An Examination of Maya Metallurgy, 1150 to 1544 A.D.

by

Katherine E. Williams

Submitted to the Department of Materials Science and Engineering
in partial fulfillment of the requirements for the degree of

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Abstract

Like everything else made by man, metallurgy is a cultural product. Ancient metallurgy can be studied using the techniques of modern materials science, and the results can provide a valuable window on the culture in which the metallurgy evolved.

The present project applies chemical and metallographic analysis to a corpus of objects excavated at Lamanai, a Maya site in Belize. The total corpus spans the period from 1150 to 1641 A.D., but this thesis focuses on the objects dating from 1150 to 1544 A.D..

The objects studied span two major periods in Maya history: the Middle and Late Post Classic. It was determined that Middle Post Classic metallurgy represented two main traditions. The first fabricated complex decorative objects from cast, unalloyed copper. The second used Cu-As and Cu-Sn to make utilitarian and decorative objects from cast and worked metal. In the Late Post Classic, a third metallurgical tradition fabricated utilitarian and decorative objects from unalloyed copper and Cu-Sn alloys.

Thesis Supervisor: Dorothy Hosler
Title: Center for Materials Research in Archaeology and Ethnology

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Chapter 1

Introduction

1.1 The Research Problem

1.1.1 Research Motivation

Metallurgy is a cultural product, and both ancient and modern metallurgy can be studied using the techniques of modern materials science. Each culture determines which metals it will use and what it will use them for based on the values and priorities of that society. For example, the peoples of West Mexico had advanced bronze technology, which they used primarily for decorative purposes, preferring to make tools and weapons from stone. The Mesopotamian cultures, however, used similar materials to produce bronze weapons and armor.

Thus, materials technology provides a vital window on culture, particularly in cases where the written record is sparse or nonexistent. Such research is interdisciplinary applying the materials scientist's knowledge of materials-processing-property relationships to questions of human history and culture.

1.1.2 Research Objectives

This thesis has three primary goals: to characterize Maya metal-working technology from 1150 to 1544 A.D., to trace the development of that technology through time, and to use an understanding of the technology to gain insights into the function of metal in Maya society during this time period.

The first objective is to characterize Maya metal-working technology. This will include the kinds of objects fabricated: was metal used to make tools or decorative objects? Because "function" is not necessarily determined by visual inspection, functionality of tool-like objects such as axes will be evaluated by examining the extent to which properties (particularly hardness) suffice for a given instrumental function. Second, the materials used must be identified. Third, the manufacturing techniques used must be determined. And, finally, the central materials science question must be answered: how were processing and choice of materials (metals and alloys) used to manipulate the properties of the material to suit the demands of a given design and the function of the object? Or, alternatively, how was design adapted to the properties of available materials?

Once the technology has been described, the second goal will be to trace any changes that may have occurred over the course of time in the kinds of objects made from metal, in the materials used, and in the fabrication techniques applied.

The last and perhaps most difficult goal is to examine the extent to which the function of metal in Maya society may have changed through time. Was it a sacred repository of status and power, or merely a resource to be used and discarded?

1.2 Background

1.2.1 The Maya

At its height the Maya empire extended from the mountains of present-day Guatemala to the lowlands of the northern Yucatan peninsula, as shown on the map in Figure 1-1. This thesis will be primarily concerned with metal artifacts used by the Maya of the Central Area, which includes most of Belize, a narrow fringe of southern Mexico, and the Peten district of Guatemala.

Most of the region is a limestone plateau lying between 300 and 700 feet above sea level. A series of steep limestone ridges provide the only well-drained, habitable land in the plateau. The troughs between the ridges become seasonal swamps during the rainy season, and are avoided by the present day inhabitants as they appear to have been by the prehistoric Maya. Though there are no major river systems in the region, Belize is drained by several short and locally important rivers.

The Maya Mountains, a low volcanic range, occupy the southern part of Belize. They were a valuable source of volcanic stone for the Maya of the Central area, but contain insignificant deposits of ore minerals.

The climate of the region is characterized by a rainy season, extending from early May to early December, and a dry season. Total rainfall ranges from 50 inches per year in the north to over 100 inches per year on the slopes of the Guatemalan mountains. Daily maximum temperatures are usually in the 80s, with nighttime lows in the 70s. Occasional cold spells in the 50s occur, but frost is completely unknown. Tropical rain forest is thus the natural vegetation of the region, providing a variety of structural woods and edible fruits and nuts. A more detailed discussion of the ecology of the region is found in [2].

