
Volume 40 Number 12 December 2013 ISSN: 0305-4403
ELSEVIER
Published in association with the Society for Archaeological Sciences
Journal of
Archaeological
SCIENCE

Journal of Archaeological Science 40 (2013) 4306–4318

Contents lists available at SciVerse ScienceDirect

Journal of Archaeological Science

journal homepage: http://www.elsevier.com/locate/jas

Metallurgical ceramics from Mayapán, Yucatán, Mexico

Jennifer L. Meanwell [a,*], Elizabeth H. Paris [b], Wilberth Cruz Alvarado [c], Carlos Peraza Lope [c]

[a] Center for Materials Research in Archaeology and Ethnology, Massachusetts Institute of Technology, 77 Massachusetts Ave., Room 8-431, Cambridge, MA 02139, USA
[b] Department of Anthropology & Sociology, University of Southern Mississippi, 118 College Drive, Box #5074, Hattiesburg, MS 39406, USA
[c] Centro Instituto Nacional de Antropología e Historia, Yucatán, Km 65 Carretera Progreso, Mérida, Yucatán 97000, Mexico

ARTICLE INFO

Article history:
Received 4 February 2013
Received in revised form
20 May 2013
Accepted 25 May 2013

Keywords:
Maya
Mesoamerica
Craft production
Metallurgy
Ceramics
Petrography

ABSTRACT

Recent excavations at the Postclassic (AD 1050–1440) Maya site of Mayapán, Mexico, have uncovered a variety of metal objects, metal production debris, and ceramic objects that appear to be linked to metallurgical activities at the site. Our present study investigates a corpus of small ceramic objects to determine if these objects was used in metallurgical processes such as lost-wax casting. A variety of analytical techniques was utilized, including x-ray fluorescence, electron probe, petrography, and reflected light microscopy. Metal residues were detected on the surfaces of several objects, and copper prills were identified within the ceramic fabric, suggesting that the ceramics were exposed to liquid metal during remelting and/or casting events. A comparison of the microstructures of these metallurgical ceramics to typical ceramics from Mayapán demonstrates that the fabrics are very different, and suggests that the metallurgical ceramics were specifically engineered to function in the high temperature environment required for metallurgy. The distribution of metal and metallurgical ceramics across the site of Mayapán suggests that metal production activities may have been more widely distributed and practiced than earlier thought.

1. Introduction

1.1. Description of research

At the Postclassic period (A.D. 1050–1440) Maya city of Mayapán, metal artifacts were luxury items used by residents as symbols of wealth and status. In 1998, a cache of metal artifacts and production debris excavated at outlying elite residential group Structure R-183b provided the first evidence that Mayapán residents may have locally manufactured their own metal artifacts, particularly small copper bells, through the lost-wax casting method (Paris, 2008). In this paper, we provide further evidence for casting at Mayapán through the analysis of additional ceramic artifacts associated with metallurgical activities. Our research reveals the technological choices made by Mayapán metal producers, and identifies the use of unusual ceramic types in metallurgical casting through the identification of metallic residues. Thin section analysis suggests that ceramic vessel supports were exposed to the high temperatures associated with melting copper or copper alloys, and that the objects were deliberately crafted to perform this function. Furthermore, these artifacts were found in multiple contexts in both the monumental center and in the southeast sector of the city, suggesting that production activities may have been less spatially and socially concentrated than previously thought.

1.2. Background

1.2.1. Mayapán

Mayapán was the most powerful city in the lowland Maya area at the height of the Postclassic period (Fig. 1; Pollock et al., 1962; Peraza Lope et al., 2006). It was notable among its contemporaries for its large size and high population density, its diverse social composition, and its central role in religious institutions (Masson and Peraza Lope, 2013). Recent settlement survey outside the city's walls has increased population estimates to 15,000–17,000 individuals during the height of its power (Russell, 2008). The site has a tightly nucleated monumental center filled with administrative and religious structures, as well as smaller administrative centers in outlying areas, surrounded by residential structures ranging from palaces and elite plaza groups to small commoner residential groups (Masson and Peraza Lope, 2013; Pollock et al., 1962). A possible marketplace located immediately

* Corresponding author. Tel.: +1 617 253 3225; fax: +1 617 253 8090.
E-mail address: jmeanwel@mit.edu (J.L. Meanwell).

0305-4403/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jas.2013.05.024

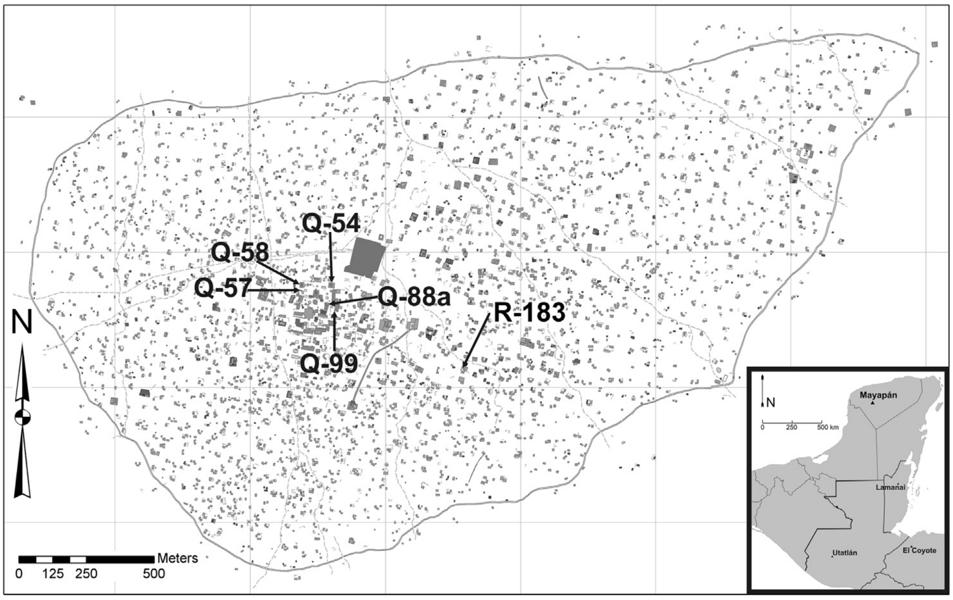

Fig. 1. Map of the site of Mayapán and its location within the Yucatan Peninsula of Mexico. Structures where metal objects or metallurgical ceramics were recovered are highlighted. Drafted by Elizabeth Paris and Timothy Hare.

northeast of the monumental center may have provided a forum for commercial exchange of agricultural products, locally produced craft items, and exotic goods provided by long-distance merchants (Masson and Peraza Lope, 2013). While most craft production took place in elite and commoner residential groups throughout the city, several workshops were nucleated at a large crafts barrio located just west of the monumental center (Masson and Peraza Lope, 2013).

Mayapán's extensive commercial ties within and beyond the Yucatán Peninsula supported long-distance merchants and local artisans alike, and made a wide range of goods available to its residents. Among these goods were a variety of metal artifacts, including small copper bells, finger rings, tweezers, needles, and artifacts made from copper, gold, and tumbaga sheet metal, recovered from numerous contexts within the monumental center and also in elite and commoner residences in outlying areas (Paris, 2008; Paris and Peraza Lope, 2013; Root, 1962). Root's analysis (1962: 397) of 19 copper alloy artifacts from Mayapán revealed that tin, silver, and lead were frequently present, while trace amounts of arsenic, antimony, bismuth, and gold were also detected.

In the Maya Lowlands, where karst terrain predominates, all metallic materials were imported to Mayapán from distant regions (Bray, 1977: 397; Paris, 2008). Sources of native copper and copper ores, gold, and tin in West Mexico, Central Mexico, the Huastec region and Oaxaca became increasingly exploited after metallurgy was introduced from South America around A.D. 600 (Hosler, 1994; Hosler and Stresser-Pean, 1992; Hosler et al., 1990). More recently, evidence suggests that smaller copper sources were exploited on the outskirts of Utatlán, Guatemala (Weeks, 1975, 1983, 2013) and El Coyote, Honduras (Blackiston, 1910; Urban et al., 2013). Mayapán metalworkers could also have remelted imported metal commodities, a practice observed in Postclassic metallurgical assemblages at Lamanai (Simmons, 2005; Simmons et al., 2009; Simmons and Shugar, 2013). Finished metal items could have been imported from numerous sources in Mesoamerica, but also could have been imported from lower Central America; for example, many artifacts found in the Cenote of Sacrifice at Chichén Itzá were gold ornaments imported from Panama (Coggins and Shane, 1984; Lothrop, 1952).

Excavations by Carlos Peraza Lope and colleagues revealed evidence that specialists at Mayapán had mastered the lost-wax casting process and were locally producing metal artifacts. In 1998 salvage excavations, a small cache was discovered in Structure R-183b consisting of a small olla containing 282 bells, two miniature ceramic vessels (one tecomate and one tripod vase) filled with discarded casting sprues and failed bells, twenty-four bell clusters, and manufacturing debris (Peraza Lope, 1998). Casting sprues are created when casting channels fill with metal, and are often trimmed from the finished object. A complete description of this cache has been published by Paris (2008). The production tools and debris represented in the cache suggest that metalworkers were engaging in secondary production activities such as lost-wax casting in or near the residential group (Paris, 2008). A second possible production context was suggested by the contents of a burial in Structure Q-92, which included two miniature tecomate vessels similar to the one found in Structure R-183b (Peraza Lope et al., 2003). No other production tools or debris were included in the burial (Paris, 2008). All four miniature vessels were of local ceramic types: Navula Unslipped and Mama Red (Smith, 1971), suggesting that all four vessels were manufactured locally. No evidence for primary production activities, such as mining or smelting has been noted at Mayapán.

