easy to detect with MSI due some very strong absorption bands in the near infrared. A major factor in damage to wall paintings and monuments is water. h4SI could map out water transport and concentrations and help chart the hydrodynamics of a site.

5) Painted marbles. There are many examples of painted Greek and Roman sculpture and marble objects in which the paint is now very faint and the motif is unclear 01 uncertain, h4Sl could help restore the painted images by picking up traces of pigment and enhancing the contrast of what is there; the spectral nature of the data would allow restoration of the original coloring. A restored imaged would help not only for interpretation but also in reassembling a fragmented object.

6) Papyri. Some imaging experiments on Egyptian papyri in Greek also showed image improvement when imaged in the infrared.

Conclusions

Multi-spectral imaging is a useful tool for archeology. It can improve contrast and legibility of ancient texts and ostraca and provide new approaches for other uses. Combined with powerful visualization software, the archaeologist can use image cubes to analyze material in new ways for sorting, classifying and reassembling.

For some applications, a full image cube may not be necessary, especially after one has taken a full image cube and knows where in the spectrum to work. For example, as we have learned, many texts can be imaged in the 970-1000 nm region, at a single wavelength, for excellent results, Knowing that going in, a simplified system of a CCD camera and an appropriate filter would reduce costs. Using what is known as a cut-on, edge, or longpass filter, will increase the image signal so that a cooled CCD is not necessary. (A cut-on filter is one that rejects all wavelengths shorter (bluer) than its cut-on wavelength; e.g., a 900 ntn cut-on transmits *only* radiation longer than 900 rim). Since CCDS arc sensitive only to 1000 nm, a CCD camera combined with a 900 nm cut-on filter would image over the spectral range of 900-1000 nm. This spectral range contains 10 times more illumination than when a 10 mm bandpass I.(TF is used for spectral selection, so much shorter exposure times arc possible.

An uncooled CCD camera is much less costly than a cooled one and the cost of an LCTF is also eliminated from the system. A digital camera is preferred, rather than an analog one with a framegrabber. Many CCD cameras have rather small arrays, -700 x 500. To avoid having to take a lot of images and then piecing them together to obtain a full image, a larger array is suggested. Market forces are driving vendors towards larger detectors, and 1024 x 1024 and 1500x 1000 arc now very common,

Electronic imaging has several advantages over film that can be leveraged to advance scholarship, speed publicat ion and improve the quality of the published data:

Electronic images arc available immediately, in real-time, and the scholar can leave the session with images in digital form, ready for further work at home. There is no time delay for chemical processing or subsequent refocusing. Ideally, the editor to whom a document is assigned can participate in imaging sessions to locate the questioned areas and provide immediate feedback. If, for example, a close-up is needed, the imaging system can be adjusted on the spot to obtain the correct spatial detail, The editor can perform, or request that the imaging technician perform, any number of image processing steps until the desired data is obtained, This precludes discovering problems after the shooting session has been completed, a characteristic disadvantage of film photography,

Digital imaging is suitable for routine production line work. A considerable amount of text (or objects) can be imaged, enhanced and made available for scholars in a short time, Providing the highest quality images in a timely manner for scholars will enhance and speed the publication process.

While some cases IR photography yields similar results, IR electronic imaging is sensitive much further into the infrared than film. And, all indications are that the relative reflectance spectral differences, and the text contrast, continue to grow beyond the infrared film cutoff. As a result, electronic images at 1 μm, say, have further improved contrast, especially after digital processing, If one is to go to the effort of re-imaging select ed documents, directly acquiring digital images provides the many advantages above, And, in those cases where a full image cube is desirable, this can *only* be done electronically, as in processing of the fresco image in Figure 11.