Maya history begins about 800 B.C. with evidence of scattered occupation by small farming groups. More immigration and growth followed. Most of the region had at least some population by 500 B.C. and major centers were commonplace by the first century A.D.. This Preclassic period was followed by the Early and Late Classic, from 250 to 600 A.D.and 600 to 900 A.D.respectively.

The Classic period is so-called because, in the early days of Maya archaeology, a large number of carved stone monuments with dates in the Maya calendar were found. All those dates fell within what is now called the Classic period, and the flowering of Maya civilization was assumed to correspond to the period when stelae were being carved. It has since been demonstrated that a highly complex culture existed several centuries before the first calendrical carvings.

The towering pyramids surmounted by stone temples that typify the ruins of the Yucatan peninsula are a product of Maya Classicism. In the Early Classic these temples were the center of large ceremonial precincts which were nearly empty except durign festivals. As the Late Classic progressed, the population of the region grew and the temples became the centers of large cities.

Then, for reasons that are not fully understood, Maya civilization collapsed. In most centers, the collapse was complete, with thriving cities replaced by echoing ruins. In some locations, however, Maya culture endured long into the Postclassic. Lamanai, on the New River in Belize, was one such site.

Lamanai, which had been occupied since Preclassic times, continued to thrive through at least the Early and Middle Postclassic (900 to 1150 A.D.and 1150 to 1300 A.D., respectively). Both periods saw major ceremonial construction and elaborate royal burials. This relative stability can be in part attributed to the site's location on the New River, which would have provided a trade and communication link to northern Yucatan and the rest of Mesoamerica [9].

In any case, Lamanai appears to have declined gradually over the centuries. Its population when Spanish missionaries arrived in 1544 A.D.is unknown, but was large enough to inspire the priests to found a church. Catholicism held some sway over the people of Lamanai from 1570 to 1640 A.D., but the church was desecrated and abandoned shortly thereafter.

1.2.2 The Corpus

The Royal Ontario Museum (Toronto, Ontario, Canada) conducted excavations at Lamanai from 1974 to 1983. The copper-based artifacts, 100 in all, produced by these excavations form one of the largest known assemblages of Maya metal objects and will be discussed further in Chapter 2. The only other groups of metal artifacts that are this large are from the Cenote of Sacrifice at Chichen Itza and from Amapa, in West Mexico.

The Cenote artifacts, discussed in detail by S. K. Lothrop [8], were dredged from a large sacrificial well. For that reason their temporal context–essential to placement within Mayan culture as a whole–is unknown.

The Amapa artifacts were subjected to chemical analysis, but not to metallographic study. Thus, nothing is known about the fabrication techniques by which they were produced.

The present study, which applies metallographic and chemical analysis methods to a large corpus of contextually placed objects, is perhaps the most extensive project of its kind to date.