1.2.2. Recent discoveries: ceramic molds and metallurgy-related artifacts

Recent excavations at Mayapán have recovered a new corpus of unusual ceramic artifacts which, as we will demonstrate below, were associated with various secondary stages of metal production. These consist of 112 ceramic artifacts recovered primarily from contexts in the monumental center and southeast mid-city center, which include small molds, cups, tripod supports, and possible casting channels. These artifacts were identified by Mayapán project ceramicist Wilberth Cruz Alvarado because they shared several common elements: dark gray paste, an absence of visible temper, the presence of greenish residues on some objects, and visual characteristics suggesting exposure to high heat, such as fire-clouding or a porous appearance. In order to investigate the possibility of these artifacts being associated with metallurgical activities, six ceramic artifacts were exported and analyzed by the senior author at the MIT Department of Materials Science and Engineering.

A possible bell mold fragment (Figs. 2a and 3a) was recovered from Structure Y-43, located 800 m southeast of the monumental center of Mayapán. Excavations recovered a small, approximately rhombus-shaped fragment of ceramic interpreted as a fragment from a mold used to cast copper bells through the lost-wax casting process. The fragment measured 5.3 cm in length, 3.3 cm in width, and had a maximum thickness of 2.1 cm. The fragment had a smooth dorsal surface, and two or three small impressions on the ventral surface similar in diameter to some of the large, globular copper bells found at the site. This suggests that multiple bells may have been cast in the same mold, a pattern suggested by several of the bells in the Structure R-183b cache (Paris, 2008). Four of the ceramic artifacts were small receptacles, potentially suitable for casting small ingots, and all four were recovered from different structures at the monumental center of Mayapán. The first artifact was a long, thin, tripod receptacle with an elliptical cross-section, a thin, rounded rim, and conical, elongated, solid supports (Figs. 2b and 3b) recovered from Structure Q-57. It measures 5.2 cm long by 2.2 cm wide. Two of the three vessel supports were broken off, likely post-depositionally. A small rectangular vessel 5.3 cm by 4.1 cm by 1.8 cm with a square rim, a flat interior base, and a slightly convex exterior base (Figs. 2c and 3c) was found in Structure Q-88a. Two small, thimble-shaped "copitas" (Figs. 2d and 3d) were recovered from Structures Q-54 and Q-58. The copitas were generally similar in size and shape; the copita from Structure Q-54 is 3.8 cm tall and 3.9 cm in diameter at the rim, while the copita from Structure Q-58 is 3.5 cm tall and 3.1 cm in diameter at the rim.

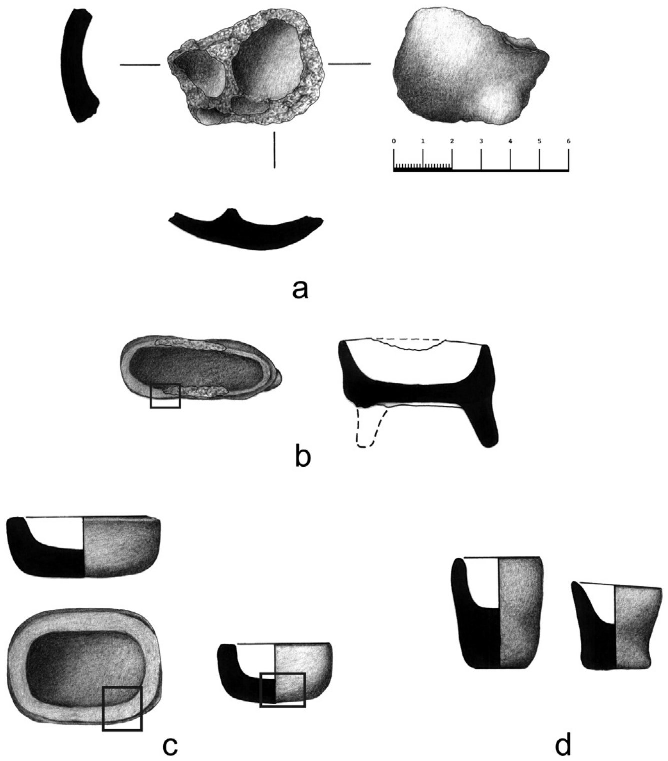

Fig. 2. a) The possible bell mold b) The elliptical tripod vessel with a box indicating the area targeted for XRF analysis c) Flat-bottomed mold or crucible recovered from Structure Q-88a with boxes indicating areas that were targeted for XRF analysis d) A small copita recovered from Structure Q-54 (left), and a small copita recovered from Structure Q-58 (right). Drawn by Wilberth Cruz Alvarado.

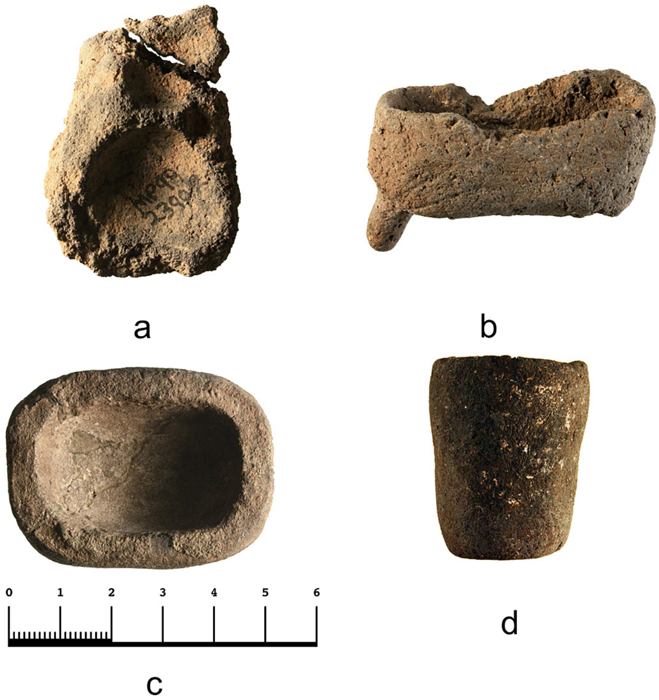

Fig. 3. a) The possible bell mold, with the small piece removed for XRF analysis visible b) The elliptical tripod vessel c) Flat-bottomed mold or crucible recovered from Structure Q-88a d) Small copita recovered from Structure Q-54. Photographs by Jennifer Meanwell.

Two of the 87 tripod supports (Fig. 4) were also examined for possible association with metal production activities. The supports are generally long, conical and solid, but have slightly irregular shapes. The feet are significantly larger than those of the small elliptical tripod receptacle, varying between 2.5 and 3.5 cm in length, suggesting that they came off of larger ceramic vessels that exhibited significant variation in size and possibly shape. However, their long, solid, tapered shapes are broadly similar in shape to those of the small elliptical tripod receptacle. Many of them had small remnants of receptacles on their proximal ends, although

Fig. 4. The two tripod feet studied via thin section and thick section analysis with MY094426-1 above and MY094426-2 below. Drawings by Nicholas Carter and photographs by Jennifer Meanwell.

these remnants were too small to determine the original vessel shape and function; other examples exhibited mid-section breaks (Fig. 5). Their appearance is not consistent with other tripod supports found at Mayapán, which have well-defined and regular geometric or zoomorphic shapes, so it is unlikely that they were recycled from other vessels and used in a metallurgical context. The two supports examined in this study were recovered from Structure Q-99. There is no evidence to suggest that the two supports were part of the same vessel; they are different lengths, and were from a sample of 41 supports from this structure. Due to the fragmentary nature of the evidence, it is unclear whether these supports may have been attached to crucibles, molds, or other metallurgical ceramics, but the walls of the footed vessels may have crumbled due to exposure to high heat during metal processing, or may have been deliberately broken to extract metal items.

2. Methodology

We follow the "materials approach" developed by Dorothy Hosler (1986, 1994: 3–6), based on concepts originally proposed by Heather Lechtman (1977) and Lechtman and Steinberg (1973). This approach examines the relationships between artifact design and function by using techniques from materials engineering to evaluate the fundamental limitations and possibilities in the properties of a specific material (Hosler, 1986, 1994: 3–6). Once the range of technical possibilities has been identified, individual choices from technically feasible alternatives can be isolated (Hosler, 1986, 1994: 4). We apply this approach to the investigation of possible metallurgical molds from Mayapán by determining which ceramics have metallic residues, and investigating whether these ceramics were produced specifically for metal production. By comparing the technological choices reflected in clay and temper selection of the metallurgical ceramics with those of typical Mayapán ceramics, we can identify the specific ways in which these ceramic objects were manufactured for the specialized function of metal working.

In order to determine whether the unusual ceramic artifacts were utilized in metal working, we performed x-ray fluorescence (XRF) analyses of the ceramic objects to look for metal residues as indicated by their elemental compositions. The non-destructive XRF analysis was employed to determine the presence or absence of metallic residues in the analyzed locations. Since our goal was to establish the presence of metal residues on the surface of these objects, a handheld device was employed. Although more analytical precision could have been obtained with a laboratory XRF device, other XRF studies have shown that the proportions of metals or oxides detected in a crucible or mold may vary significantly from those of the original melt due to differences in the activity and volatility of different metal elements (Kearns et al., 2010: 48).

