SOURCING THE PALYGORSKITE USED IN MAYA BLUE: A PILOT STUDY COMPARING THE RESULTS OF INAA AND LA-ICP-MS

Dean E. Arnold, Hector Neff, Michael D. Glascock, and Robert J. Speakman

Maya Blue is an unusual blue pigment consisting of a clay-organic complex of indigo and the unusual clay mineral palygorskite (also called attapulgite). Used on pottery, sculpture, and murals from the Preclassic to Late Colonial periods largely in Mesoamerica, blue was the color of sacrifice and ritual. Did the palygorskite used to make Maya Blue come from a restricted source in Yucatán like Shepard, Arnold, Arnold and Bohor believed, or from widespread sources like Littmann argued? This report presents the results of a pilot study comparing INAA and LA-ICP-MS analysis of 33 palygorskite samples collected from different parts of the Maya area. These data reveal that it is possible to discriminate mineral source locations, and that it should be possible to determine whether the palygorskite used to make Maya Blue came from widespread sources or was traded widely from one or a few sources. Consideration of contextual information such as agency, landscape and language suggest that the Shepard/Arnold/Bohor hypothesis is more plausible than that of Littmann. No matter which hypothesis is supported, however, each has significant implications for the relationship of the diffusion of Maya Blue (or the knowledge of its production) to Maya social organization.

El azul maya es un inusual pigmento que posee una estructura molecular que combina la tinta añil y la arcilla palygorskita, también llamada atapulgita. Utilizado en cerámica, escultura y pinturas murales desde el Pre-clásico hasta tiempos coloniales en la mayor parte del sur y centro de Mesoamérica, el azul era el color litúrgico y de sacrificio. ¿La procedencia de la arcilla palygorskita estaba limitada a una fuente en Yucatán como Shepard, Arnold, y Arnold y Bohor sugeríen; o a un espectro de fuentes ampliamente distribuidas como sugiere Littmann? Presentamos un estudio piloto en el que comparamos los resultados de los análisis de 33 muestras de palygorskita realizados por INAA y LA-ICP-MS, procedentes de diferentes lugares del área maya. Estos datos indican que se pueden discriminar distintas fuentes de palygorskita. Así mismo, es posible determinar si se utilizó palygorskita para fabricar el azul maya de una fuente limitada, o de varias -quizás por intercambio. Considerando la información lingüistica, de agencia social y del paisaje, se sugiere que la hipótesis de Shepard/Arnold/Bohor es más plausible que la de Littman. Sin embargo, y más allá de cuál es la más adecuada, cada una de ellas brinda implicancias significativas para entender la difusión del azul maya (o el conocimiento de su producción) en la organización social maya.

Maya Blue is an unusual blue pigment applied to pottery, sculpture, and murals in a large portion of Mesoamerica from northern Yucatán to highland Guatemala and central Mexico (Cabrera Garrido 1969; Gettens 1962; Reyes-Valerio 1993). Used predominantly during the Classic and Postclassic periods, production also appears to have survived into Colonial times (Cabrera Garrido 1969; Gettens 1955, 1962:560; Haude 1998; Ortega et al. 2001; Polette et al. 2000; Reyes-Valerio 1993; Sánchez del Río et al. 2004; Tagle et al. 1990; Torres 1988). Not based on copper, lapis lazuli, or azurite (José-Yacamán et al. 1996), Maya Blue is a unique pigment in which indigo is chemically bound to the clay mineral palygorskite (Cabrera Garrido 1969; Chianelli et al. 2005:133; Fois et al. 2003; Gettens 1955, 1962:563; Hubbard et al. 2003; Kleber et al. 1967:44-46; Ortega et al. 2001:755). It is resistant to diluted mineral acids, alkalis, solvents, oxidants, reducing

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agents, moderate heat, and biocorrosion and shows little evidence of color deterioration over time, even after centuries of exposure to the harsh tropical climate of southern Mesoamerica (Fois et al. 2003; Gettens 1962; Sánchez del Río et al. 2006). These characteristics and its widespread use in ritual contexts have stimulated the interest of archaeologists, chemists, and material scientists for more than 75 years since Maya Blue was first identified by Merwin (1931) on the murals of the Temple of the Warriors at Chichén Itzá.

The use of Maya Blue in ritual contexts implies that the pigment was highly valued and that it came from restricted sources. Was Maya Blue or the palygorskite used to make it widely traded, or was the pigment made from local sources?

Ethnographic research has revealed palygorskite mining, use, and trade among the contemporary Yucatec Maya in Ticul and Sacalum (Figure 1; Arnold 1967, 1971; Arnold and Bohor 1975, 1976; Folan 1969), and has suggested two probable ancient mining sites for the mineral. The first was the cenote at Sacalum (Arnold 1967, 2005b; Arnold and Bohor 1975, 1976; Folan 1969). The second source was located at Yo' Sah Kab near Ticul (Arnold 2005b). But, could palygorskite have been mined by the ancient Maya in other locations?

Between 1965 and 1994, Arnold and Bruce F. Bohor, a clay mineralogist formerly of the Illinois Geological Survey and the U.S. Geological survey, identified several palygorskite sources in the Maya area and collected samples from them. Are these sources different enough chemically that they can be discriminated to find a source (or sources) for Maya Blue, or for the palygorskite used to make it? Or, are palygorskite clays sufficiently similar in composition to preclude source identification? Because instrumental neutron activation analysis (INAA) has been used successfully to discriminate contemporary resource areas of pottery making communities in Yucatan and Guatemala (Arnold 2005a; Arnold et al. 1991, 1999, 2000), INAA would seem to be the technique of choice to discriminate the palygorskite sources used in Maya Blue. Laser ablation-inductively coupled plasma-mass spectroscopy (LA-ICP-MS), however, also can analyze numerous elements with high precision and sensitivity. LA-ICP-MS is also relatively fast, and does not require pigment removal for analysis; thus it may be a better technique for the analysis of palygorskite and Maya Blue. In this paper, we compare INAA and LA-ICP-MS analyses of palygorskite from several different sources in order to assess the feasibility of the LA-ICP-MS approach.

The Palygorskite Component of Maya Blue

Palygorskite was first identified as a component of Maya Blue in the early 1960s (Shepard 1962) when the mineral was called attapulgite (see Bailey et al. 1971:131; Carroll 1970:42). Although it is classed as a clay mineral and is plastic, palygorskite does not have a platy morphology like other clay minerals. Rather, like sepiolite, it has a fibrous or needle-like structure (Carroll 1970:42; Grim 1968:44-45; Moore and Reynolds 1997:243).

