Multispectral Imaging and Spectral Classification of Naj Tunich Pigments

Gene A. Ware
Brigham Young University
Provo, Utah

James E. Brady
California State University at Los Angeles
Los Angeles, California

Curtis E. Martin
United States Air Force Academy
Colorado Springs, Colorado

Abstract

Archaeologists frequently discover artifacts that contain a great deal more information than can be detected with the human eye. This is particularly true of contexts with inscriptions or paintings. Painted texts in Maya caves are among the rarest of these contexts with only five sites currently known. Naj Tunich is preeminent among these as its corpus of inscriptions exceeds that of the other four combined. Because caves were considered sacred features in the ancient Maya landscape, cave inscriptions may deal with esoteric beliefs and fundamental tenets of Maya religion that are not recorded elsewhere. The decipherment of these texts may, therefore, provide important insights into Maya culture.

Visible and near-infrared multispectral images of the Naj Tunich inscriptions have been obtained. Selected images have been analyzed and differences in the spectral reflectance of the pigments noted. Spectral signatures were used to classify pigments and suggest that markedly different pigment compositions were used at Naj Tunich. At least three different pigments have been shown to be in use. Several drawings contain more than one pigment and show evidence of touch-up or over-painting.

Pigment compositional differences have been used to reevaluate proposed artistic relations between drawings. Spectral classification has isolated unsuspected temporal and artistic complexity in the Naj Tunich inscriptions which have led to increased archaeological understanding of the production and significance of these works. Spectral classification results and implications for the Naj Tunich corpus are presented.

1. Introduction

Discovered in 1980, Naj Tunich is a large cave site located in the foothills of the Maya Mountains in southeastern Petén, Guatemala. The Naj Tunich black line-paintings, which tend to be located deep in the 3.5 km of tunnels, were recorded by Andrea Stone.[1] Stone, working without the benefit of the information presented here, stylistically analyzed the corpus of almost one-hundred drawings and distinguished ten different artists' hands that she felt had been responsible for more than a single drawing.

Stylistic analysis, particularly with non-Western art, is by its very nature an intuitive and impressionistic undertaking. This is in part due to the fact that most analyses focus exclusively on iconographic motifs. Even when great pains are taken to clearly define the criteria that guide decision making, disagreements inevitably arise simply because other analysts perceive elements or their organization differently.

Recent advances in imaging technology and software now permit us to characterize pigments using spectral reflectance characteristics and create a data set that is independent of the iconography. While this data cannot eliminate all of the uncertainty of stylistic analysis, the utility of a set of objective data points to guide the analysis of the Naj Tunich inscriptions will be demonstrated.

2. Multispectral Imaging at Naj Tunich

The basic techniques of archaeological multispectral imaging originate with the remote imaging of the earth from aircraft and satellites. Remoteness in an archaeological setting, however, has more to do with locations in steamy jungles and humid caves than the distance from the sensor. In archaeological imaging, the distance from the sensor is measured at most in a few meters. Images of the same scene, each at a different wavelength, may be stacked on top of each other to form a multispectral image cube. This multispectral image cube may then be processed in a variety of ways to reveal image information associated with spectral differences.

In June of 1998, more than a third of the Naj Tunich inscription corpus were multispectrally imaged using a Kodak Megaplus Camera (Model 4.2i) with a spatial resolution of 2024 by 2044 pixels. Spectral definition was obtained by using a set of optical interference filters mounted in a filter wheel. The filters, centered at wavelengths of 400 through 1000 nm in increments of 50 nm, have a bandwidth of 40 nm. Those filters selected for the analysis reported herein include the 450, 550, 650, 750, 850, and 950 nm center wavelengths.

The topography of Naj Tunich is expansive both in the cross section of its passages and in the extent to which the passages penetrate the limestone. Operation as deep as one kilometer into the cave required the camera, lighting, and associated computer hardware to be operated from a marine battery which was recharged with a generator outside of the cave. Ring and auxiliary strobe units were used for lighting to focus, set camera parameters, and the final images. Image data were recorded on computer hard drives and transferred to compact disks (CDs) on site.