Four of the artifacts were analyzed using a Bruker Tracer III-SD handheld XRF device, including the two crucibles, the possible bell mold, and one tripod foot. The two copitas proved to be too small and curved to allow useful analysis using the handheld XRF setup, because a reasonably flat geometry is needed to prevent scattering of the resultant x-rays from the surface of interest. To create a flat surface to analyze on the bell mold, a small piece was carefully unglued and analyzed (Fig. 3a).

Four different analytical setups were used on the flat-bottomed crucible to isolate peaks of interest. The instrument was used without a filter at 15 kV and 40 kV, with a Cu, Ti, and Al "green" filter at 40 kV, and with a Ti "blue" filter at 15 kV. The higher (40 kV) energy source allows elemental detection of elements heavier than Mg. The "green" filter allows x-rays from 17 to 40 keV to hit the sample and is optimized for elements with atomic weights between those of Fe and Mo. The "blue" filter is optimized for elements with atomic weights below Fe (except Ti and Sc) and blocks Rh and Pt L-peaks to allow detection of Cl and S. Peaks of Rh and Pt in the results are an artifact of the instrument itself and are not necessarily present in the sample. A subset of these analytical protocols was used on the remaining objects, always beginning with an unfiltered 40 kV scan to determine the range of elements present in the sample, followed by scans using the green or blue filters when we wished to confirm the presence of weak peaks. While the results indicate the presence or absence of different elements, they do not allow quantitative calculations of their concentrations. However, if two areas of the same object are analyzed,

Fig. 5. Group of 36 of the 41 tripod feet recovered from Structure Q-99 showing a range of shapes, sizes, and breakage patterns. Photograph by Elizabeth Paris.

then the peak heights of individual elements can be compared to determine their relative abundance.

Temperature-induced changes within the ceramic fabrics were investigated to determine whether the ceramics were exposed to temperatures related to metal production. Two thin sections and one thick section were created by the senior author from the two tripod feet (MY094426-1 and MY094426-2) using standard techniques (Stoltman, 2001: 298) to identify non-plastic inclusions and to observe areas along the edges of the feet suspected to be thermally altered. Due to the small sample size, any conclusions about thermal alterations are necessarily tentative. The two feet were cut vertically through the center of the foot, and the cut passed through visible surface features (Fig. 4), such as vitrified areas identified by their bubbly appearance. We then compared the thin sections of tripod feet to sections from ceramic vessels from standard paste types, particularly the Chen Mul and Mama Red types, which are considered to be local Mayapán products (Smith, 1971), provided by Leslie Cecil, who used the samples in her interregional ceramic study (Cecil, 2012).

During the initial processing, a large copper prill was identified within MY094426-1; prills are small drops of molten metal, and are often created when metal is spilled during the casting process. Metal is opaque to transmitted light, so the thick section of the foot containing the large metal prill was polished to conduct reflected light microscopy and electron probe analysis. The JEOL JXA-773 Superprobe at the MIT Department of Earth, Atmospheric and Planetary Sciences was used to determine the chemical composition of this prill with quantitative accuracy. An initial characterization of the prill using the attached energy dispersive x-ray spectrometer (EDS) suggested the only elements present were Cu, Fe, and As. Therefore, the probe was calibrated for these elements, and a transect of ten points spaced 10 μm apart was taken across the prill. In addition, non-quantitative chemical characterization of the clay matrix and some of the smaller prills was performed using EDS.

3. Results

3.1. XRF

The results of the XRF analysis suggest that all four ceramics subjected to this technique were associated with metal production. Two separate areas of the flat-bottomed rectangular vessel were analyzed: first, an area of possible vitrified residue visible on the flattened rim; and second, the exterior end, which was unlikely to have touched molten metal during use (Fig. 2c). A wide suite of elements was identified (Fig. 6), including Al, Si, Cl, K, Ca, Ti, Mn, Fe, Ni, Cu, As, Sr, Ag, Sn, Au, Y and Zr. Many of these elements are expected in the clay body, especially Al, Si, Cl, K, Ca, Ti, Mn and Fe. The presence of the Cu, As, Ag, Sn and Au, however, is explained most parsimoniously by suggesting that the vessel was in contact with molten metal, leaving metal residues on the surface. The vessel may have been used more than once to mold alloys of varied compositions, or to mold a melt produced from a variety of recycled objects with different alloy compositions. While copper deposits commonly include more than one element, it is not common to find silver, gold, arsenic, and tin in a single copper ore source (Craddock, 1995: 23–31). Similar mixed compositions have been found for historic period objects from Lamanai, Belize, which has been interpreted as recycling of metal (Hosler, 1994: 214; Simmons and Shugar, 2013: 144). Copper alloys with these trace elements were also noted by Root (1962) in his analyses of metal objects from Mayapán. A comparison of the spectra from the end and the edge of this vessel demonstrates that the Cu, As, Ag, Au, and Sn peaks are absent or significantly smaller on the end than on the vitrified area of the edge. The peaks for elements present in the clay, such as Al, Si, and Fe, however, are similar in height for both areas.

The bell mold and the flattened proximal end of tripod foot MY094426-1 also have small copper peaks (Figs. 7 and 8). However, these peaks are much smaller than those seen for the flat-bottomed vessel, and suggest less copper residue on the surfaces of these objects. The elliptical tripod vessel, on the other hand, produced strong Cu and Sn peaks, and a smaller Ag peak (Fig. 9). Copper-tin bronze was a commonly used alloy in Mesoamerica after approximately AD 1200, which is consistent with the height of occupation at Mayapán (Hosler, 1994: 197), and tin was the most common alloying element detected by Root (1962: 397).

The XRF analysis supports the use of the two vessels in metal production, most likely as ingot molds, but the functions of the bell mold and tripod feet remain less clear. The lack of a strong copper peak from the bell mold suggests that it may have broken during the initial wax removal firing and was never exposed to molten metal (Ybarra, 2012), or that the portion of the mold that was tested did not retain copper residue. It is probable that the tripod feet were attached to the base of larger vessels, such as crucibles or molds, and would not, therefore, have been exposed to liquid metal during the production process. An alternative explanation for the copper peaks observed for the bell mold and the tripod foot is discussed in Section 3.3.

3.2. Petrography

3.2.1. Petrography of tripod feet

Two tripod feet were analyzed in thin section using standard petrographic techniques (Stoltman, 2001). The fabric of both feet is very dark in thin section, but close inspection allows inhomogeneities in the fabric to be distinguished. Few grains of mineral temper are distinguishable, although tiny fragments of quartz can occasionally be seen. No high temperature minerals, such as mullite, were observed. Very fine grained calcareous material is present in some locations, usually in pores, and is likely a post-depositional deposit (Fig. 10). The fabric changes texture toward the edge of the foot and a zone of bubbles is visible on the exterior surface (Fig. 11), which matches a zone of vitrification visible in thin section. The presence of vitrification on the exterior surfaces of Mayapán tripod feet suggests that the exterior of the feet were exposed to high heat, and may have been used to stabilize a metallurgical vessel such as a crucible or a mold within a charcoal fire.

In most cases, vitrification of ceramic pastes begins at a firing temperature between 900 and 1100 °C, depending on the presence of fluxing agents, such as feldspars (Rice, 1987: 91). These temperatures permit the remelting of copper alloys, since pure copper melts at 1083 °C, and alloys melt at lower temperatures. Bubbled and porous textures in ceramics are the result of bloating, which occurs when gases that are released during the firing process get caught in the vitrifying (partially liquid) ceramic (Rice, 1987: 107). It is impossible to determine what these gases may have been; CO_2 from combusting organic material or decomposing calcite is possible, although there is no evidence for voids from organic temper. A determination of the exact temperature reached on the Mayapán tripod feet cannot be determined without a refiring experiment; however, this technique has the potential to change the feet enough that it would not be acceptable to the excavators.

3.2.2. Petrography of other Mayapán material

Fifty thin sections of other Mayapán ceramics provided by Leslie Cecil (2012) were compared to the thin sections of the feet to compare the clay recipe for the metallurgical ceramics to that of the