1.3 Figures

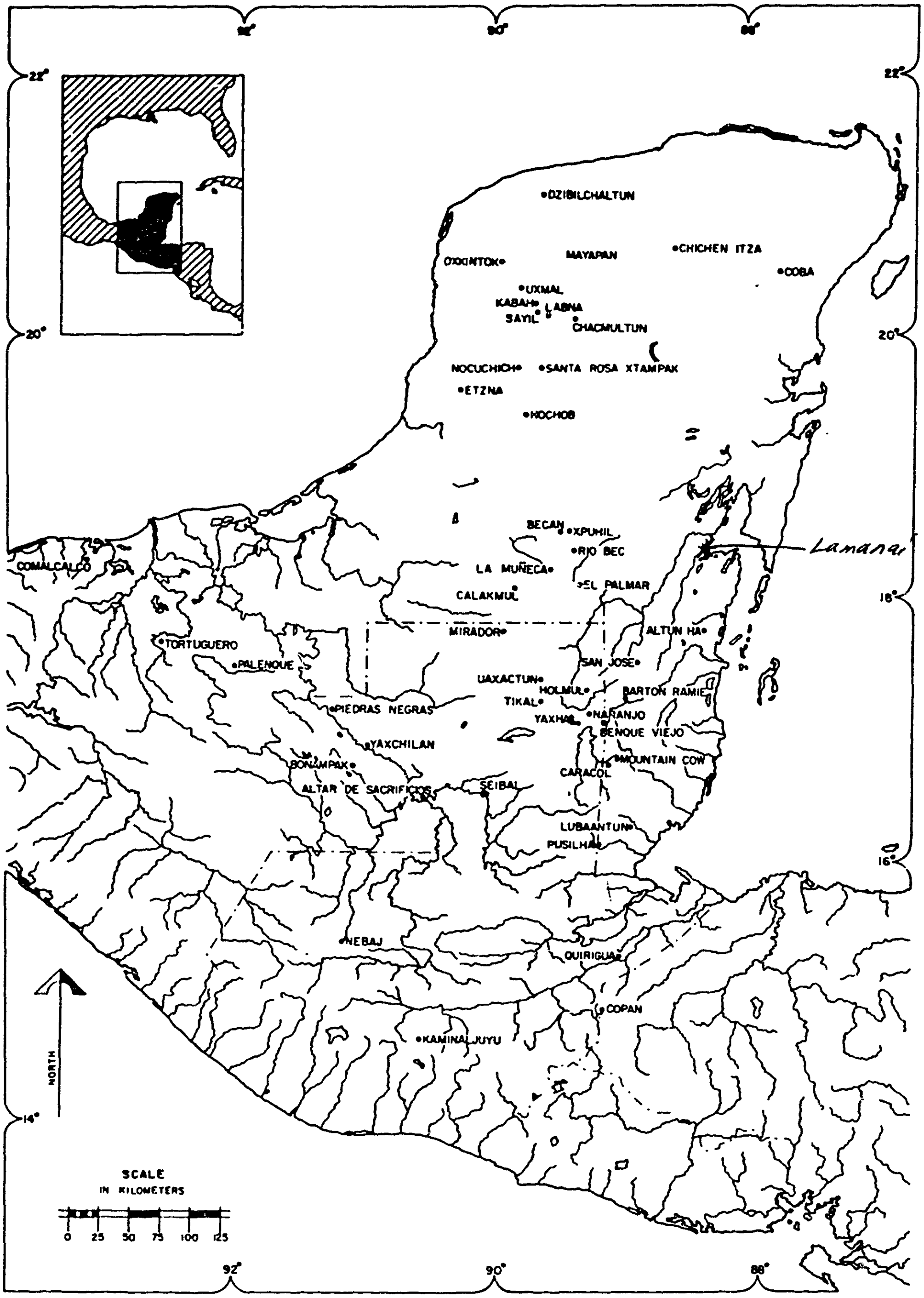

Figure 1-1: Map of the Central Maya Area.

Chapter 2

Methods

2.1 The Corpus

As previously discussed, research for this thesis was based on a corpus of 100 copper and copper alloy artifacts excavated at Lamanai, Belize by Dr. David Pendergast of the Royal Ontario Museum. Based on the archaeological context in which it was found, each of the objects has been dated to one of three periods: Middle Post Classic (1150-1300 A.D.), Late Post Classic (1300-1544 A.D.), or Historic (1544-1641 A.D.) [10]. These periods are abbreviated in tables here and elsewhere in this thesis as shown in Table 2.1.

The objects are summarized in Table 2.2, which also indicates the numbers of objects sampled for qualitative chemical analysis as discussed in more detail on page 18. In the earliest period, all but two of the 27 objects are bells, buttons, and other decorative objects. The exceptions, an axe and a tweezer, are utilitarian in form. All of the objects from this period were found in burials.

Period	Abbreviation	Dates
Middle Post Classic	Middle PC	1150-1300 A.D.
Late Post Classic (1st subperiod)	Late PC*	1300-1400 A.D.
Late Post Classic (2nd subperiod)	Late PC	1400-1544 A.D.
Historic	Hist.	1544-1641 A.D.

Table 2.1: Abbreviations used in tables.

Type	Period	Quantity	Number Sampled	% Sampled
Axe	Middle PC	1	1	100
Axe[a]	Hist.	12	6	50
Decorated bell	Middle PC	7	4	57
Other bell	Middle PC	3	3	100
Bell	Late PC	2	2	100
Bell	Hist.	28	6	21
Hemisphere button	Middle PC	6	3	50
Wirework button	Middle PC	7	3	43
Fishhooks	Hist.	3	1	33
Ingot[b]	Hist.	4	4	100
Needle	Hist.	5	3	60
Ring	Middle PC	2	2	100
Ring	Late PC	1	1	100
Ring[c]	Historic	3	2	67
Sheet Metal	Late PC*	1	1	100
Tweezer	Middle PC	1	1	100
Tweezer	Late PC*	1	1	100
Tweezer	Late PC	1	1	100
Possible Awl Tip	Late PC	1	1	100
Unidentified Metal	Hist.	11	1	9

Table 2.2: Summary of objects in Lamanai corpus.

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[a] One of the axes, 790/1, was found buried near the surface.

[b] The largest ingot, 894/1, was a surface find and cannot be precisely dated.