3. Spectral Classification

If multispectral images are stacked on top of each other in a vertical fashion, the resulting image cube may be viewed downward from the top at a particular spatial location. Such a view will produce a sequence of image pixels from the same image location but with different wavelengths. This pixel sequence defines a spectral reflectance vector for the selected spatial location. The multispectral image cube, then, may be regarded as a set of spectral reflectance vectors, $\bar{\mathbf{x}}_{ij}$, one for each spatial pixel location in the images.

The objective of spectral classification is to group or cluster spectral reflectance vectors with similar spectral characteristics in such a way that a particular vector is more like the center of its assigned cluster than it is like the center of any other cluster. In order to do this, a metric for the distance between vectors must be defined. The metric chosen for this analysis is

$$d(\hat{\mathbf{x}}, \hat{\mathbf{y}}) = 1 - \hat{\mathbf{x}} \cdot \hat{\mathbf{y}}, \tag{1}$$

where $d(\hat{\mathbf{x}}, \hat{\mathbf{y}})$ is the metric, $\hat{\mathbf{x}}$ and $\hat{\mathbf{y}}$ are normalized spectral reflectance vectors, and the dot represents the inner or dot product. Since $\hat{\mathbf{x}} \cdot \hat{\mathbf{y}}$ is equivalent to $\cos\theta$, where θ is the angle between the two normalized reflectance vectors, this metric is angle-based and commonly known as a spectral-angle measure.

Linde, Buzo, and Gray proposed an unsupervised vector quantization (VQ) algorithm known as the LBG algorithm.[2] The approach of this traditional VQ algorithm is to group spatial vectors selected from adjacent locations in a particular image into clusters where each spatial vector is closer to the center of its assigned cluster than it is to the center of any other cluster. At the completion of the algorithm, a cluster center is the arithmetic mean of all vectors in the cluster. This conceptually straightforward algorithm does not require accurate knowledge of the data statistics and selects the clusters in an unsupervised manner.

The LBG algorithm, with the traditional distance-based metric replaced by the spectral-angle measure, was used to process selected Naj Tunich inscriptions with the objective of pigment classification. Application of the modified LBG algorithm, constrained to two clusters, separated pigmented from unpigmented vectors in virtually every case. When two pigments appeared to be present in a drawing, a four-cluster analysis assigned two clusters to the pigments and distributed the remaining clusters to the background.

4. Spectral Classification Results

Drawing 62* is a profile representing a human face (Fig. 1). At visible wavelengths (represented by 550 nm), it appears uniformly dark—so much so that Stone indicates that the pigment is both original and well preserved. However, portions of the drawing around the nose, eye, lip, and fang fade significantly in the infrared. The pigment that remains dark in the infrared is likely carbon-based, while the pigment that fades in the infrared may be mineral-based. With two different pigments present, it is appears that the drawing was either overpainted at the time of creation or touched up at a later date.

Spectral classification previously performed with D62 using four clusters clarifies the pigment differences.[3] Not clearly illustrated by Fig. 1, Fig. 2 show that vestiges of both pigments remain along the rear of the jaw with small remnants of the carbon-based pigment on the nose, lip, and fang.

Sixteen 10×10 pixel swatches were taken from 14 different drawings at Naj Tunich for the spectral classi-

*We will follow the numbering system initiated by Stone for all the drawings in the Naj Tunich corpus. Also, rather than repeating the designation "Drawing" each time, we will abbreviate it as D followed by the number, e.g., D28 for Drawing 28.

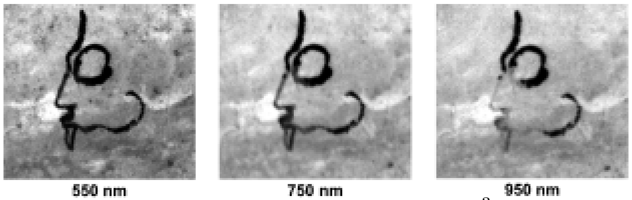

Figure 1: *Drawing 62 at 550, 750, and 950 nm.*[3]