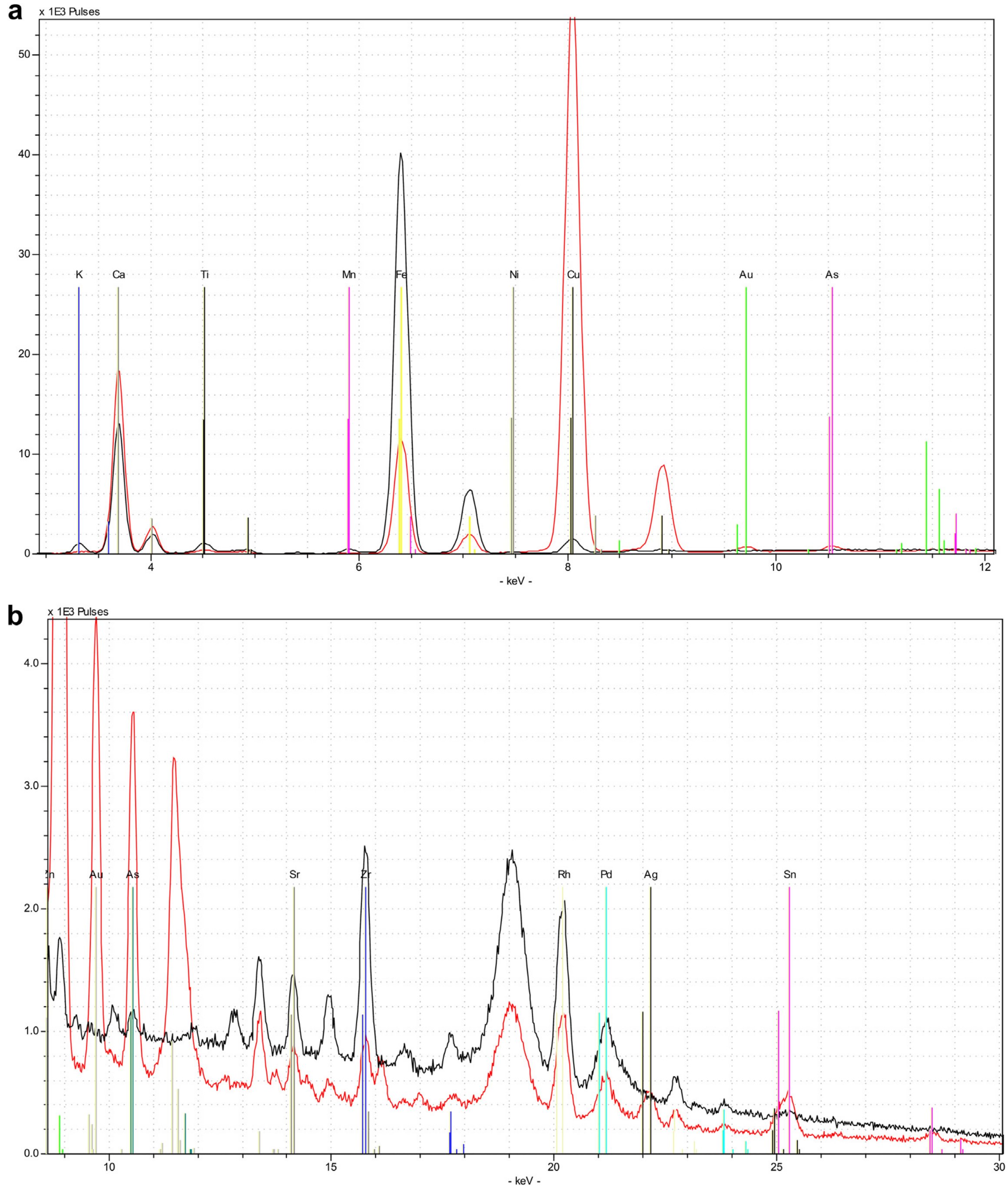

Fig. 6. a) XRF spectra of the residue area of the flat vessel (red/gray line) compared with the end of the vessel (black line). Note the significant difference in the height of the Cu peaks and the absence of the Au and As peaks in the end spectrum b) The presence of Ag and Sn is confirmed with a 40 kV scan with no filter. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

typical Mayapán ceramics. Notably, all of the local (as well as many of the possibly imported) ceramic sections included high volume fractions of calcareous non-plastic inclusions such as crushed limestone and dolomite (Fig. 12). Several of the Mayapán ceramics also contained pieces of grog added as a tempering material (Fig. 13). The clay fabric of these pieces was also optically active, suggesting that the ceramics were not fired at temperatures high enough or for durations long enough for significant sintering or vitrification to occur. While a specific firing temperature cannot be determined, it is unlikely that the typical ceramics at Mayapán were fired above 800 °C.

Because calcite breaks down at firing temperatures reportedly as low as 650 °C, which can cause spalling during rehydration (Rice, 1987: 98), it is unlikely that the highly calcareous recipe used for typical Mayapán ceramics could have been successfully used for metallurgical ceramics without significant processing. The abundance of calcareous material in typical Mayapán ceramics suggests that many of these were natural inclusions in the clay rather than deliberate tempering agents added to the clay. This is consistent with the geology of the Yucatán Peninsula, which is a large limestone shelf (Schultz et al., 1971), although surveys of clay resources in the Yucatán (Schultz et al., 1971) do suggest that kaolin clays are

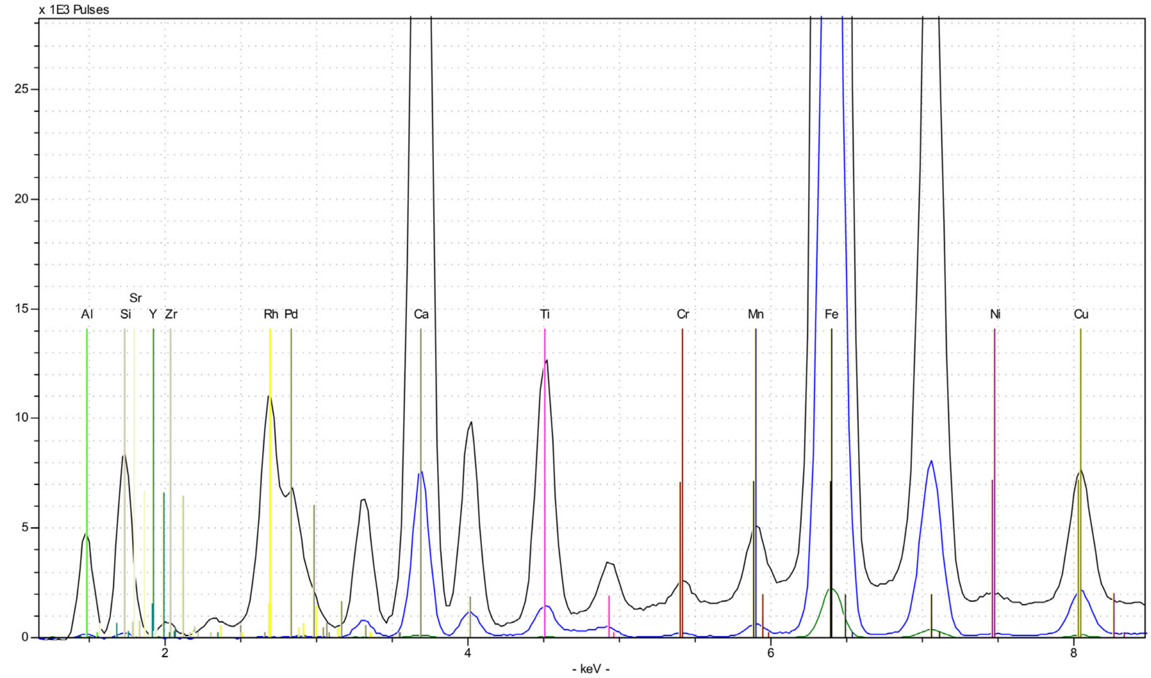

Fig. 7. XRF spectra of the small piece of the bell mold with three different analytical configurations. The black line is a no-filter 40 kV scan, the green/gray line is 40 kV with the green filter, and the blue line (PDF) or gray line (print) is 15 kV with the blue filter. Note the presence of a copper peak, but it is much smaller than the iron peak, which is in contrast to the residue area of the flat crucible. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

present and that some clay deposits may have formed from weathered volcanic ash or due to precipitation from shallow sea water (Krekeler and Kearns, 2008). The absence of calcite in the metallurgical ceramics suggests two possibilities: first, that producers of metallurgical ceramics used different clay sources with fewer calcite inclusions than those used to create typical Mayapán ceramics; or second, that a common clay source was used for both kinds of ceramics, but that the producers of metallurgical ceramics heavily processed the clays to remove calcareous material so that they would exhibit the proper refractoriness.

Previous archaeological evidence suggests that the Postclassic Maya were familiar with the manipulation of chemical and

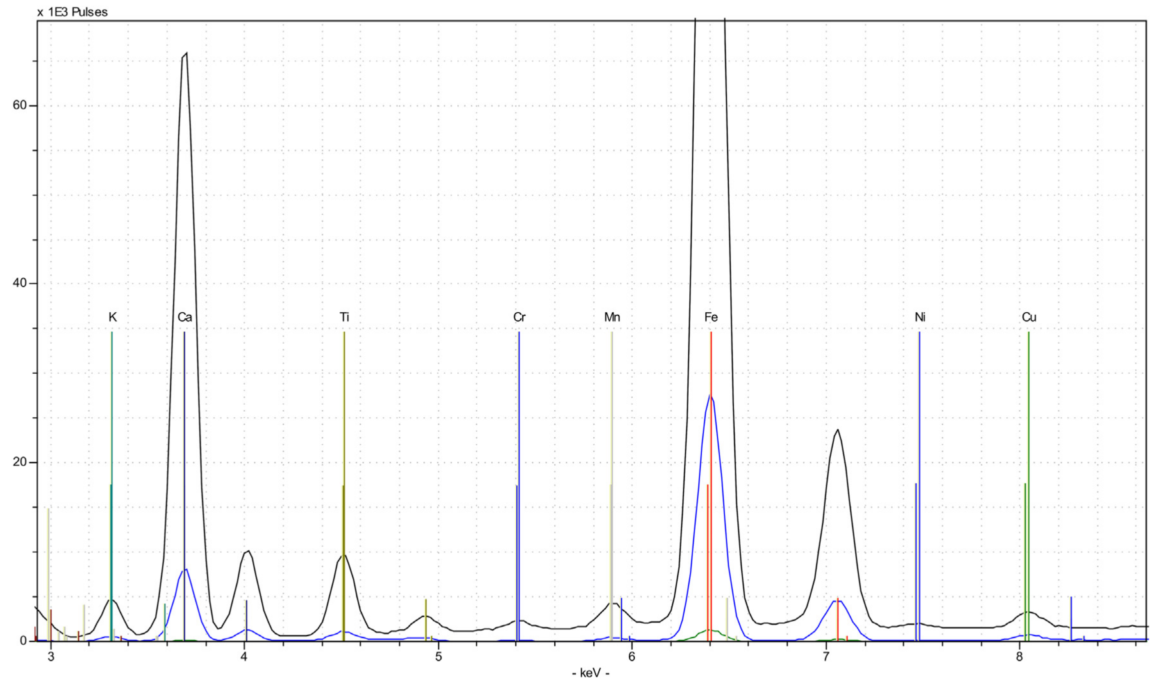

Fig. 8. XRF spectra of the flat inner surface of the tripod foot with three different analytical configurations. The black line is a no-filter 40 kV scan, the green/gray line is 40 kV with the green filter, and the blue line is 15 kV with the blue filter. Note the presence of a copper peak, but it is much smaller than the iron peak, which is in contrast to the residue area of the flat crucible. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