At present, the spatial resolution or "spot size" of film images is superior to that of CCD cameras and high magnification images are best done with film. Within a year affordable CCD cameras should match film in this area, Enlarging a 1024 x 1024 digital image too much can produce pixellation, where the discrete nature of the image pixels is visible. However, data from the field project gives clues as to the spatial resolution necessary for DSS, and *by and large this is not a concern for the DSS and other texts*. The physical scale of half-column images of the Genesis Apocryphon is 1 mm/7 pixels, or 142 μm/pixel. At that scale, the text is -18 pixels tall and the letters range from -12-17 pixels wide. As the figures show, the text is clearly legible at this spatial resolution,

Bibliography

Asmus, J. And A, Marshack, Proceedings of the 2nd International Conference on Non-destructive Testing, April, 1988, p. 71.

Appendix A

lAA Documents Imaged During 1994 imaging Pilot l'reject

IAA fragment #	document	PAM #	date imaged
ROC 800	4Q365 RP[c]	43.372-43.373	6-22-94
ROC 198	4Q26 Lev[d]	43.040	6-23-94/6-26-94
ROC 900	4Q317 cryptA Phases of the Moon	43.380	6-22-94/6-26-94
ROC 311	4Q225 psJub[a]	43.251	6-21-94
ROC 406	4053 Sam[c]	43.077	6-23-94
ROC 698	**4Q270** De	43.295	6-23-94
ROC **1119**	**4Q107** Cant[b]	43.093	6-21-94
ROC 1085	**4Q27** Num[b]		6-22-94
ROC 830	**MUR 9** **MUR 10**	41.658/41.256 40.192/41.327	6-26-94
ROC 122B	**4Q377** apocrMoses C	43.154-verso	6-26-94
ROC 1092	**4Q47** Josh[a]	43.060/43.057	6-27-94
ROC 215	4Q2 Gen[b]	43.004	7-11-94
ROC 127	4Q407 ShirShabb[h] 4Q413 Sapiential Work	43.485 43.499	7-11-94