[c] One ring, 227/2 was found in a Colonial burial.

The next period, the Late Postclassic, is represented by a far smaller group of objects (7) than either the Middle Post-Classic or the Historic period, as Table 2.2 indicates. Both decorative and utilitarian objects are represented. The Late Postclassic can be divided into two subperiods: 1300 to 1450 A.D.and 1450 to 1544 A.D.. Artifacts indicated with an asterisk in Table 2.2 are from the earlier period. The ring and bells were found in burials, while all the other objects were found in refuse.

The last period, from 1544 to 1641 AD, yielded the largest quantity of metal, with 65 objects in all. With the exceptions noted in Table 2.2, this material was found scattered across the interior surfaces of one large building.

The Historic period is marked by a dramatic increase in the number of utilitarian objects. Several object types, all of them utilitarian in nature, appear in the Historic period for the first time: ingots, needles, and fishhooks. Except for tweezers, all of the object types which appear in the early periods also appear in the Historic period.

2.2 The Sample

It was not possible to apply all four analytic techniques—qualitative and quantitative chemistry, metallography, and microhardness testing—to all of the 100 objects in the corpus. The objects actually sampled were chosen to be as representative as possible of the entire corpus and are enumerated by time period and functional type in Tables 2.3, 2.4, and 2.5. As Table 2.2 indicates, 47 of the total of 100 objects were sampled. The tables indicate the kinds of analyses performed on each sampled object. Archaeological contexts are as indicated in Table 2.2.

2.2.1 Rationale.

As discussed previously, one of the primary goals of this thesis was examination of the changes in Maya metallurgy during the period from 1150 to 1641 AD. For that reason, I chose the objects to be sampled for each time period independently. Because more objects date to the Historic period, a larger percentage of the total objects present was sampled in the Middle Post Classic group (17 of 27) than in the Historic group (21 of 65), but the number of objects sampled is comparable for the two groups (see tables, page 19). Care was taken to ensure that all of the samples were representative of the types and time periods under consideration. Table 2.2 summarizes the functional types present in each time period, and specifies the number of objects actually sampled.

In general terms, the corpus may be divided into two types of objects: those that are primarily decorative in nature and those that are utilitarian in form. These two broad classes were considered for sampling separately from each other in order to ensure that enough data to trace both classes through time was obtained.

Particular attention was paid to those types which appear in more than one time period, and which may therefore be viewed as linking the three periods. Bells and rings, for instance, appear in all three periods, as Table 2.2 indicates. Such types were sampled in each of the time periods in which they appeared, as the tables (page 19) show.

2.2.2 Qualitative analysis

Qualitative chemical analysis was performed by the Strnad Spectroscopic Laboratory at MIT using emission spectroscopy techniques. This technique shows the elements present in the sample being tested, together with their relative concentrations: major, minor, or trace. It allows identification of both trace elements and any alloying elements which may be present in larger concentrations.

The sample for qualitative analysis was the largest of the four sample groups. Objects were chosen based on type and time period, in an effort to obtain a twenty per cent sample of each type-time period subgroup. Twenty per cent, as a rule of thumb, is an adequate sample for this kind of research [5]. Since a twenty per cent sample was achieved, the results may be generalized to all of the objects in the corpus.

2.2.3 Quantitative analysis

Quantitative analysis, performed at the Strnad Laboratory using atomic absorption spectrometry techniques, provides precise concentrations for each of the elements specified. This technique was used to definitively identify intentional alloys. It was also applied to all of the metallographically analyzed objects in order to facilitate interpretation of microstructures and the functionality of the object.

2.2.4 Metallographic analysis

Metallographic analysis forms the cornerstone of this thesis. As metallography is both the most important and the most time consuming of the four techniques, the objects to be sampled were chosen somewhat more subjectively than for the other techniques. First and foremost, objects to be sampled were selected because of their relevance to one or more of the goals of the thesis. As much as possible, the metallographic sample is representative of all three of the time periods and both of the major classes of objects present at Lamanai.

Second, the objects were chosen because they were typical of one of the functional types. For the most part, unique objects were avoided. Third, the sample was chosen in order to make use of comparative data available from other sources (notably [3]). Finally, objects were chosen based on the amount of information they could yield about Maya metal-working technology. Complex designs were thus selected over simple designs, when that could be done without compromising the other aims of the work.

2.2.5 Microhardness testing

One of the most interesting questions concerning the utilitarian objects in the corpus was that of functionality. If the various tool-like objects could have been used as tools, that would support different conclusions about the culture than if they were incapable of performing their apparent function. An axe-shaped object that cannot cut wood of necessity serves a different cultural purpose than one that can.