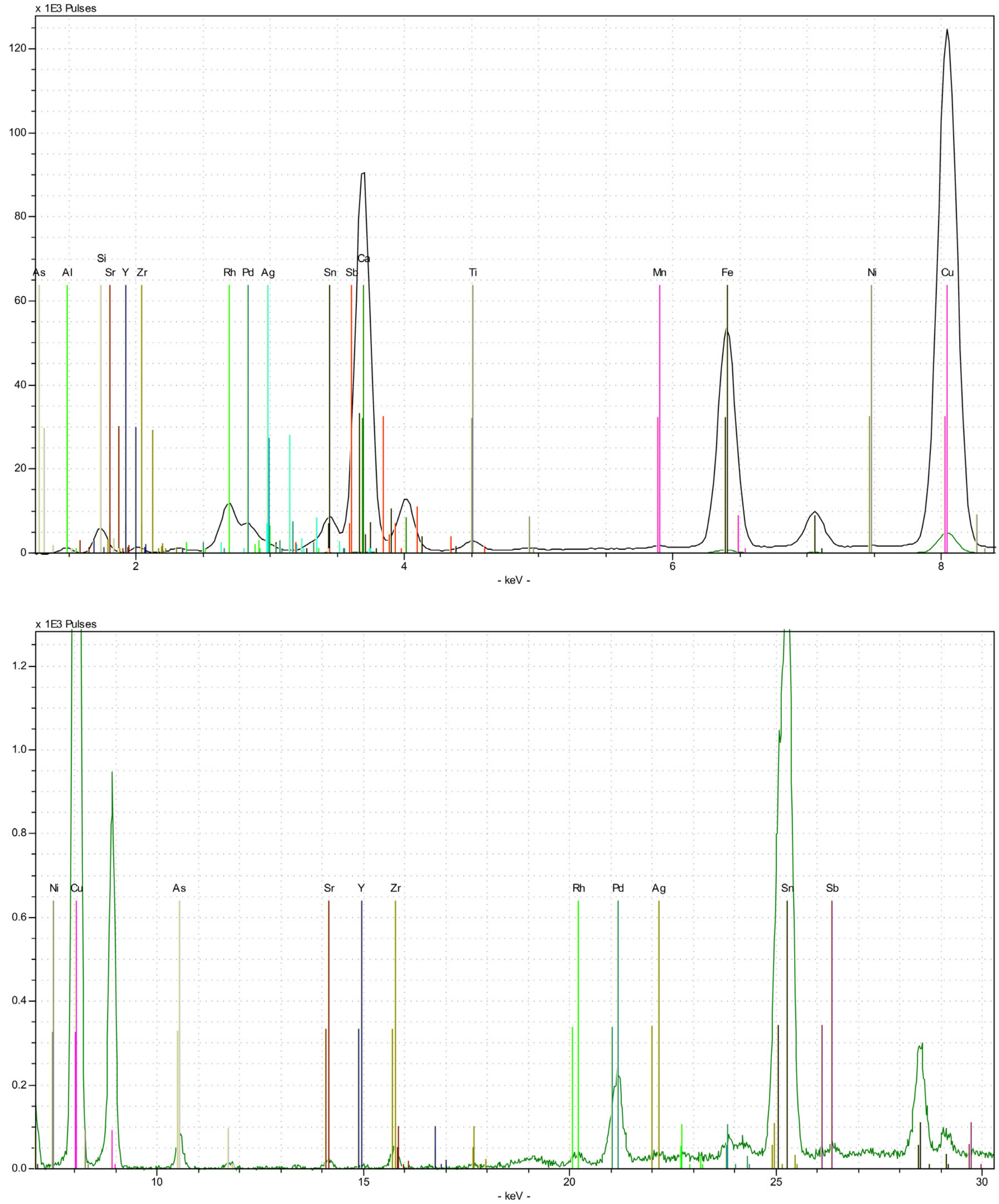

Fig. 9. XRF spectra of the elongated vessel with two different analytical configurations. The black line is a no-filter 15 kV scan and the green/gray line is 40 kV with the green filter. The upper figure shows the lower energy portion of the data, while the lower figure shows the higher energy portion. Note the presence of peaks for copper, tin, and silver. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

physical properties of clays for different functions. For example, Mayapán residents widely used Maya Blue pigment on effigy incense burners and murals (Gettens, 1962; Shepard and Gottlieb, 1962), a compound created by combining indigo with palygorskite, an alumino-silicate clay mineral with low calcium content (Arnold, 1971, 2005; Arnold and Bohor, 1976). Multiple palygorskite deposits are located within the Yucatán peninsula (Arnold, 2005; Arnold et al., 2007; Krekeler and Kearns, 2008; Shepard, 1962), but the sources most likely used at Mayapán are the Sacalum and Yo' Sah Kab sources, located approximately 25 km south of the site (Arnold et al., 2007; Shepard and Gottlieb, 1962). While this suggests that palygorskite was commonly imported to the site, at least after it had been transformed into Maya Blue pigment, there is no strong evidence that palygorskite was used for metallurgical ceramics.

3.3. Thick section

During analysis with reflected plane-polarized light, a large metallic prill was easily visible. The prill appeared to be a coppery

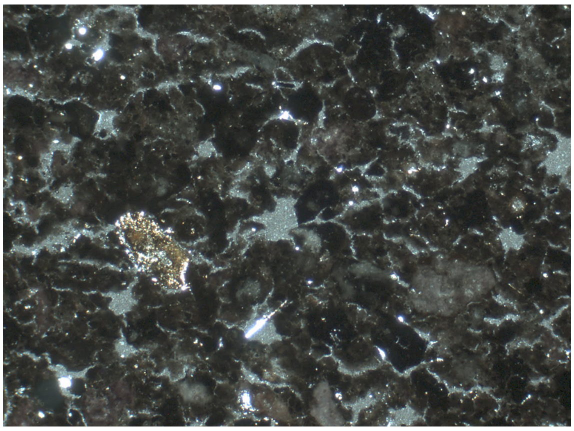

Fig. 10. Photomicrograph of sample MY094426-1 taken in cross-polarized light at 40× magnification. Note the extremely dark fabric with an extensive pore network, and the area of calcareous deposits in the middle left portion of the photomicrograph. Photomicrograph by Jennifer Meanwell.

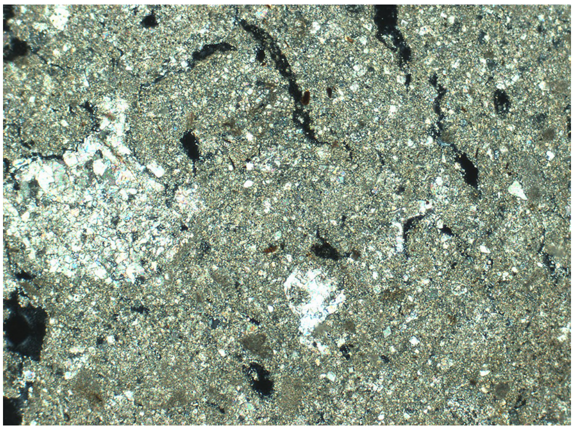

Fig. 12. Photomicrograph of a Mama Red sample from Leslie Cecil (PCD051) taken in cross-polarized light at 40× magnification. Note the abundant non-plastic inclusions (mostly limestone) and the high optical activity of the clay matrix. Photomicrograph by Jennifer Meanwell.

color, but was surrounded by a corrosion layer. When the prill was observed with reflected cross-polarized light, this area of corrosion appeared red, suggesting that the corrosion layer is cuprite, a copper (I) oxide (Fig. 14). Further analysis, described in Section 3.4, determined the elemental composition of the prill.

Observation with reflected light microscopy also identified multiple tiny prills of metal spread throughout the ceramic fabric of the tripod feet that are not visible to the naked eye. These prills are most commonly found in clusters inside darker areas of the foot (Fig. 15), but are also occasionally observed in isolation. The extensive scattering of prills and their location within the ceramic fabric suggests that the metal prills were introduced during the fabrication of the ceramic vessels, and were not introduced during use.

Two possible pathways for the introduction of this metal have been suggested. The first scenario assumes that metallurgical ceramics were being produced in close spatial association with the metallurgical activities, and that small metal fragments were accidentally introduced into the clay as the vessels were formed. The abundant metal scraps recovered from the Structure R-183b cache and the Structure Q-92 miniature ceramic vessels (Paris, 2008) suggest that metallurgists at Mayapán did remove and save sprues and other casting material from finished objects, and copper dust would be produced during this process. A second scenario is that metallurgical ceramics were recycled after use in one casting by being crushed and added as grog temper to the next set of metallurgical ceramics. The metal residues on any ceramic surfaces that were in contact with the molten material would thus have been distributed throughout the fabric of subsequent metallurgical ceramics. Typical ceramic types from Mayapán do have grog temper, as observed in the thin sections provided by Leslie Cecil. Other metallurgical ceramics may also be filled with these prills; this could explain the small copper peaks seen in the bell mold and on the end of the flat-bottomed rectangular vessel, since these areas do not seem to have otherwise been exposed to molten metal.