A MULTI-SPECTRAL IMAGING CUBE

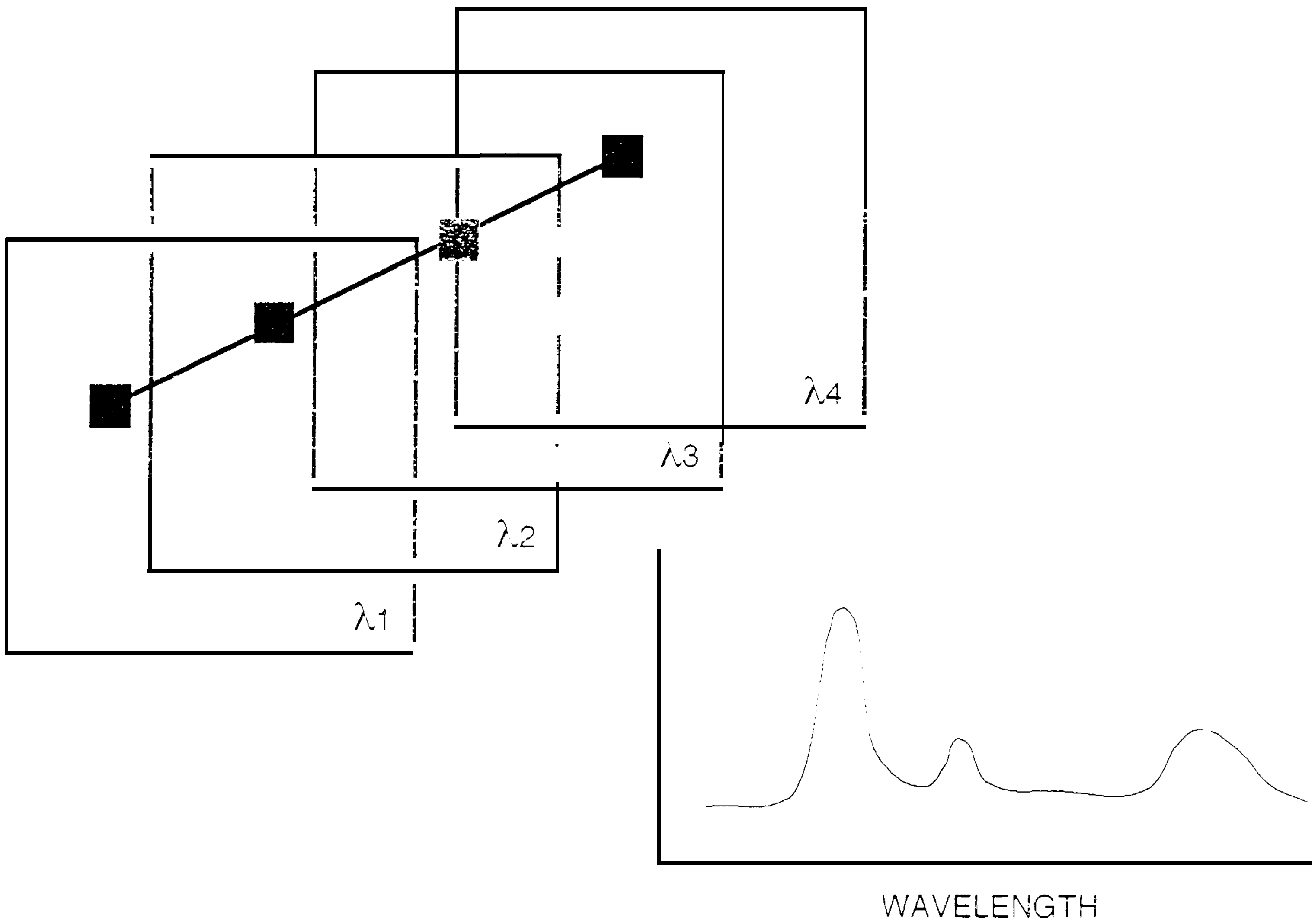
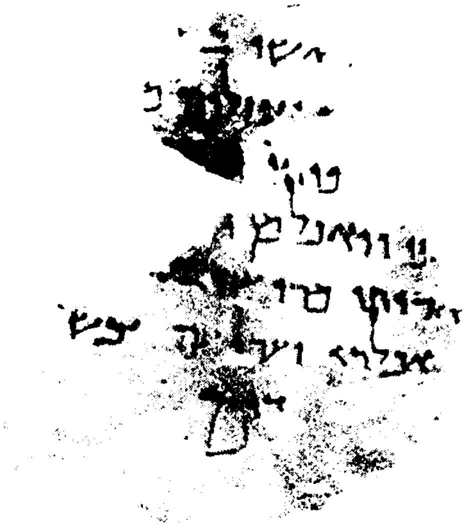