Because the indigo in Maya blue is an organic compound, it has no trace elements like those present in inorganic clays, but rather consists of carbon, hydrogen, nitrogen, and oxygen (Cabrera Garrido 1969:29; Leona et al. 2004:40). Palygorskite, on the other hand, is a hydrated magnesium aluminum silicate (Grim 1968) that contains many trace elements. Identifying palygorskite sources thus could provide a surrogate compositional signature for the Maya Blue pigment itself because most of the inorganic trace elements in the pigment come from the clay, not from the indigo.

Although preparation practices probably added some trace elements to the palygorskite in making Maya Blue, they would not be expected to significantly affect the ability to relate the pigment to palygorskite sources. First, experimental data has revealed that Maya Blue can be made with .5 to 2 percent indigo (Hubbard et al. 2003; Sánchez del Río et al. 2006; Van Olphen 1966). In the context of the 33 elements used in the compositional analyses in this study, it is likely that trace elements from the indigo and those from the trace element "contamination" from preparation practices, if they exist, would not significantly affect the ability to characterize the Maya Blue pigment compositionally and relate it to the composition of palygorskite sources. Second, the use of laser ablation combined with a scanning electron microscope can select pigmented palygorskite for analysis and exclude any extraneous mineral (such as calcite or dolomite) or organic material. Finally, trace elements of soluble salts that would "contaminate" the palygorskite in

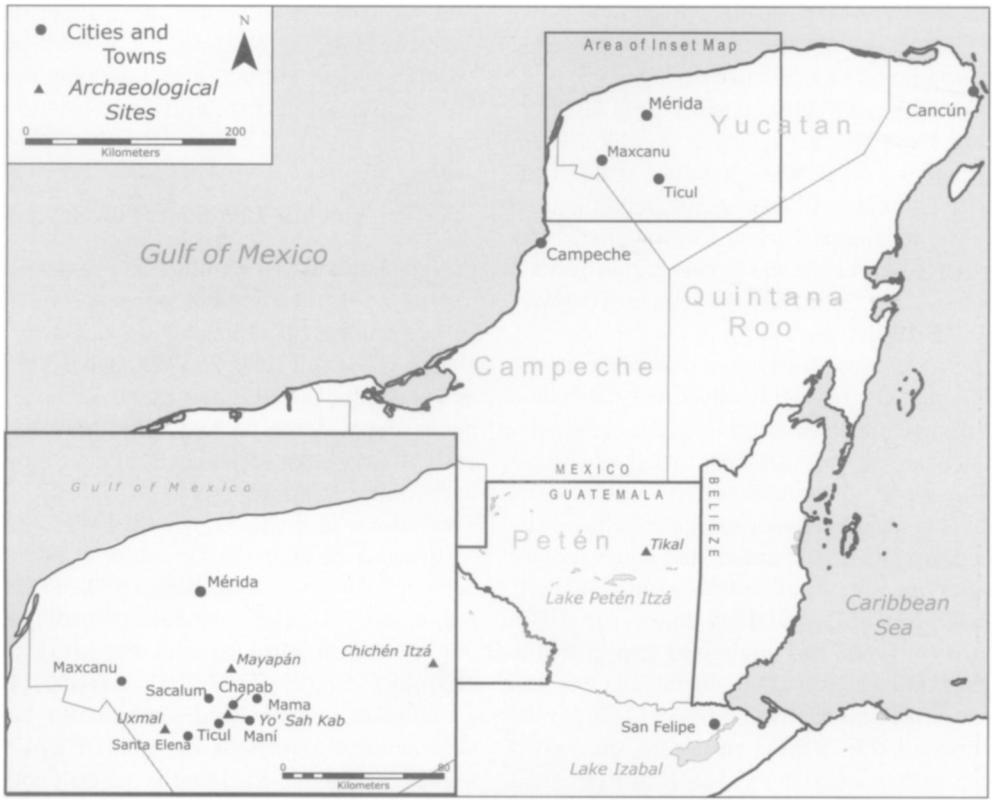

Figure 1. Map of the Yucatan peninsula and adjacent area showing cities, towns and archaeological sites mentioned in the text.

the preparation of Maya Blue are few in number compared to the diversity of insoluble elements found exclusively in the clay. In sum, the preparation of Maya Blue would not appear to affect significantly the ability to characterize sources of Maya Blue using the analysis of palygorskite as a surrogate.

The late Edwin R. Littmann (1980) challenged previous research and suggested that at least some Maya Blue was a blue montmorillonite. Unfortunately, significant problems existed with Littmann's analyses and interpretations (Arnold 2005b; Roundhill et al. 1989). Although Littmann (1980) knew about the previously published analyses that had already established that Maya Blue was a combination of indigo and palygorskite (Cabrera Garrido 1969; Kleber et al. 1967), he chose not to take them seriously (Roundhill et al. 1989). Indeed, 13 years earlier, Kleber et al. (1967) identified the components of attapulgite (palygorskite) and indigo in Maya Blue using X-ray diffraction and infrared absorption spectroscopy. A subsequent analyst (Cabrera Garrido 1969) used the techniques of Kleber et al. (1967) to create a flow chart for analysis of Maya Blue using those techniques. Contrary to Littmann's montmorillonite hypothesis, however, continuing technical work on Maya Blue affirms the crucial role of palygorskite in the unique qualities of this unusual pigment and the unique chemical bonding between palygorskite and indigo (Chianelli et al. 2005; Fois et al. 2003; Hubbard et al. 2003; José Yacamán et al. 1996; Ortega et al. 2001; Polette et al. 2000; Sánchez del Río et al. 2004, 2006).

Cultural Awareness of Palygorskite

Maya Blue is not just an interesting and unusual pigment that was valued and used in the ritual of the ancient Maya. Rather, the modern Yucatec Maya of Ticul and Sacalum (Figure 1) recognize the properties of palygorskite itself (called *sak lu'um* 'white earth') and utilize it for medicinal purposes (Arnold 1967:35, 1971, 2005b). The pot-

ters of Ticul use it as the crucial ingredient in a mixture with calcite and dolomite for tempering all noncooking pottery (Arnold 1967, 1971, 2005b).