3.4. Electron probe and EDS

Because the initial EDS analysis found only copper, iron, and arsenic in the large prill found in the thick section of tripod foot MY094426-1, the electron probe was calibrated for those three elements and quantitative measurements were taken at ten points across the sample. The results are given in Table 1. Most of the points are nearly pure copper with trace amounts of iron and arsenic present. The atomic percentage results are mathematically

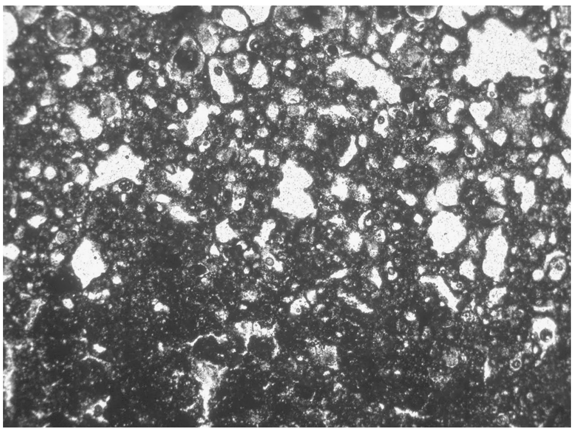

Fig. 11. Photomicrograph of sample MY094426-2 taken in plane-polarized light at 40× magnification. Note the change in microstructure toward the top of the image, where the pores are frequent and rounded. Photomicrograph by Jennifer Meanwell.

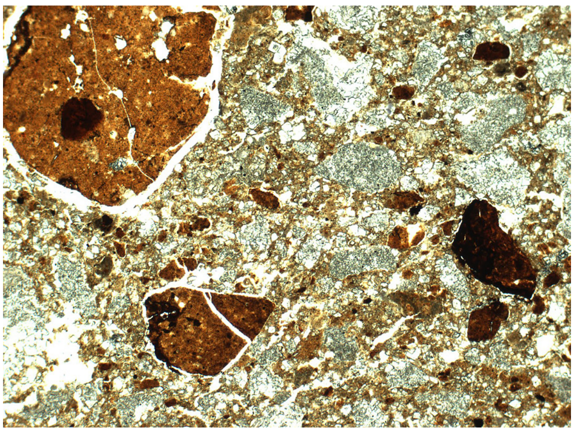

Fig. 13. Photomicrograph of a Chen Mul sample from Leslie Cecil (PCD007) taken in plane-polarized light at 40× magnification. Note the large darker areas bordered by pores. These are fragments of grog. Photomicrograph by Jennifer Meanwell.

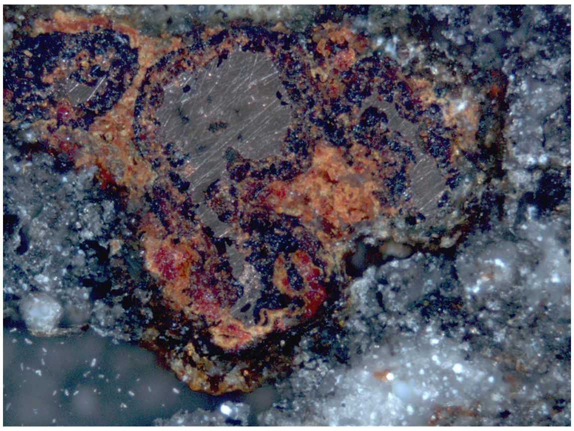

Fig. 14. Photomicrograph of the largest metal prill in MY094426-1 taken at 200× magnification with cross-polarized reflected light. Note the reddish color of the corrosion product around the central prill. Photomicrograph by Jennifer Meanwell. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

manipulated to sum to 100%, but points 6 and 8 did not originally reach 100%, suggesting there may be small amounts of another element or elements not detected. The contribution of these other elements is likely small.

Additional EDS analysis was performed on small prills and on a small cubic crystal visible within the large prill. These prills varied in composition; at least one included a significant proportion of arsenic, while others contained some lead or silver. The cubic crystal was mainly silver with some copper. This variability suggests that the prills may have resulted from different casting events, although this result does not help distinguish between the two scenarios for how the prills were introduced to the clay.

EDS spectra were also analyzed for the clay matrix to determine if chemical changes could be detected between the bulk of the sample and the vitrified (bubbly) area along one edge. The spectra, however, were basically identical; with perhaps slightly more iron in the vitrified area, suggesting that the heat exposure that caused the vitrification and bloating of the ceramic fabric did not result in chemical changes. There were no large chemical differences between the elements identified within the clay matrix of the foot with EDS and the elements detected on the end of the crucible with XRF.

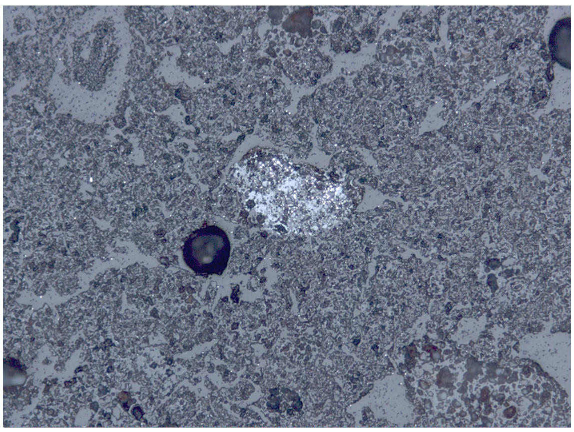

Fig. 15. Photomicrograph of a grouping of metal prills within MY094426-1 taken at 40× magnification with plane-polarized light. Photomicrograph by Jennifer Meanwell.

Table 1
Elemental and atomic percentages from the electron probe transect across the prill. Points that do not sum to at least 100% in the elemental column likely contain additional elements not measured.

Point #	Elemental %				Atomic %			
	Cu	Fe	As	Total	Cu	Fe	As	Total
1	98.02	1.81	2.17	101.96	96.17	2.02	1.81	100
2	97.95	2.03	2.12	102.10	95.98	2.26	1.76	100
3	96.83	2.07	2.36	101.26	95.69	2.33	1.98	100
4	96.64	2.71	1.36	100.71	95.81	3.05	1.14	100
5	96.89	1.71	1.67	100.27	96.65	1.94	1.41	100
6	90.16	1.31	3.31	94.78	95.46	1.58	2.96	100
7	54.35	22.53	22.67	99.55	54.79	25.83	19.38	100
8	86.45	2.27	2.30	91.02	95.02	2.84	2.14	100
9	14.31	50.15	36.89	101.35	13.94	55.59	30.47	100
10	96.45	1.91	2.38	100.74	95.83	2.16	2.01	100

4. Discussion

4.1. Use of ceramics in metal production

The analyses presented here provide further evidence of metal production activities at the site of Mayapán and advance understandings of the relationship between the production of metal items and metallurgical ceramics. Past studies suggested that secondary metal production activities were conducted at Mayapán itself, such as the remelting of metals and the lost-wax casting of metal objects, as reflected in the contents of Structure R-183b metal cache and the metal-filled miniature vessels found at Structure Q-92 (Paris, 2008). The discovery of additional metallurgical ceramics at Mayapán suggests a close relationship between the production of metal objects and the production of the metallurgical ceramics required to create them. In small-scale production, as at Mayapán, *contingent crafting* may occur when the same artisans create both the metallurgical ceramics and the metal items (Hirth, 2009: 23); in large-scale operations where production processes are segmented, *co-production* may occur when there are close collaborative relationships between artisans specializing in two or more different crafts (Shimada, 2007; Li, 2007). Both contingent crafting and co-production have been cross-culturally observed in many premodern metal production contexts from Shang bronze foundries in China (Li, 2007) to Sicán artisan workshops in Peru (Goldstein and Shimada, 2007). Contingent crafting and co-production would both require artisans to command knowledge of multiple crafts, and would allow them to experiment and make informed technological choices, as well as minimize the frequency of production errors.

The confirmation of a mixed-metal vitrified layer on several small ceramic vessels suggests their use as molds or crucibles. Vitrification is common on crucibles used to melt metals in antiquity (Bayley, 1991: 115; Davey, 1985: 142), and can result from the reaction between the metal and the clay of the crucible, or from the reaction between the clay of the crucible and wood ash (Tylecote, 1976: 19). Although the same (sometimes calcareous) clay sources utilized for domestic pottery are often used for metallurgical crucibles in early metallurgy (Frame, 2004; Thornton and Rehren, 2009; Yener et al., 2003), these clays are generally processed with organic temper, thick-walled, and heated from above to compensate for their low refractoriness (Thornton and Rehren, 2009; Rehren, 2003, 2009; Yener and Vandiver, 1993). The limited amount of heat alteration is more consistent with a remelting crucible than a smelting crucible (Rehren, 2009). The location of the small amount of vitrification on the tripod feet is suggestive that the vessels attached to the feet were exposed to high temperatures, most likely from below. There is also no evidence for organic temper. The small vessels have more localized slag-like vitrification, and are more likely to have functioned as molds, where the mold material is not exposed to high temperatures for long periods of time.