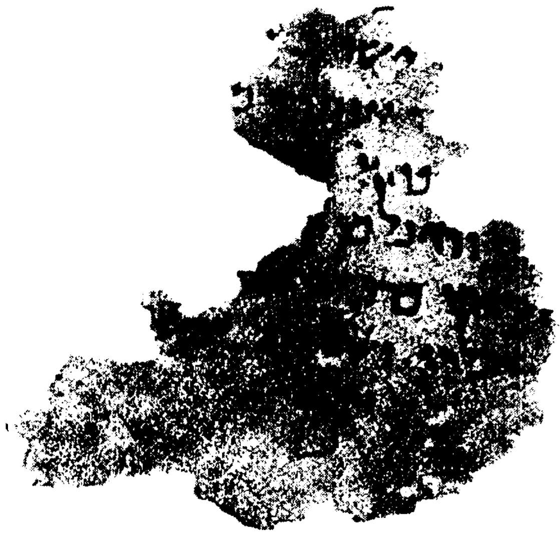
Figure 2

Figure 4



Canticles 3a

Canticles 3b



Canticles 3c

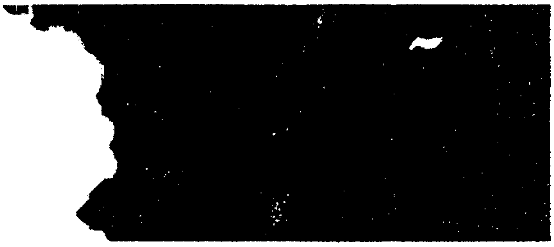
Canticles 3d

Figure 5

Canticles 1a

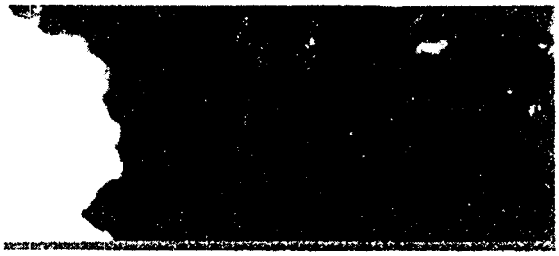
Canticles 1b

Figure 6

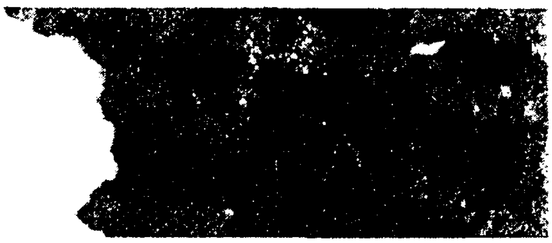


640 nm

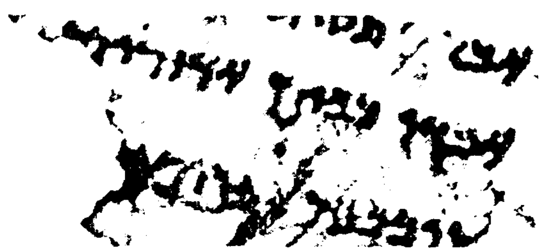
680 nm



720 nm



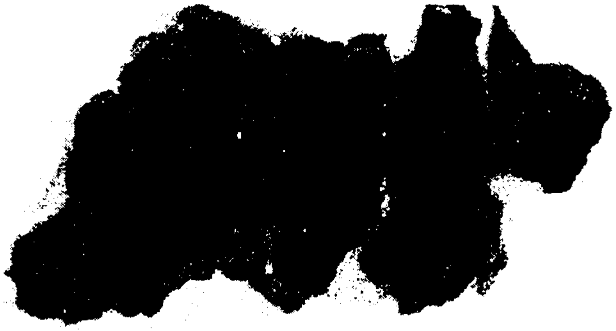
970 nm



Enhanced image

[illegible]