The link between palygorskite and Maya culture was first established by Arnold's ethnographic work in Yucatán during 1965 and 1966 (Arnold 1967, 1971, see Arnold 1991:328-330, 2005b for a summary). Arnold's comparison of ethnographic and mineralogical categories revealed that Ticul potters' practical knowledge of the properties of *sak lu'um* ('white earth') corresponded to the known scientific properties of palygorskite that potters deliberately added to pottery temper (Arnold 1967, 1971, 2005b).

Sources of Palygorskite

Between 1965 and 1997, 33 palygorskite samples were collected in Yucatán and in the Petén (Figure 1; Table 1). These samples were originally selected using at least one of three criteria: (1) samples of *sak lu'um* selected by informants; (2) samples identified as *sak lu'um* by informants at the sources, (3) samples with the properties of *sak lu'um* collected by Arnold, Arnold and Bohor, or Bohor; and, (4) samples containing palygorskite. Almost all were "cultural" samples selected by informants or by criteria used by those informants. Most were identified as palygorskite using X-ray Diffraction by B. F. Bohor, and a few were previously published (Arnold 1967, 1971).

Selection criteria are critical because, like the modern Maya who mine and sell *sak lu'um*, the ancient Maya were probably selecting it using cultural and physical criteria: (1) *sak lu'um* came from sources that had a strong "sense of place" for the contemporary Maya (see Arnold 2005b), and (2) *sak lu'um* was white, hard, light in weight and it fell apart in water (Arnold 1971). Needless to say, the mere presence of any palygorskite in soils and clays of Yucatan was probably not important to the Maya. The ancient Maya were not selecting for the presence of the clay mineral palygorskite, but rather probably made choices using cultural and social criteria based upon the dramatic physical properties of palygorskite that contrasted with other mineral materials (Arnold 1971).

With some exceptions, the *sak lu'um* samples analyzed thus were selected in a way that simulated how the ancient Maya could have collected them by using contemporary Maya informants (at Yo' Sah Kab, Sacalum, Uxmal) or by using a criteria used by them that was known by Arnold and/or Bohor (Maxcanu, Petén). Two other samples were included in this data set because Bohor found palygorskite in them using X-ray diffraction (Maní, Mama).

Culturally Recognized Sources

In surveys of pottery-making communities in Yucatán in the 1960s and in 1994, Ticul and Sacalum were the only places where a Yucatec Maya semantic category matched the unique properties of the mineral category of palygorskite (Arnold 2005b). The inhabitants of these towns were the only populations that used the linguistic label *sak lu'um* ('white earth') to signify this category, and they were the only towns that recognized its physical properties and mined it for medicinal use (Sacalum) and as an additive (Ticul) to pottery temper (Arnold 1967, 1971). These facts suggested a historical association between palygorskite and the sources in (Sacalum) or near (Yo' Sah Kab) these communities; they were likely precolumbian palygorskite sources used by the ancient Maya to make Maya Blue (Arnold 1967:35–38, 2005b; Arnold and Bohor 1975, 1976; Folan 1969).

Yo' Sah Kab. The first culturally recognized source of palygorskite is Yo' Sah Kab ('over *sah kab*' in Yucatec Maya). Located along the road to Chapab 3.3 km to 3.6 km from the Plaza of Guadalupe in Ticul (Figure 1), Yo' Sah Kab consists of an area of approximately 10 ha (.1 km^2) of both publicly owned, but individually worked, communal (*ejido*) land, and a privately owned portion that belonged to the Maya Cement Company. Until the late 1980s (see Arnold 2000, 2005b), Yo' Sah Kab was the only location at which *sah kab* temper could be mined and prepared because it was the only location where *sak lu'um* occurred in the immediate area of Ticul.

Potters' oral history and descriptions by others have indicated that Yo' Sah Kab has been the only temper source for Ticul Potters during most of the twentieth century (Barrera Vázquez 1937:164; Brainerd 1958; Rendón 1947; Thompson 1958:69). Yo' Sah Kab has a strong sense of place for potters and the location was associated with rather unique religious and mythological connotations (Arnold

Table 1. List of Samples of Palygorskite (*sak lu 'um*) and Palygorskite-Containing Materials Used in this Study. Sample MB31 Was Collected by Dr. Fred Strotbeck Using Arnold's Informants.

Source	Sub-source	Source Detail	Year Collected	Sample Number
Cultural Sources				
Yo' Sah Kab	(private portion)	Layer 2 m thick	1967	MB24
Yo' Sah Kab	(private portion)		1967	MB2
Yo' Sah Kab	(private portion)		1967	MB1
Yo' Sah Kab	(private portion)	Shaft No. 4 floor	1968	MB22
Yo' Sah Kab	(private portion)	Shaft No. 3	1968	MB23
Yo' Sah Kab	(private portion)		1967	MB3
Yo' Sah Kab	(potter's house)		1965	MB29
Yo' Sah Kab	(private portion)	Lower Level	1967	MB15
Yo' Sah Kab	(public portion)		1965 (Dec.)	MB31
Sacalum	mine	Near entrance	1968	MB27
Sacalum	mine		1967	MB13
Sacalum	mine	Back of mine	1968	MB14
Sacalum	mine		1967	MB5
Sacalum	mine		1967	MB11
Sacalum	mine		1968	MB16
Sacalum	mine		1967	MB8
Sacalum	mine		1967	MB7
Sacalum	mine		1967	MB6
Sacalum	mine		1967	MB12
Chapab			1994	MB18
Chapab			1994	MB20
Chapab			1994	MB21
Chapab			1994	MB19
Other Sources				
Uxmal	Road cut		1967	MB4
Uxmal	Road cut	South side	1968	MB10
Uxmal			1968	MB26
Uxmal	Road cut	Below rock	1968	MB17
Peten	Road cut 'B'		1970	MB33
Peten	Road cut 'A'		1970	MB32
Maxcanu	Railroad cut	Halfway up SE face	1968	MB9
Maxcanu	Road cut		1968	MB25
Mani	Cenote		1967	MB30
Mani			1967	MB28

2005b). These beliefs appear to be related, at least partially, to Yo' Sah Kab's exclusivity as a source of *sak lu'um* and *sah kab* for pottery temper. This uniqueness, in turn, is related to the distinction between *sah kab* for construction purposes that is ubiquitous in Yucatán, and the linguistically homophonous *sah kab* temper that was only mined at Yo' Sah Kab. Both types are called *sascab* in Spanish, but they are semantically different depending on the context (Arnold 1967, 1971). Both types are mixtures of clay and calcite and dolomite. *Sah kab* for construction purposes, however, is natural marl consisting of montmorillonite, calcite, and dolomite (Arnold 1967, 1971). *Sah kab* temper, on the other hand, is a carefully prepared cultural mixture of palygorskite, calcite, and dolomite that occasionally included some montmorillonite (Arnold 1967, 1971). The presence of *sak lu'um* (palygorskite) in Ticul temper is cultural in that potters and miners deliberately select it for inclusion; it is clearly a semantic and behavioral choice of the potters (Arnold 1967, 1971) and is used for tempering all noncooking pottery in Ticul. While this temper was formerly used to make a variety of utilitarian, service, and ritual pottery among the modern Yucatec Maya, almost all of the pottery produced since the 1970s consists of plant pots and tourist ware bound for the resort of Cancun. Because Ticul potters have made little cooking pottery since 1965, palygorskite-containing temper has been the dominant temper used in Ticul during the last 40 years.