Crucibles can exhibit a highly diverse array of forms, and although the greatest proportion of early crucibles are hemispherical, elliptical plans, flat bases and tripod bases have all been reported (Tylecote, 1962: Fig. 31, 1976: Fig. 13). However, the shape of the small rectangular vessel does not bear close similarities with other examples of non-ferrous crucibles from other prehistoric sites (Davey, 1985: 143). The small size, square rims, and lack of spouts or indented rims would have made pouring melted metal from the Mayapán vessels a risky and difficult endeavor. We suggest that they functioned as ingot molds rather than as crucibles. The form of the rectangular, flat-bottomed vessel is analogous to the rectangular copper ingot molds recovered at Utatlán (Weeks, 1975), but the copitas, elongated tripod vessel, and bell molds do not have known parallels in Mesoamerica. The tripod feet suggest that larger vessels also existed; however, since complete tripod vessels have not yet been recovered, their size, form and function cannot be confirmed.

Because tiny metal prills are found within the fabrics of these metallurgical ceramics, we suggest that these ceramics were being produced in close association with the metallurgy, perhaps by the metallurgists themselves. This metal was likely introduced accidentally due to the co-production of metal objects and metallurgical ceramics in shared activity areas (Hirth, 2006, 2009; Shimada, 2007), or was deliberately added to clay recipes as part of crushed grog temper made from previously used metallurgical ceramics. The fact that multiple clusters of metal prills are found within the vessel may strengthen the argument that they are the result of grog, but both hypotheses are possible.

4.2. Spatial and social distribution of production loci

The spatial and social distribution of metallurgical ceramics at Mayapán suggests that metallurgical ceramics were not restricted to a single workshop, but are associated with ritual and administrative structures within the monumental zone, as well as residential structures in the southeast sector of the city. Many of these objects were deposited in elite ritual and administrative structures in and near the main plaza of the site's monumental center; these include the two vessels, two copitas and two tripod feet analyzed in this study. The flat-bottomed rectangular vessel was recovered from Structure Q-88a, a colonnaded hall on the east side of the central site of the plaza. One of the copitas analyzed in this study was found in Structure Q-58, also called the "Crematorio," a burial shaft temple in the northwest corner of the main plaza of the monumental zone. The elliptical tripod vessel was recovered from Structure Q-57, a small platform to the south of the Crematorio. A second copita analyzed in this study was recovered nearby in Structure Q-54, which is a second colonnaded hall located on the western edge of the main plaza. The two tripod feet analyzed in this study, as well as 39 other feet (41 in total) and four additional copitas were recovered from Structure Q-99, another colonnaded hall located to the east of the main plaza. It is noteworthy that many of the confirmed metallurgical ceramics, including both crucibles and possible lost-wax casting mold fragments were recovered at religious structures such as temples and temple platforms as well as structures with a likely administrative function such as colonnaded halls.

Other possible metallurgical ceramics were associated with elite and commoner residences within and beyond the monumental zone. The 41 tripod feet recovered at Structure Q-99 are among 87 total tripod feet recovered from various structures at Mayapán. Twenty-six tripod feet were recovered from Structure Q-40a, while eight were recovered from the neighboring Structure Q-39. Both of these structures were small residential structures that compose part of an elite crafts barrio immediately to the west of the monumental zone where residents engaged in the multicraft production of a variety of different industries such as shell, pottery, effigy censers, chert, chalcedony, and obsidian (Masson and Peraza Lope, 2013: 214). However, it should be noted that other isolated households at Mayapán practiced multiple specialized craft activities, including in commoner contexts (Masson and Peraza Lope, 2013: 385). Tripod feet were also found at secondary elite housegroups in the mid-city southeast sector, with five at Structure R-151b, and one in Structure R-183b. Additional tripod feet were found at smaller residences in the mid-city southeast sector, which are thought to represent commoner dwellings; these include three feet in Structure Y-44 and two in Structure Y-43. However, our current sample of metallurgical ceramics appears to be predominantly (but not exclusively) associated with the city's elites, including the temples and colonnaded halls of the monumental zone, and residential structures of the elite crafts barrio and the mid-city southeast sector.

5. Conclusions

Although the conclusions drawn from the metallurgical ceramics discussed here must be tentative due to the small sample size, we argue that their association with metallic residues and metal prills and their specialized ceramic properties reflects use in the production of metal objects at Mayapán. The metal peaks, especially the copper, silver, gold, arsenic, and tin, identified from the XRF spectra are unlikely to be present in ceramics that have not been exposed to molten metal. Additionally, the suite of metals matches typical alloys in use in Mesoamerica and the alloys of other objects found at Mayapán (Hosler, 1994; Root, 1962). The XRF analysis of the bell mold and the tripod foot suggested that these two objects were not in direct contact with molten metal, although the presence of small metal peaks in the XRF analysis and the metal prills in the ceramic fabric of the tripod feed suggest that they were associated with the metal production process. We suggest that they represent fragments of crucibles or molds which were broken during the original firing or in subsequent casting events.

The petrographic analyses suggest that metallurgical ceramics were produced using special clay resources that would enable them to withstand the high temperatures and thermal stresses of the remelting and casting process. We suggest that they were created by individuals involved in the metal production process, because copper and copper alloys were incorporated in these ceramics. Metal prills may have been incorporated into ceramic fabrics as either accidental inclusions or deliberate grog temper; the latter would have further enabled the ceramics to withstand high temperatures. Further research will focus on determining the extent of variability in clay resources near Mayapán. Additional work will also focus on characterizing the temperatures required for remelting of the copper alloys in use, as well as the properties required for a successful ceramic mold.

Finally, the distribution of metallurgical ceramics throughout the cityscape of Mayapán suggests that metal production sites may not have been restricted to a single workshop. Our current sample of metallurgical ceramics suggests an association with the monumental core and the southeast sector of the city. Future research will investigate the role of specialized metalworkers in elite households at Mayapán, and the ways in which they integrated exotic goods, raw materials, and technical knowledge into the high-skill domestic production of luxury items in the most powerful urban center of the Postclassic Maya world.

Acknowledgments

This research owes a great debt of gratitude to many. The metallurgical ceramics were excavated by the Economic Foundations of Mayapan Project (2001–2009) directed by Marilyn Masson, Carlos Peraza Lope, and Timothy S. Hare (NSF Awards 1018919 and 1069128; NGS Award 8598-08), and by the Proyecto Mayapán (1996–2009) directed by Carlos Peraza Lope, and we thank these directors and staff members of these projects for their support. We thank the Instituto Nacional de Antropología e Historia for their permission to analyze these objects and for their continued permission granted to the Economic Foundations of Mayapan Project and the Proyecto Mayapan over the years. Special thanks are due to Leslie Cecil for generously allowing us to use her thin sections of typical Mayapan ceramic pastes to compare with the metallurgical ceramics. Scott Speakman of the Center for Materials Science and Engineering at MIT generously donated XRF equipment time. Nilanjan Chatterjee assisted with the electron probe analysis, which was funded by a University at Albany, SUNY Graduate Student Organization Research Grant (2011). We particularly thank Dorothy Hosler for her insightful feedback at numerous stages of this research. Prudence Rice and an anonymous reviewer provided insightful comments that improved this paper.