Figure 7



700 nm

900 nm

970 nm

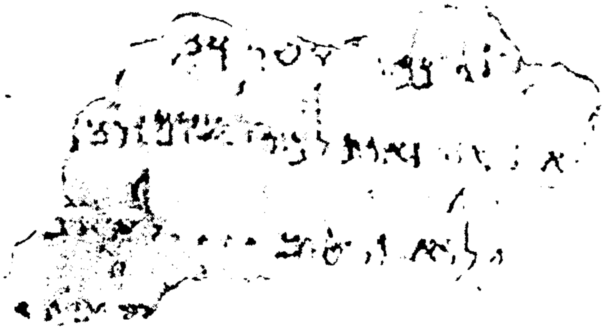


Figure 8

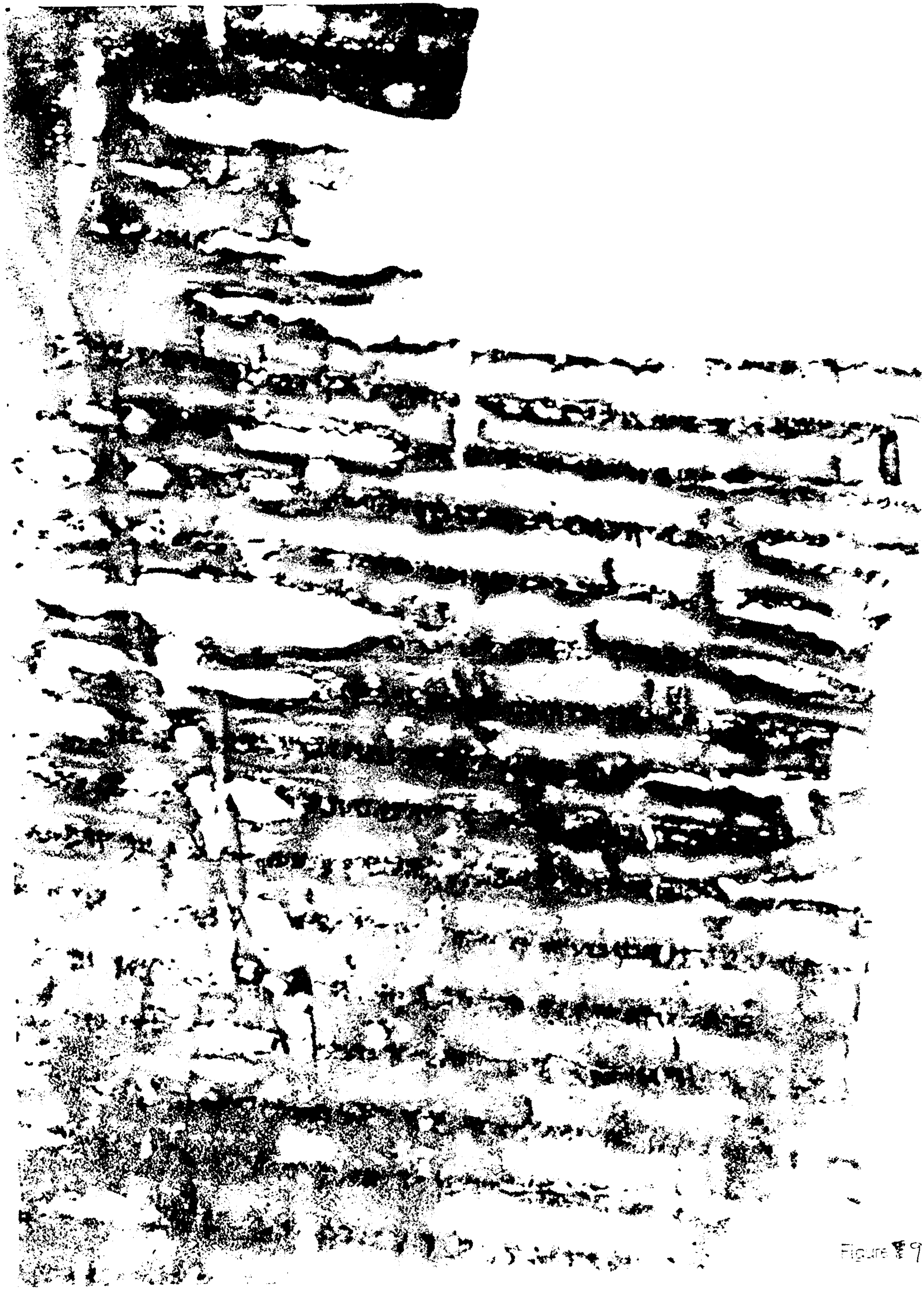
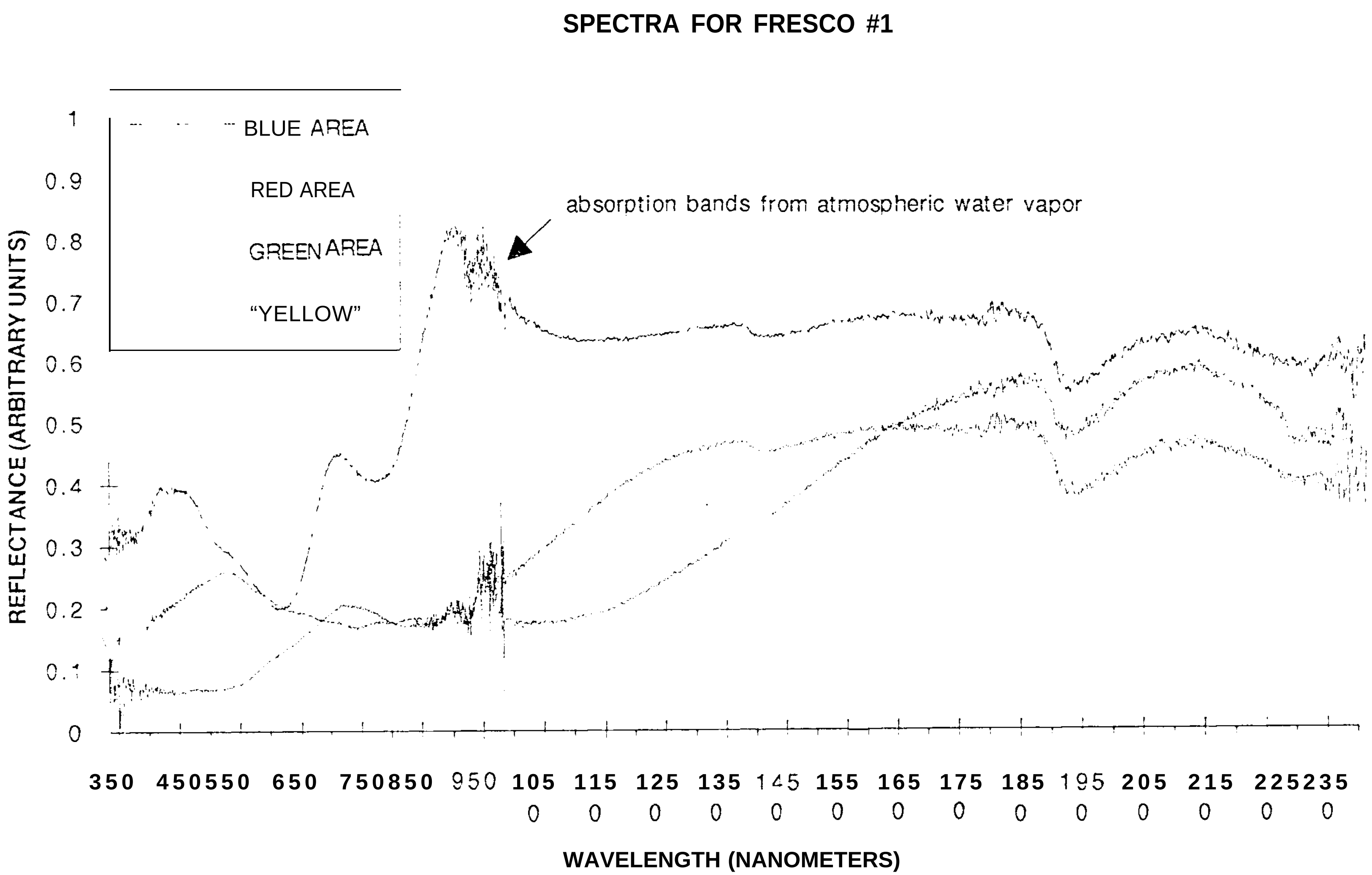