Mining areas at Yo' Sah Kab have changed greatly since 1965 and the samples analyzed in this study come from several of them. Most of the samples were collected by informants or identified by informants as *sak lu'um*, and came from the mining areas on communal land as well as from those on the Maya Cement Company land. In 1968, however, Bohor collected samples of *sak lu'um* from several square test shafts that the Maya Cement Company dug in the late 1950s or early 1960s (see Bohor 1975). They were identified as palygorskite by Bohor using X-ray diffraction. From this sample group, Arnold selected samples that had the physical properties of *sak lu'um* for the analyses reported here.

Sacalum. The word "Sacalum" is a hispanicized form of the Yucatec Maya expression for *sak lu'um* ('white earth') and is the name of a village 12 km northwest of Ticul (Figure 1). The material that gave the town its name comes from the cenote in the town's plaza where informants reported that it had been mined for medicinal purposes for many years (Arnold 1967:35–38, 2005b).

At least two palygorskite sources occurred in the cenote. The first consisted of the thin bands of palygorskite (*sak lu'um*) on the cenote walls that Folan (1969) observed being mined in 1962. The second source consisted of a large mined-out cavity adjacent to the bottom of the cenote that resulted from the removal of a 1 m palygorskite layer (Arnold 1967; Arnold and Bohor 1975, 1976).

Chapab Source. In the 1980s, Yo' Sah Kab was becoming heavily exploited and the difficulty of mining temper there increased. About 1983, one of the men who transported temper to Ticul discovered *sak lu'um* on his land 5 km closer to Chapab. By 1988, pottery temper was being mined at this source and was sold by the owner to potters in Ticul (Arnold 2000, 2005b). Although temper mining continued at Yo' Sah Kab, its importance progressively declined relative to the Chapab source so that by 1997, most temper used in Ticul came from the Chapab source. Visits to this new source in 1994 and 1997 revealed that *sak lu'um* was mined from a thick (1–2 m) layer; temper was prepared in the same way as it was at Yo' Sah Kab (Arnold 1971). Samples of *sak lu'um* were collected from the mines and the tailings of the mining operation, but they were not analyzed using X-ray diffraction. Potters recognize that the *sak lu'um* from the Chapab source was identical to that mined at Yo' Sah Kab and this equivalency indicates that the *sak lu'um* from the Chapab source is probably palygorskite.

Other Deposits of Palygorskite

Outside of culturally recognized deposits of palygorskite described above, Arnold and/or Bohor found a number of other palygorskite deposits and collected samples from them. Undoubtedly, many more will be found.

Uxmal. Between 1959 and 1981, small group of Ticul potters made pottery at a workshop at the Hacienda Uxmal. During that time, they occasionally obtained *sak lu'um* from a road cut through a knoll on the highway between Uxmal and Santa Elena. An informant took Arnold to the deposit in 1967, where he collected a sample. Arnold and Bohor collected samples from both sides of the road in 1968.

The Petén. During an overland trip from Guatemala City to Tikal in 1970, Arnold collected four samples from four road cuts in two areas in the Petén region of Guatemala. These deposits had some of the same characteristics as the deposit near Uxmal. The first area was in the southern Petén northwest of Lake Izabal and the second was in, or near, Tikal National Park. These samples were analyzed by Bohor using X-ray diffraction, but only one was identified as palygorskite (with much dolomite and some quartz). This sample (Petén road cut "B" [MB33]) came from a road cut in a hill northwest of the ferry at San Felipe as the road climbed into the Sierra de Santa Cruz. One other sample (Petén road cut "A" (MB32)) was analyzed for this paper and looked like palygorskite when it was selected for analysis. When Arnold's notes from the Petén trip and his correspondence with Bohor in 1970 were found later, Bohor had not identified palygorskite in this sample.

Maxcanu. A deposit of palygorskite (identified by X-ray Diffraction by Bohor) was found on the east side of the first railroad cut into the northernmost portion of the Puuc ridge near Maxcanu (see Bohor 1975).

Mama. Palygorskite was identified in a raw material (called *xlu'um hi'*) for making pottery (Sample MB28, Table 1) that was collected from a sinkhole (see Thompson 1958:66). Several other samples from this sinkhole were identified as containing palygorskite, but were not analyzed here.

Shepard and Pollock (1971; Shepard 1971) also identified palygorskite in one of the raw materials used by Mama potters from samples collected by Raymond Thompson (1958) in 1951. Potters and miners of raw materials in Mama, however, did not recognize the unique physical characteristics of any material that corresponded to palygorskite, and did not know the linguistic and semantic category *sak lu'um*.

Maní. Bohor visited the cenote in Maní in 1967 and collected a sample of what appeared to be palygorskite from its wall.

Analytical Procedures

INAA and LA-ICP-MS provide elemental compositions of high precision and reliability. INAA is a well-known technique used for decades for the analysis of pottery and other materials. Do the two techniques provide similar or different results?

Each sample was split into four parts. Two sets were archived and one set was analyzed by Glascock and Speakman using INAA at the Missouri University Research Reactor (MURR). The INAA employed standard MURR analytical procedures (Glascock 1992; Neff 2000) identical to those used for ceramics and ceramic raw materials in previous papers (Arnold et al. 1991; Arnold et al. 1999; Arnold et al. 2000). The fourth set of samples was analyzed by LA-ICP-MS by Neff at California State University at Long Beach (CSULB) using the Perkin Elmer 6100DRC ICP-MS with a New Wave UP-213 laser-ablation system as the sample introduction system. The LA-ICP-MS data were calibrated to parts per million using NIST glass standards (SRM-612 and SRM-610), Little Glass Buttes Obsidian, and Ohio Red Clay. The basic approach to calibration involves fitting standardized concentrations (ratios to aluminum) in the standards to standardized counts (ratios of raw counts to raw aluminum counts). The approach is similar to that used by Gratuze (1999) and described by Speakman and Neff (2005), except that multiple calibration standards are used and a least-squares line is fit to the standards data.