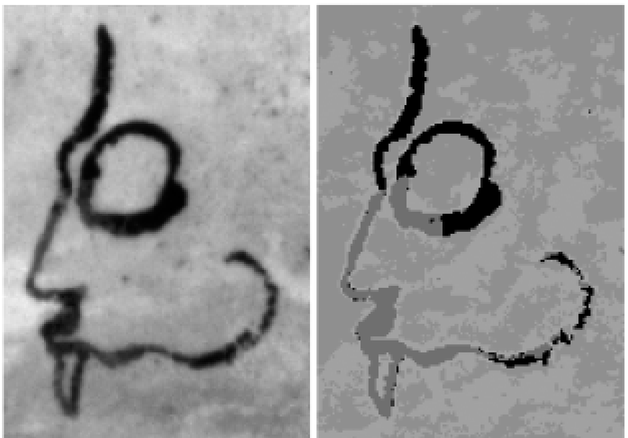

Figure 2: *Drawing 62 at visible wavelengths (left) and the results of four cluster spectral classification (right).*[3]

fication analysis reported herein. Multiple swatches were taken from D34 and D62 because previous work[3] had shown that these drawing contained multiple pigments. The results of the spectral classification analysis of D18, D25, D28, D34 (dark and light pigment), D39, D40, D49, D52, D62 (pigment from the lip and dark eye), D65, D70, D72, D76, and D83 are:

1. D70, D72, and D83 cluster together,
2. D18 clusters with D76
3. D34$_{light}$ is associated with the D18–D76 cluster,
4. D34$_{dark}$ is about half D65 and half D34$_{light}$,
5. D65 clusters with D62$_{lip}$,
6. D39 clusters with D62$_{eye}$, and D39 is associated with D40,
7. D49 clusters with D52,
8. D28 spans the region between the D18–D39 and D62$_{eye}$–D76 clusters,
9. D25 does not appear to cluster with any other drawing.

In prior work,[4,5] the normalized spectral reflectance curves of D49 and D52 were so similar that it was suggested that both had been painted with the same pigment. Also, a lack of similarity was noted between the curves for D34$_{dark}$ and D34$_{light}$, and between the curves for D25 and D49. All three of these conditions are verified by the above clustering results providing some confidence in the current analysis.

5. Archaeological Implications

Pigments which do not fade in the infrared likely have a strong carbon component. One such pigment is that used for the seated dwarf of D83. The clustering of D70 and D72 with D83 (item 1) implies that all three are carbon based. Another apparent carbon-based pigment is D62$_{eye}$ which clusters D39 and D40 (item 6). Given this apparent fineness of discrimination between carbon-based pigments, the cases of pigment clustering become particularly important because they suggest that the very same paint was used in more than one drawing.

From stylistic analysis, Stone assigns 31 of the Naj Tunich inscription to 10 different artists. The current analysis does not test pigments from the drawings Stone assigned to Artist 1 and Artist 5, and not all drawings assigned to the remaining artists were sampled.

Stone attributes the seated figure of D72 and the royal dwarf of D83 to Artist 6. This is clearly supported by the cluster of item 1. Stone also assigns the figure of D18 to Artist 6, but item 2 shows that the pigment of D18 clusters with that of D76, which figure Stone assigns to Artist 7. Stone indicates that the style of Artists 6 and 7 is closely related and that they may indeed be the same individual. This undoubtedly made the stylistic decision particularly difficult.

D68 contains both glyphs and figures through which Stone links the glyphs of D70 with the figure of D76 and assigns both to Artist 7. However, D70 is clustered with the figures of D72 and D83 (item 1), which Stone assigns to Artist 6. If Artists 6 and 7 were distinct, they each appear to have used the same two pigments in their drawings. All of this is not to say that Stone's stylistic analysis is incorrect, but it would certainly be useful to examine these drawings a second time in light of the results from spectral classification.

Spectral classification previously performed on the entire D34 has shown that the original carbon-based pigment (D34$_{dark}$) was likely over-painted with a mineral pigment (D34$_{light}$).[3] This two-pigment result is also supported by the clusters of items 3 and 4. It is the later D34$_{light}$ mineral pigment that matches with the pigment in D18–D76 cluster (item 3). The carbon-based pigment of D34$_{dark}$ appears to be a combination of D34$_{light}$ and D65 (item 4), which is not surprising because of the apparent overpainting. Stylistically, Stone assigns D34 and D65 to Artist 4, D18 to Artist 6, and D76 to Artist 7 with the qualification that Artists 6 and 7 may be the same individual—a possibility strongly supported by the D18–D76 cluster of item 2. The clustering data also supports Stone in assigning D34 and D65 to Artist 4, but raises the possibility that Artists 4, 6, and 7 are the same individual.