Figure 9

Figure 10d


SPECTRA FOR FRESCO #1
BLUE AREA
RED AREA
GREEN AREA
"YELLOW"
absorption bands from atmospheric water vapor
REFLECTANCE (ARBITRARY UNITS)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350 450 550 650 750 850 950 1050 1150 1250 1350 1450 1550 1650 1750 1850 1950 2050 2150 2250 2350
WAVELENGTH (NANOMETERS)

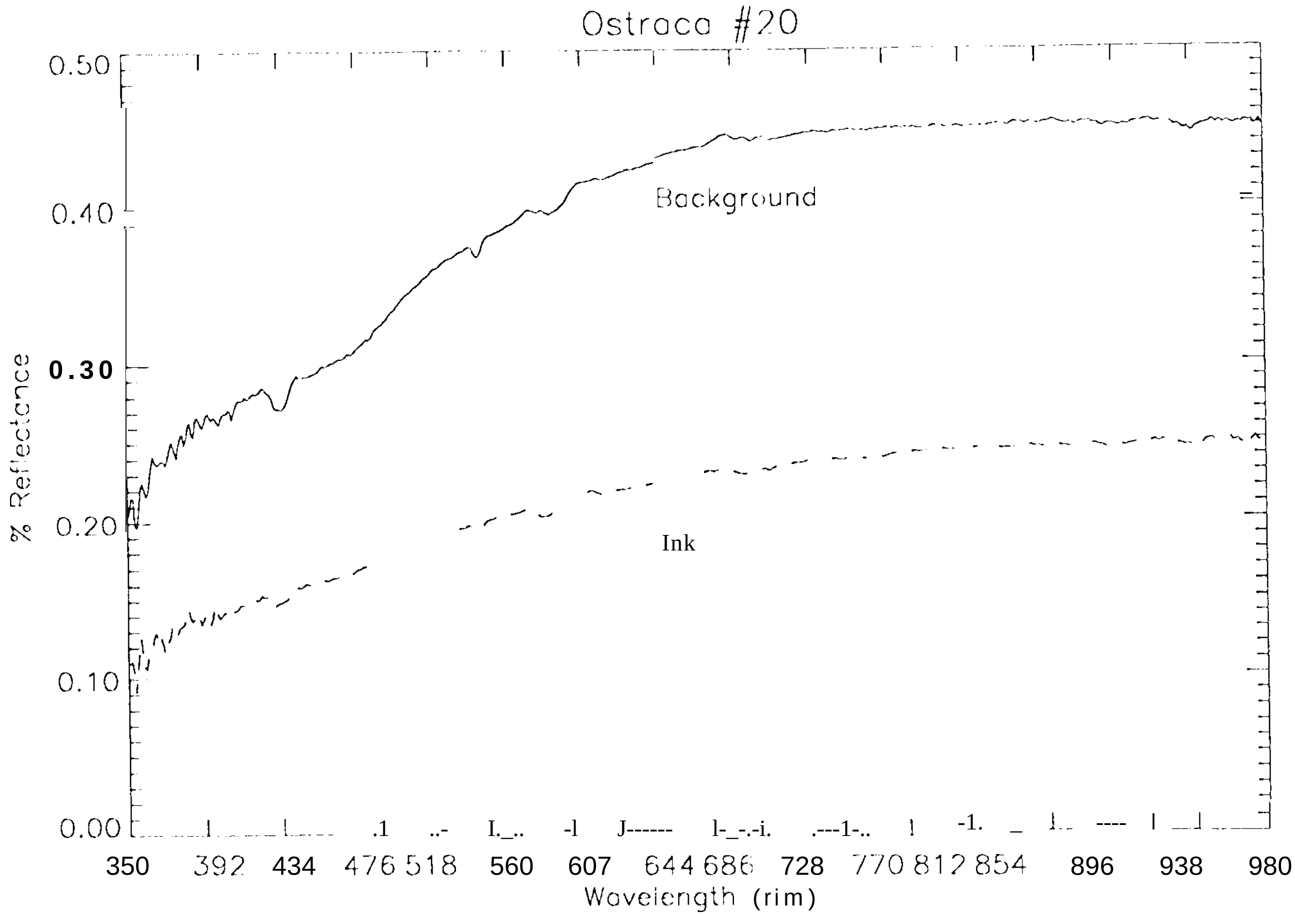

Ostraca #20
Background
Ink
% Reflectance
0.50
0.40
0.30
0.20
0.10
0.00
350
392
434
476
518
560
607
644
686
728
770
812
854
896
938
980
Wavelength (rim)