Results

Correlations between the INAA and LA-ICP-MS data for the same samples provide one method for comparing the two techniques. Correlation coefficients for all elements except zirconium (Zr), hafnium (Hf), strontium (Sr), and arsenic (As), are above .5, and most are much higher (Table 1). Zirconium and hafnium are probably anomalous because they are concentrated in minute zircon grains that were not represented well in the small areas ablated in the LA-ICP-MS analyses. Strontium and arsenic were below detection in many of the INAA samples, which accounts for the poor agreement of the INAA and ICP analyses for these elements. For the other elements, it is remarkable that two completely independent analytical techniques yield such high correlations.

Table 2. Comparison between INAA and LA-ICP-MS Data, Based on 29 Palygorskite Samples Analyzed by Both Techniques. Two Samples Were Not Analyzed by Both Techniques.

Element	Correlation	LA-ICP-MS vs INAA Ratio
Na 23	.91	1.68
Al 27	.66	1.11
K 39	.92	.89
Ca 44	.78	3.44
Sc 45	.50	1.24
Ti 47	.84	.72
V 51	.58	1.29
Cr 52	.95	.95
Mn 55	.97	.82
Fe 57	.64	1.14
Co 59	.96	.90
Ni 60	.97	1.22
Zn 66	.66	1.39
As 75	.31	1.81
Rb 85	.86	.99
Sr 88	.22	.55
Zr 90	-.20	2.33
Sb 121	.63	1.07

Besides the strong correlation of the concentration of many elements between the two techniques, the data patterning from the two analyses is very similar (Figures 2–6). Rubidium effectively separates Uxmal from the other source areas, and the differences in concentration produced by the two techniques are highly consistent. The Yo Sah Kab source is highly variable; the only projection on which it appears different from the other sources is the Rb-Vn projection from the INAA data (Figure 2). The Yo Sah Kab samples MB022 and MB024 align with the Uxmal source on Rb, while the others are consistent with Chapab and Sacalum; this pattern exists in the INAA data (Figure 2 and 3) as

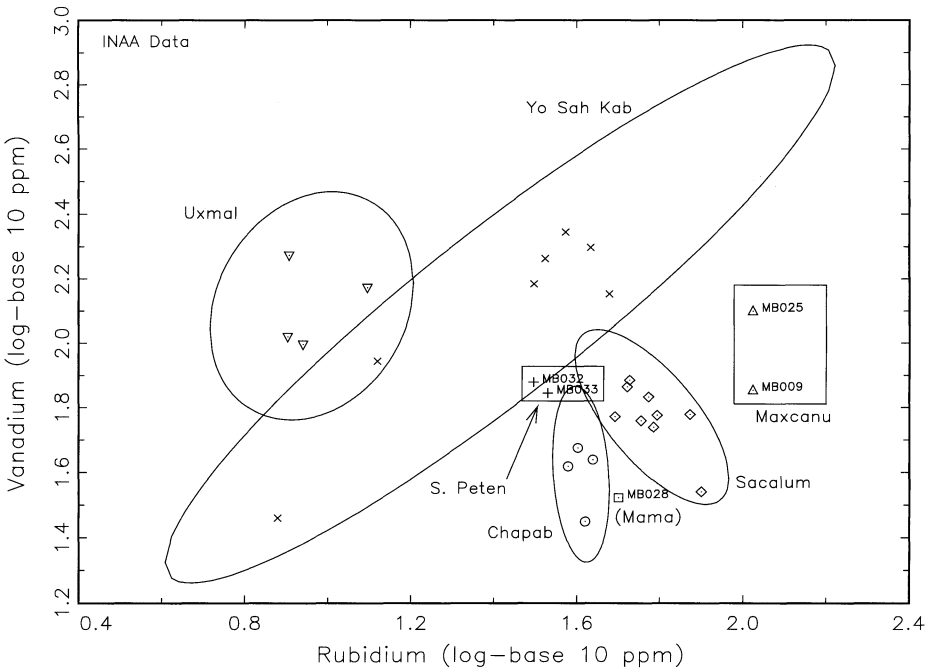

Figure 2. Rubidium and vanadium log concentrations in the palygorskite samples, as determined by INAA. Ellipses represent 90 percent probability of membership in the groups.

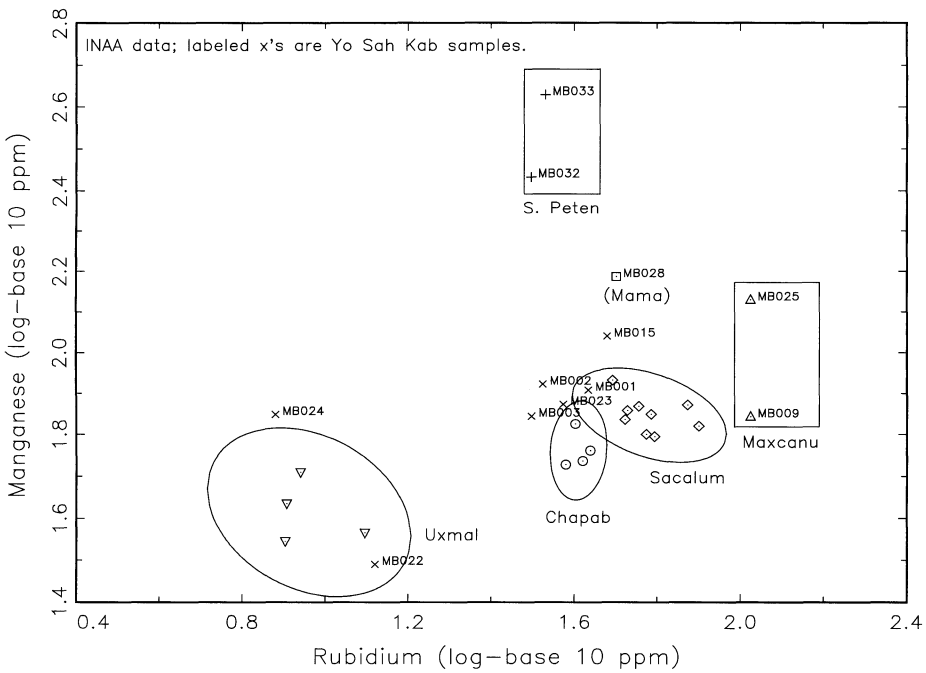

Figure 3. Rubidium and manganese log concentrations in the palygorskite samples, as determined by LA-ICP-MS. Ellipses represent 90 percent probability of membership in the groups.