References

Arnold, D.E., 1971. Ethnomineralogy of Ticul, Yucatán potters: etics and emics. American Antiquity 36, 20–40.
Arnold, D.E., 2005. Maya Blue and palygorskite: a second possible pre-Columbian source. Ancient Mesoamerica 15, 51–62.
Arnold, D.E., Bohor, B.F., 1976. An ancient attapulgite mine in Yucatán. Katunob 8, 25–34.
Arnold, D.E., Neff, H., Glascock, M.D., Speakman, R.J., 2007. Sourcing the palygorskite used in Maya Blue: a pilot study comparing the results of INAA and LA-ICP-MS. Latin American Antiquity 18, 44–58.
Bayley, J., 1991. Anglo-saxon non-ferrous metalworking: a survey. World Archaeology 23, 115–130.
Blackiston, A.H., 1910. Recent discoveries in Honduras. American Anthropologist 12, 536–541.
Bray, W., 1977. Maya metalwork and its external connections. In: Hammond, N. (Ed.), Social Process in Maya Prehistory: Studies in Honour of Sir Eric Thompson. Academic Press, New York, pp. 365–404.
Craddock, P.T., 1995. Early Metal Mining and Production. Smithsonian Institution Press, Washington D.C.
Cecil, L.G., 2012. Inter-regional Socioeconomic and Sociopolitical Relations of the Postclassic Maya of North-Central Yucatan, Mexico, Belize, and Guatemala. (Electronic document accessed 01.28.13.). http://faculty.sfasu.edu/cecillg/index.html.
Coggins, C.C., Shane, O.C.I., 1984. Cenote of Sacrifice: Maya Treasures from the Sacred Well at Chichen Itza. University of Texas Press, Austin.
Davey, C.J., 1985. Crucibles in the Petrie Collection and hieroglyphic ideograms for metal. The Journal of Egyptian Archaeology 71, 142–148.
Frame, L.D., 2004. Investigations at Tal-i Iblis: Evidence for Copper Smelting During the Chalcolithic Period (B.S. thesis). Department of Material Science and Engineering, Massachusetts Institute of Technology.
Gettens, R.J., 1962. Maya Blue: an unsolved problem in ancient pigments. American Antiquity 27, 557–564.
Goldstein, D.J., Shimada, I., 2007. Middle Sicán multicraft production: resource management and labor organization. In: Shimada, I. (Ed.), Craft Production in Complex Societies. University of Utah Press, Salt Lake City, pp. 44–67.
Hirth, K.G., 2006. Introduction: obsidian craft production at Xochicalco. In: Hirth, K.G. (Ed.), Obsidian Craft Production in Ancient Central Mexico. The University of Utah Press, Salt Lake City, pp. 3–17.
Hirth, K.G., 2009. Craft production, household diversification, and domestic economy in prehispanic Mesoamerica. Archeological Papers of the American Anthropological Association 19, 13–32.
Hosler, D., 1986. The Origins, Technology, and Social Construction of Ancient West Mexican Metallurgy (Unpublished Ph.D. dissertation). Department of Anthropology, University of California, Santa Barbara.
Hosler, D., 1994. The Sounds and Colors of Power: the Sacred Metallurgical Technology of Ancient West Mexico. MIT Press, Cambridge, Mass.
Hosler, D., Lechtman, H., Holm, O., 1990. Axe-monies and Their Relatives. Dumbarton Oaks Research Library and Collection, Washington, D.C.
Hosler, D., Stresser-Pean, G., 1992. The Huastec region: a second locus for the production of bronze alloys in ancient Mesoamerica. Science 257, 1215–1220.
Kearns, T., Martinón-Torres, M., Rehren, T., 2010. Metal to mould: alloy identification in experimental casting moulds using XRF. Historical Metallurgy 44 (1), 48–58.
Krekeler, M.P.S., Kearns, L.E., 2008. A new locality of palygorskite-rich clay from the southeastern Yucatán: a potential material source for environmental applications. Environmental Geology 58, 715–726.
Lechtman, H., 1977. Style in technology: some early thoughts. In: Lechtman, H., Merrill, R.S. (Eds.), Material Culture: Styles, Organization, and Dynamics of Technology. West Publishing, Saint Paul, pp. 3–20.
Lechtman, H., Steinberg, A., 1973. The history of technology: an anthropological point of view. In: Bugliarello, G., Doner, D.B. (Eds.), The History and Philosophy of Technology. University of Illinois Press, Urbana, pp. 135–160.
Li, Y., 2007. Co-craft and multicraft: section-mold casting and the organization of craft production at the Shang Capital of Anyang. In: Shimada, I. (Ed.), Craft Production in Complex Societies. University of Utah Press, Salt Lake City, pp. 184–223.
Lothrop, S.K., 1952. Metals from the Cenote of Sacrifice, Chichen Itza, Yucatan. With Sections by W. C. Root and Tatiana Proskouriakoff and an Appendix by William Harvey. The Peabody Museum, Cambridge.
Masson, M.A., Peraza Lope, C., 2013. Kukulkan's Realm: Urban Life at Ancient Mayapán. University of Colorado Press, Boulder (in press).
Paris, E.H., 2008. Metallurgy, Mayapan and the Postclassic world system. Ancient Mesoamerica 19, 43–66.
Paris, E.H., Peraza Lope, C., 2013. Breaking the mold: the socioeconomic significance of metal artifacts at Mayapan. In: Simmons, S.E., Shugar, A.N. (Eds.), Archaeometallurgy in Mesoamerica: Current Approaches and New Perspectives. University of Colorado Press, Boulder, pp. 161–201.
Peraza Lope, C., 1998. Salvamento arqueológio en la modernización de la carretera Mérida-Mayapán-Oxkutzcab (Tramo Mayapán-Teabo). Informe de Actividades al Consejo de Arqueología del Instituto Nacional de Antropología e Historia, Mérida, Yucatán, México.
Peraza Lope, C., Delgado Kú, P., Ojeda Escamilla, B., Delgado Kú, M., 2003. Trabajos de Mantenimiento y Conservación Arquitectónica en Mayapán, Yucatán. Informe de Actividades al Consejo de Arqueología del Instituto Nacional de Antropología e Historia, Mérida, Yucatán, México.
Peraza Lope, C., Masson, M.A., Hare, T.S., Delgado Kú, P.C., 2006. The chronology of Mayapan: new radiocarbon evidence. Ancient Mesoamerica 17, 153–175.
Pollock, H.E.D., Roys, R.L., Proskouriakoff, T., Smith, A.L. (Eds.), 1962. Mayapan, Yucatan, Mexico. Carnegie Institute of Washington Publication No. 619, Washington, DC.
Rehren, T., 2003. Crucibles as reaction vessels in ancient metallurgy. In: Craddock, P., Lang, J. (Eds.), Mining and Metal Production Through the Ages. The British Museum Press, London, pp. 207–215.
Rehren, T., 2009. From mine to microbe – the Neolithic copper melting crucibles from Switzerland. In: Shortland, A.J., Freestone, I.C., Rehren, Th (Eds.), From Mine to Microscope: Advances in the Study of Ancient Technology. Oxbow Books, Oxford, U.K, pp. 155–162.
Rice, P.M., 1987. Pottery Analysis: a Sourcebook. The University of Chicago Press, Chicago and London.
Root, W.C., 1962. Report on the metal objects from Mayapan. In: Pollock, H.E.D., Roys, R.L., Proskouriakoff, T., Smith, A.L. (Eds.), Mayapán, Yucatan, Mexico. Carnegie Institute of Washington Publication No. 619, Washington, DC, pp. 391–399.
Russell, B.W., 2008. Postclassic Maya Settlement on the Rural–Urban Fringe of Mayapán, Yucatán, Mexico: Results of the Mayapán Periphery Project.
Schultz, L.G., Shepard, A.O., Blackmon, P.D., Starkey, H.C., 1971. Mixed-layer Kaolinite-Montmorillonite from the Yucatan Peninsula, Mexico. Clays and Clay Minerals 19, 137–150.
Shepard, A.O., 1962. Maya Blue: an alternative hypotheses. American Antiquity 27, 565–566.
Shepard, A.,O., Gottlieb, H.B., 1962. Maya Blue: Alternative Hypotheses. Notes from a Ceramic Laboratory No. 1. Carnegie Institution of Washington, Washington, D.C.
Shimada, I., 2007. Introduction. In: Shimada, I. (Ed.), Craft Production in Complex Societies. University of Utah Press, Salt Lake City, pp. 1–21.
Simmons, S.E., 2005. Investigations in the Church Zone: Maya Archaeometallurgy at Spanish Colonial Lamanai, Belize. In: Research Reports in Belizian Archaeology, vol. 2, pp. 231–239.
Simmons, S.E., Pendergast, D.M., Graham, E., 2009. The context and significance of copper artifacts in Postclassic and early historic Lamanai, Belize. Journal of Field Archaeology 34, 57–75.
Simmons, S.E., Shugar, A.N., 2013. Archaeometallurgy at Lamanai, Belize: new discoveries and insights from the southern Maya lowland area. In: Simmons, S.E., Shugar, A.N. (Eds.), Archaeometallurgy in Mesoamerica: Current Approaches and New Perspectives. University of Colorado Press, Boulder, pp. 135–159.
Smith, R.E., 1971. The Pottery of Mayapan. Peabody Museum of Archaeology and Ethnology, Cambridge, Mass.
Stoltman, J., 2001. The role of petrography in the study of archaeological ceramics. In: Goldberg, P., Holliday, V.T., Ferring, C.R. (Eds.), Earth Sciences and Archaeology. Kluwer Academic/Plenum, New York, pp. 297–326.
Thornton, C.P., Rehren, T., 2009. A truly refractory crucible from fourth millennium Tepe Hissar, Northeast Iran. Journal of Archaeological Science 36, 2700–2712.
Tylecote, R.F., 1962. Metallurgy in Archaeology. Edward Arnold (Publishers), LTD, London.
Tylecote, R.F., 1976. A History of Metallurgy. The Metals Society, London.

Urban, P.A., Shugar, A.N., Richardson, L., Schortman, E., 2013. The production of copper at El Coyote, Honduras: processing, dating, and political economy. In: Simmons, S.E., Shugar, A.N. (Eds.), Archaeometallurgy in Mesoamerica: Current Approaches and New Perspectives. University of Colorado Press, Boulder, pp. 77–112.
Weeks, J.M., 1975. The Archaeology of Greater Utatlán: El Resguardo and Pakaman Excavations (Unpublished M.A. thesis). Department of Anthropology, University at Albany, SUNY, Albany.
Weeks, J.M., 1983. Chisalin: a Late Postclassic Maya Settlement in Highland Guatemala. In: BAR International Series 169. Oxford.
Weeks, J.M., 2013. Late prehistoric K'iche' metalworking at Utatlán, Guatemala. In: Simmons, S.E., Shugar, A.N. (Eds.), Archaeometallurgy in Mesoamerica: Current Approaches and New Perspectives. University of Colorado Press, Boulder, pp. 113–133.
Ybarra, R., 2012. Análisis de un hornillo o brasero de orfebrería prehispánico. Revista de la Biblioteca de Joyería. (Electronic document accessed 08.28.12.). http://www.raulybarra.com/instructor/bitácora.htm.
Yener, K.A., Adriaens, A., Earl, B., Özbal, H., 2003. Analyses of metalliferous residues, crucible fragments, experimental smelts, and ores from Kestel tin mine and the tin processing site of Göltepe, Turkey. In: Craddock, P., Lang, J. (Eds.), Mining and Metal Production Through the Ages. The British Museum Press, London, pp. 181–197.
Yener, K.A., Vandiver, P.B., 1993. Tin processing at Göltepe, an Early Bronze Age Site in Anatolia. American Journal of Archaeology 97, 207–238.