Figure 11a

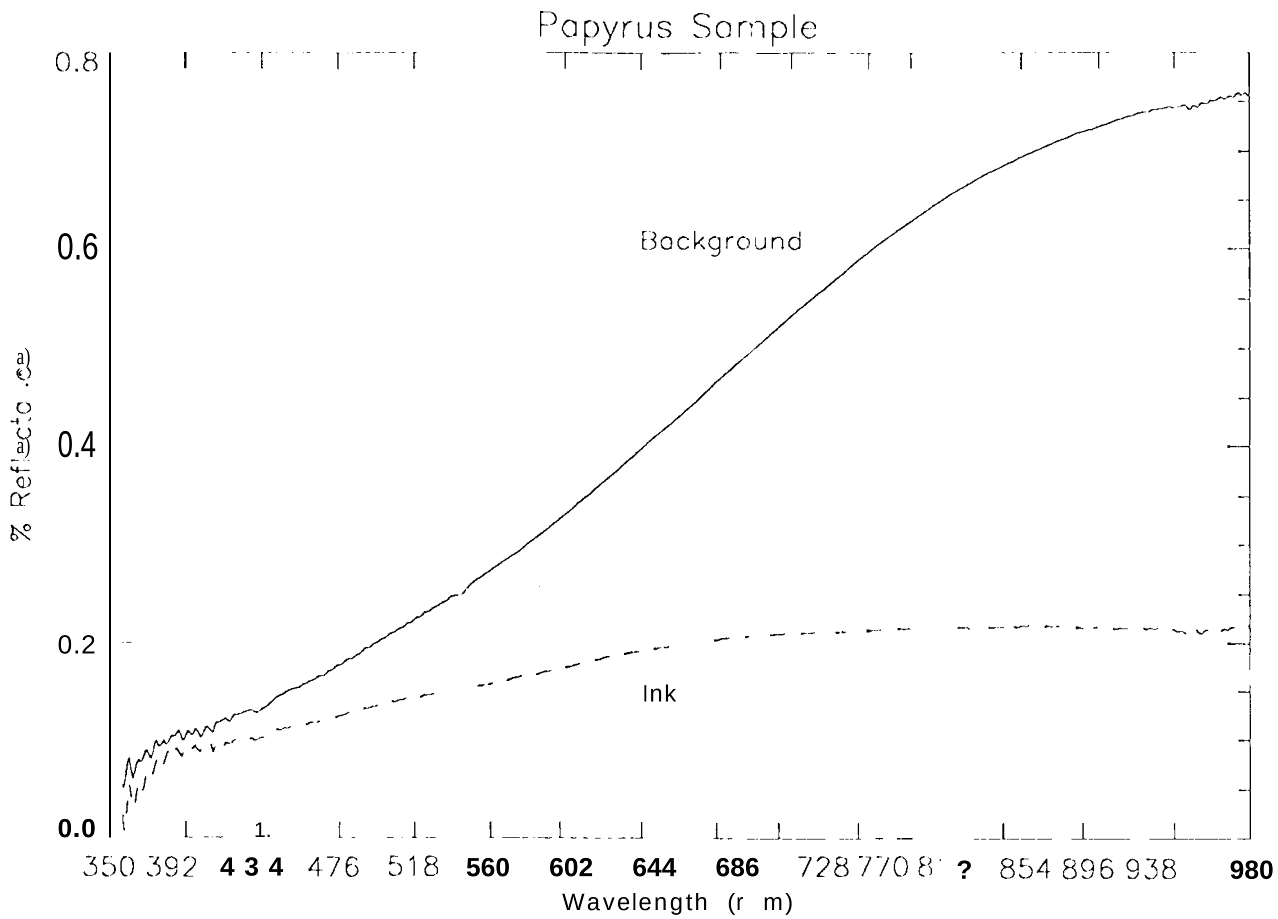

Papyrus Sample
Background
Ink
% Reflectance
0.8
0.6
0.4
0.2
0.0
350 392 434 476 518 560 602 644 686 728 770
854 896 938 980
Wavelength (nm)

Figure 1lb