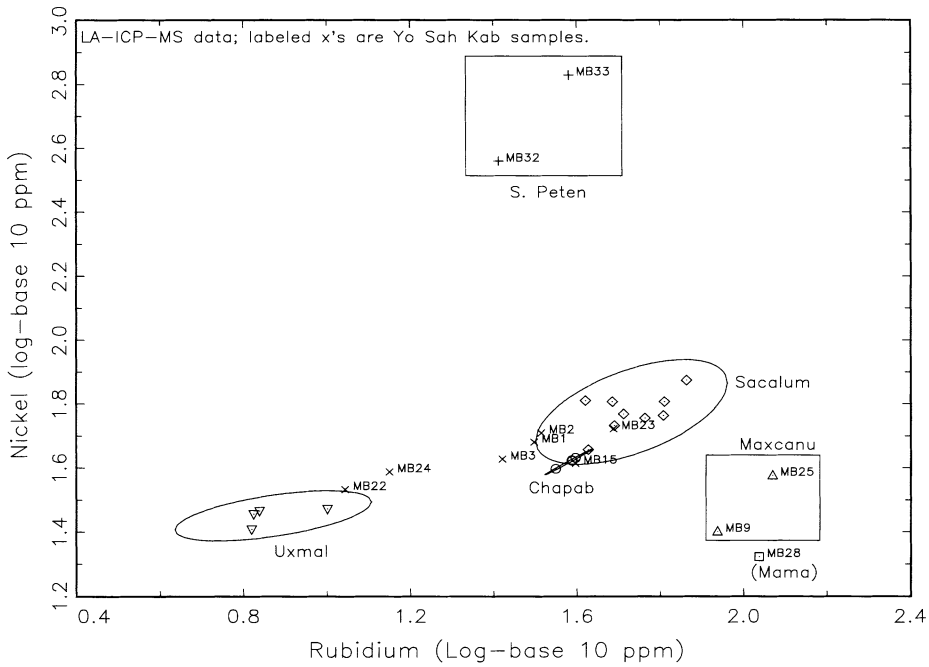

Figure 4. Rubidium and nickel log concentrations in the palygorskite samples, as determined by LA-ICP-MS. Ellipses represent 90 percent probability of membership in the groups.

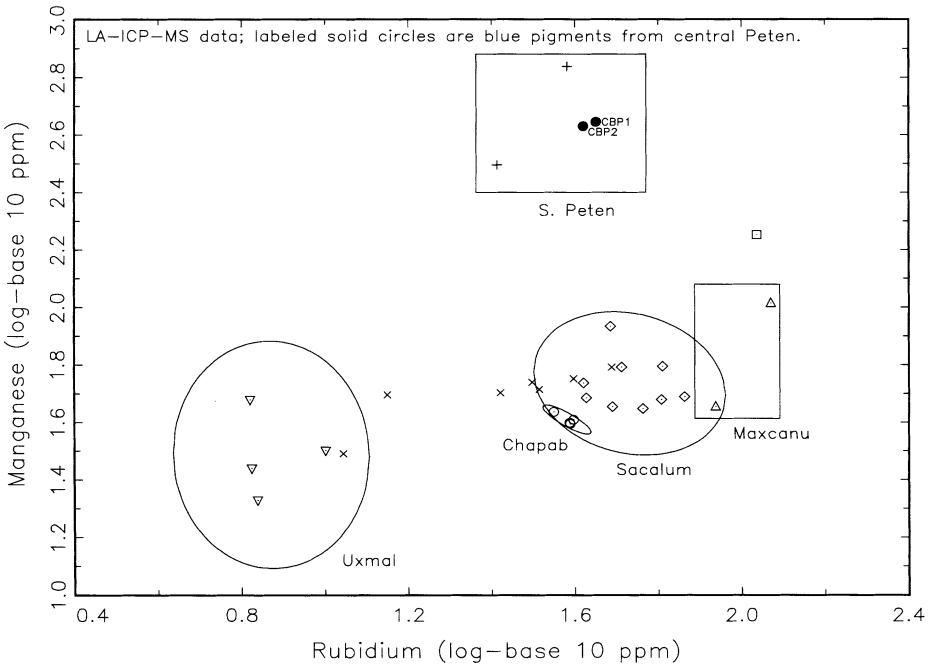

Figure 5. Rubidium and manganese log concentrations in the palygorskite samples, as determined by LA-ICP-MS. Labeled solid circles are blue pigment samples from central Petén Late Postclassic contexts (courtesy of Leslie Cecil). Ellipses represent 90 percent probability of membership in the groups.

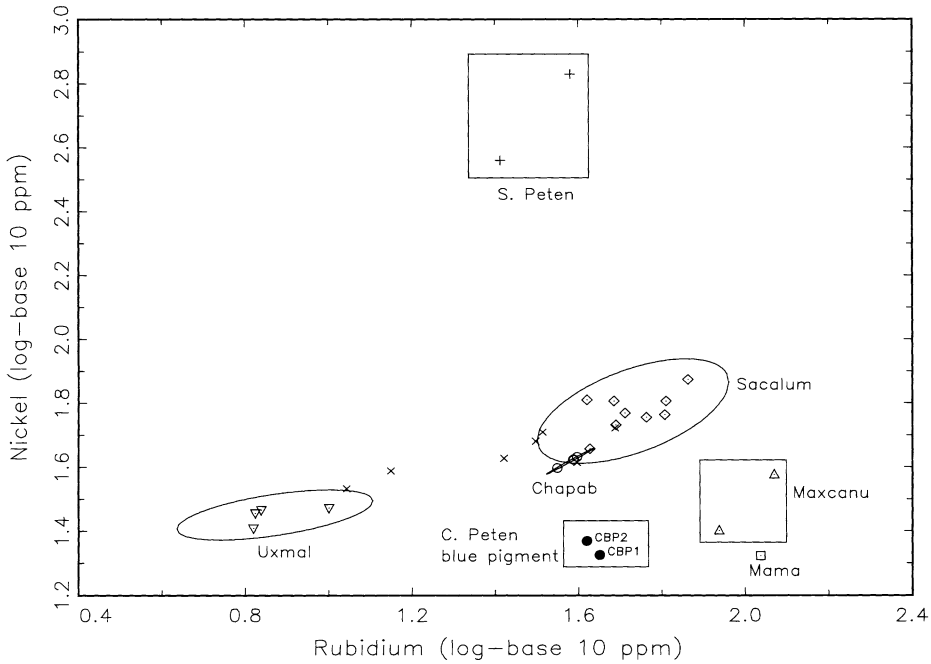

Figure 6. Rubidium and Nickel concentrations in palygorskite samples as determined by LA-ICP-MS. Labeled solid circles are blue pigment samples from central Petén Late Postclassic contexts (courtesy of Leslie Cecil). Ellipses represent 90 percent probability of group membership.