The previous analysis of D62, illustrated by Fig. 2, indicated that two pigments were in use. This conclusion is also supported by items 5 and 6 of the current analysis. This drawing was probably initially painted with the carbon-based $D62_{eye}$ pigment and later touched up with the $D62_{lip}$ mineral-based pigment. Stone assigns D62 along with untested D60, D61, and D63 to Artist 9. The D65–$D62_{lip}$ cluster of item 5 indicates that D62 should be associated with Artist 4 (and possibly Artists 6 and 7) for the touch up. It is possible, however, that these three artists were distinct but used the similar pigments. The D39–D40 cluster of item 6 supports Stone's assignment of D39 and D40 to Artist 8, which was done on the basis of their close proximity. The D39–$D62_{eye}$ cluster (item 6) links the original rendering of D62 with Artist 8 in place of Stone's assignment of Artist 9.

The D49–D52 cluster of item 7 does not support Stone's assignment of D52 to Artist 3 and D49 to Artist 10. Stone also assigns D25 to Artist 10, but the lack of clustering in item 9 would indicate that D25 and D49 are not related. The five-way association described in item 8 requires further investigation.

6. Conclusions

The initial results of the spectral classification of the Naj Tunich pigments show that the method assists stylistic analysis by providing independent and objective data points to guide decision making. Although our data have been used to "test" Stone's results, we see the method as being complementary rather than in conflict with stylistic analysis.

We were pleased that many of the attributions made by Stone were supported by the spectral clustering analysis. In some cases, Stone was forced to make difficult decisions because of the close stylistic similarity of the drawings. Here, spectral classification provided additional insight detecting relationships not stylistically apparent. Spectral classification also grouped drawings that were difficult to link stylistically because they had no common points for comparison such as D49–D52 and D39–D62. We have also shown that an attribution made on the basis of the close proximity of two drawings was probably correct. In this case, Stone made difficult decisions with little stylistic evidence. In all of these situations, the data provided by spectral classification were especially helpful.

The possibilities do not end here. Many of the Naj Tunich inscriptions are so fragmentary that stylistic analysis simply is not possible. Spectral classification, however, can recover relationships from a single spot of pigment.

7. Acknowledgments

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8. References

1. Andrea J. Stone, *Images from the Underworld: Naj Tunich and the Tradition of Maya Cave Painting*, Austin: University of Texas Press, pp. 112–117, 217, (1995).
2. Yoseph Linde, Andrés Buzo, and Robert M. Gray, "An Algorithm for Vector Quantizer Design," *IEEE Transactions on Communications*, **COM-28(1):**84–95, (1980).
3. Gene A. Ware, Douglas M. Chabries, Richard W. Christiansen, James E. Brady, and Curtis E. Martin, "Multispectral Analysis of Ancient Maya Pigments: Implications for the Naj Tunich Corpus," *Proceedings of the IEEE 2000 International Geoscience and Remote Sensing Symposium*, **VI:**2489-2491, (July 24–28, 2000).
4. James E. Brady and Gene A. Ware, "Las Inscripciones de Naj Tunich: Avances Recientes de la Imagen Multi-Espectral," Paper presented at the XIV Simposio de Investigaciones Arqueológiacas en Guatemala, Guatemala, (July 17-21, 2000).
5. Gene A. Ware and James E. Brady. "Multi-Spectral Analysis of Ancient Maya Pigments: Implications for the Naj Tunich Corpus," *Center*, National Gallery of Art, **19:**132–135, (1999).

9. Biographies

Gene A. Ware received a PhD degree in Electrical Engineering from Utah State University and has taught at both Utah State University and Brigham Young University. Dr. Ware developed a visible/NIR multispectral imaging system and has specialized in archaeological multispectral imaging and analysis.

James E. Brady received his PhD in Archaeology from UCLA in 1989. He taught at The George Washington University from 1994–1998 and at California State University, Los Angeles since 1988. He is interested in the role of religion and ideology in Maya society and has specialized in cave archaeology.

Curtis E. Martin received a BSEE degree from Brigham Young University in 1991, and MS (1993) and PhD (1996) degrees from the Air Force Institute of Technology, both in Electrical Engineering. He is currently an assistant professor of mathematics at the U.S. Air Force Academy. His current research interests include data clustering, vector quantization, and multispectral image processing.