well as the LA-ICP-MS data (Figures 4–6). The composition of the Chapab and Sacalum samples are similar, although differences in concentration exist between the LA-ICP-MS and INAA data. Because the INAA data for Sacalum are slightly less variable in the samples analyzed here, discrimination at the 90 percent level is somewhat better in the INAA data (e.g., Figures 2 and 3 vs. Figures 4–6). The samples from the southern Petén and from Maxcanu are separated statistically from Sacalum and Chapab easily on a number of dimensions in both data sets (e.g., Figure 3 for the INAA data, Figures 4–6 in the LA-ICP-MS data).

One blue pigment sample from a Late Postclassic Petén site was analyzed previously by Neff using LA-ICP-MS during a collaborative project with Leslie Cecil of Baylor University. Two analyses were carried out on different days, and both data points are shown in Figures 5 and 6. The compositional profile of this pigment is consistent with the palygorskite composition presented here although it does not seem to fall into any specific palygorskite source group. The Rb-Ni plot (Figure 5) would suggest that this sample is consistent with the southern Petén palygorskite source whereas the Rb-Mn plot (Figure 6) would suggest that it is closer to northwest Yucatán sources.

Future Research

This pilot study suggests some directions for future research. First, it is necessary to analyze more samples from the palygorskite sources described here in order to completely characterize within-source variability and improve its statistical characterization. Second, more Maya Blue pigments, especially samples from northern Yucatán, should be analyzed in order to verify that the sampled palygorskite sources were indeed those exploited for preparation of Maya Blue pigment. Because sample preparation for LA-ICP-MS is far easier than that required by INAA and necessitates a far smaller analytical investment, LA-ICP-MS would be the technique of choice for future analyses. Moreover, because LA-ICP-MS can target intact surfaces, many samples from ceramic vessels and figurines can be analyzed virtually nondestructively. Some small refinements, such as multiple analyses of

each specimen, would improve precision further, making LA-ICP-MS even more powerful for the application described here. Nevertheless, the data should permit testing of each of the following hypotheses:

The Shepard/Arnold/Bohor Hypothesis. This hypothesis is based upon Shepard's belief that Maya Blue was widely traded from a source on the Yucatán Peninsula because its copious use on pottery intended for household ritual at Mayapán indicates a local source (Shepard 1962; Shepard and Gottlieb 1962). Because Sacalum is only 20 km from Mayapán, Arnold (1967:37–38) and Arnold and Bohor (1975, 1976) suggested that Sacalum could easily be the source of palygorskite for the Maya Blue of Mayapán and perhaps for elsewhere in the Maya area. Yo' Sah Kab is 25 km from Mayapán and could also be a source for the Maya Blue found there.

The Littmann Hypothesis. Although Littmann's (1980) first article argued that Maya Blue was a blue montmorillonite and his analyses had technical problems (Arnold 2005b; Roundhill et al. 1989), his second article built on a personal communication from Wayne Ipshording that palygorskite was widespread in the Maya area (Littmann 1982:404). He thus hypothesized that Maya Blue was made from local palygorskite deposits and that the technical knowledge of how to make Maya Blue moved rather than the pigment itself.

These hypotheses have very different implications for Maya archaeology. Was Maya Blue widely traded like other elite goods such as jade? Did the pigment move, or did the knowledge of production move? Or, did both the clay *and* the knowledge of how to make Maya Blue move?

It would seem that each of these hypotheses is equally plausible for the source clay of Maya Blue. Anthropology, however, is a contextual discipline and it recognizes the importance of the context of behavior, human agency, and the social embeddedness of technology. These factors need to be reflected in the formation of deductive hypotheses (like those above) because hypotheses come out of a cultural context and this context is just as significant to understanding cultural behavior as the hypothesis to be tested. Hypotheses cannot be isolated from their implied cultural context without losing an understanding of the ancient culture.

Obviously, the simplest hypothesis is that palygorskite was mined at Sacalum and Yo' Sah Kab, was made into Maya Blue nearby, and then traded. A corollary is that the palygorskite was mined in these locations, was traded and then made locally into Maya Blue at the different centers perhaps during the burning of incense. This hypothesis has much contextual evidence in its favor. First, it recognizes human agency; humans are selecting, mining, and moving the raw material based upon an ethnographic analogy with contemporary Yucatec Maya. Second, the restriction of Maya Blue to ritual contexts of pottery, offerings, copal balls, and murals suggest that Maya Blue was an elite, valued material and access to it was restricted either by a lack of access to the raw materials (more likely *sak lu'um* than indigo plants) and/or the lack of access to the knowledge of how to produce it. Elites may have restricted access to the palygorskite sources, but its medical use today and perhaps in the late prehistoric period (Folan 1969) suggest that access to *sak lu'um* was not restricted, but the clay may have been culturally scarce because the Maya may have had access to it at only two sources. If access to the sources was not restricted, then the knowledge of how to make Maya Blue may have been restricted, and perhaps known only by ritual specialists. The Maya Blue on copal balls in and on incense burners suggests that Maya Blue might have been made during the burning of incense as Cabrera Garrido (1969) suggested, or in some way was produced during rituals in a way known only by ritual specialists. Because prolonged moderate heat is required to make the pigment (Van Olphen 1966), the burning of incense to "create" Maya Blue may have underscored its elite and religious value because of its ritual associations.

A second kind of contextual evidence favoring the Shepard/Arnold/Bohor hypothesis is that the sources of culturally recognized palygorskite (Sacalum and Yo' Sah Kab) have a sense of place for the modern Maya, and each location had religious significance (Arnold 2005b). This sense of place and religious association would argue for the superiority of the Shepard/Arnold/Bohor hypothesis over the Littmann hypothesis.

Third, both the Sacalum cenote and Yo' Sak Kab have evidence of Terminal Classic occupation (Arnold 2005b; Folan 1969). The Terminal Classic site that formerly existed on top of the palygorskite deposit at Yo' Sah Kab indicates that the

mineral underneath the site probably had value to the Terminal Classic population that lived there (Arnold 2005b).

Fourth, even with the alterations of the modern landscape of Yucatan, *sak lu'um* continues to be mined in Sacalum and exported to other locations (Arnold 2005b). Even with many other palygorskite sources exposed in the contemporary landscape of Yucatán, procurement persists in traditional mining locations.

Fifth, there is some evidence that knowledge of a Maya Blue-like pigment may have persisted until the twentieth century. Gettens (1962) and Shepard and Gottlieb (1962) report the existence of a pigment called 'a*zul de Tekax'* that had been collected ethnographically in the early twentieth century. This pigment turned out to have been made with palygorskite (attapulgite) and for all intents and purposes, it was Maya Blue. As a result, Shepard tried to see if the pigment was still made in Yucatan by going to the town of Tekax. In Yucatec Maya, however, *kax* (or *k'ash*) is the word for forest (or '*monte*' in Spanish) and the particle '*te-*' is a locative indicating a place or towards a place. The '*azul de Tekax'* thus could be translated as the 'blue of/from a location towards (or, 'of') the forest' or simply 'blue of the forest' (Arnold 1967). This translation fits with the widespread occurrence of the most common species of the indigo plant, *Indigofera suffruticosa* that grows wild in a wide range of areas in the New World (Arnold 1987).

Contrary to the Shepard/Arnold/Bohor hypothesis, the Littmann hypothesis is based upon the assumption that palygorskite was widespread in the Maya area and local sources of the clay were used in the production of Maya Blue. In contrast to the advantages of the cultural context of the Shepard/Arnold/Bohor hypothesis, several problems of context and agency exist with the Littmann hypothesis.

First, scientific views of landscape and geology are the agencies that drive cultural behavior in this hypothesis rather than the agency of the ancient Maya population. While it appears that palygorskite is fairly widespread in Yucatán, geological occurrence of palygorskite does not necessarily mean that the mineral was accessible to the ancient Maya. Except for the deposits at Yo' Sah Kab, Chapab, and Sacalum, most other palygorskite deposits reported here are very small (except for the Maxcanu railroad cut) compared to the thick palygorskite beds in Sacalum and Yo' Sah Kab (and now the Chapab source). The palygorskite in these deposits does not exist in sufficient quantities to use for pottery temper, treatment for illness, or to produce Maya Blue.

Second, most of the palygorskite deposits mentioned here (except for the culturally known deposits of Yo' Sah Kab, Chapab, and Sacalum) are found in road or railroad cuts, and were probably inaccessible to the ancient Maya. The belief in the widespread occurrence of palygorskite was, at least partially, based on the analyses of samples collected from road cuts (cited by Littmann 1982:404). Sources of palygorskite for the ancient Maya, however, need to be understood in relationship to the ancient Maya landscape, rather than a landscape altered by modern technology. The modern landscape is culturally modified and altered by roads and railroads; it does not necessarily indicate that the ancient Maya had access to palygorskite deposits because they lacked metal tools, heavy earth moving equipment, and explosives (Arnold 2005b).

Third, the ancient Maya (like the modern Maya) were probably concerned about the physical properties of *sak lu'um*, and probably selected raw materials with those properties. Consequently, the occurrence of palygorskite in the Maya area needs to be viewed through the eyes of the Maya and their technological choices (e.g., their ethnomineralogy [Arnold 1971]). These choices should be understood relative to the context of the ancient Maya landscape, not a landscape altered by modern technology and interpreted through modern geology and physical science analyses.

A final problem with the Littmann hypothesis is that it requires considerable social contact between Maya centers to learn the technology to make Maya Blue. How would that technological knowledge be spread? If the production was in the hands of the elites such as priests, was the knowledge of how to make Maya Blue learned through apprenticeship, or was it learned through intergenerational transmission in elite households that provided social contact long enough to learn the technology? If descent was patrilineal and postnuptial residence was virilocal, then how would knowledge of making Maya Blue be transferred from center to center? What social mechanism could account for this transfer among elites or priests?

If the makers of Maya Blue were female potters, however, knowledge of the production of Maya Blue existed at the grass roots level, and the transfer of Maya Blue technology could occur between Maya centers with each potter's exogamous marriage outside of her community. In any case, the Littmann hypothesis is much more complicated than if Maya Blue was simply one of several elite trade goods.

Ironically, those who appear to favor the Littmann hypothesis are physical scientists who are least able to deal with the social questions of technology transfer. The details of this model cannot be inferred nor investigated by physical science methods alone without some analogical leap such as assuming the equivalency of the ancient and modern landscapes. Rather, such details can only be provided by a social theory that relates Maya behavior and society to the physical science data. At best, such details could be best provided by an active collaboration between physical scientists and anthropologically trained archaeologists. Such collaboration, as many have previously suggested, can provide a powerful tool in learning about the human past.

Conclusion

The comparison of the analyses of the palygorskite samples from the Maya area reveals a strong correlation between data generated by INAA and LA-ICP-MS and in the patterned diversity in the sources of this mineral. These results imply that identifying sources of palygorskite used in Maya Blue should be possible using either technique. Some ambiguity, however, may be unavoidable. Based on the samples analyzed so far, for example, Yo Sah Kab appears to have two distinct compositional fingerprints, one that would link it with Uxmal and one that would link it with Sacalum or Chapab.

Although the results of both techniques are similar, one important advantage of LA-ICP-MS is that it is fast, reliable, and nondestructive. Furthermore, LA-ICP-MS determines certain major elements, especially Mg and Si, that INAA does not determine. Finally, LA-ICP-MS enables the discrimination of the palygorskite in Maya Blue apart from, and if desired, along with, extraneous material such as calcite or dolomite. Because INAA deals with a bulk sample, it is not possible to make such discrimination.

Finally, using these techniques makes it possible to evaluate whether the palygorskite used in Maya Blue came from a highly restricted source in Yucatan such as Shepard, Arnold, and Bohor have suggested, or from a variety of sources as Littmann has proposed. In the latter case, the diffusion of the technology would be responsible for the creation of the pigment. Because the diffusion of technology is a social process, it cannot be inferred from physical science analyses alone without some social theory that links compositional analyses and society.

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