Microhardness testing was performed on the sections from the five utilitarian objects indicated in the tables (page 19) in order to determine the extent of any work hardening. Hardness data in turn allowed evaluation of the functionality of these objects.

In addition to the work performed for this study, three of the objects were sampled by other researchers for studies of artifact chemistry and fabrication techniques. Those samples are included in the totals in Tables 2.3, 2.4, and 2.5 and the results are noted accordingly in the text. Overall, 47 objects, nearly half of the total, were sampled for qualitative chemical analysis. Twenty-six of these were also sampled for quantitative analysis. Finally, metallographic studies were done on nineteen objects, and microhardness testing was done on six utilitarian objects of those nineteen. The goal of a statistically valid sample was thereby achieved.

Number	Type	Qual.	Quant.	Metal.	Hard.
557/2	Axe	Y	N	Y	Y
61/13	Bell	Y	N	N	N
69/6	Bell	Y	Y	Y	N
69/7	Bell	Y	Y	Y	N
69/8b	Bell	Y	N	N	N
69/8c	Bell	Y	N	N	N
91/2a	Bell/Pin	Y	Y	Y	N
91/2b	Bell/Pin	Y	N	N	N
69/9b	Button	Y	Y	Y	N
69/9c	Button	Y	N	N	N
69/9f	Button	Y	N	Y	N
90/8a	Button	Y	Y	N	N
90/8c	Button	Y	N	N	N
90/8f	Button	Y	N	N	N
68/3	Ring	Y	Y	Y	N
118/11	Ring	Y	N	N	N
557/3	Tweezer	Y	Y	Y	Y
Total	All	17	7	8	2

Table 2.3: Middle Post Classic objects sampled.

Number	Type	Qual.	Quant.	Metal.	Hard.
774/20	Bell	Y	N	N	N
774/23	Bell	Y	Y	Y	N
774/3	Ring	Y	N	N	N
614/2 *	Sheet metal	Y	N	N	N
614/1 *	Tweezer	Y	Y	Y	Y
905/1	Tweezer	Y	Y	N	N
922/2	Awl Tip	Y	N	N	N
Total	All	7	3	2	1

Table 2.4: Late Post Classic objects sampled. An asterisk indicates those objects from the early subperiod (1300-1400 A.D.).

Number	Type	Qual.	Quant.	Metal.	Hard.
790/1	Axe	Y	N	Y	N
855/1	Axe	Y	Y	Y	Y
856/1	Axe	Y	Y	Y	Y
856/6	Axe	Y	Y	N	N
871/1	Axe	Y	Y	Y	Y
908/2	Axe	Y	N	N	N
823/10	Bell	Y	Y	Y	N
834/3	Bell	Y	Y	Y	N
834/4	Bell	Y	N	N	N
867/2	Bell	Y	Y	N	N
878/7	Bell	Y	N	N	N
885/23	Bell	Y	N	N	N
834/1	Fishhook	Y	Y	Y	N
858/11	Ingot	Y	Y	N	N
881/1	Lump/ingot	Y	Y	Y	N
894/1	Ingot	Y	Y	N	N
908/1	Ingot	Y	Y	N	N
856/3	Needle	Y	Y	N	N
858/21	Needle	Y	Y	N	N
916/26	Needle	Y	N	N	N
227/2	Ring	Y	N	N	N
822/1	Ring	Y	Y	Y	N
878/3	Misc. metal	Y	Y	N	N
Total	All	23	16	8	3
Grand Total	All	47	26	19	6

Table 2.5: Historic objects sampled.

Chapter 3

Prehistoric Maya Metallurgy

This chapter will discuss my findings concerning the pre-Spanish objects in the Lamanai corpus. Time constraints prohibit complete discussion of the objects dating to the Spanish Colonial period.

3.1 The Middle Post Classic, 1150-1300 A.D.

3.1.1 Cast Objects

The results of the qualitative and quantitative chemical analyses, detailed in Appendix A, show that the 25 Middle Post Classic objects fabricated by casting were made primarily from copper, the exception being a bell (#69/6) made from a Cu-1.33% As alloy. Here and elsewhere in this thesis, objects are described as alloys when they contain more than 0.75% of the alloying element. In the bronze alloy systems, Cu-As and Cu-Sn, this percentage is the minimum addition necessary to affect the working properties of the material, as can be seen from the phase diagrams in Appendix B.

Copper Objects. The 24 unalloyed copper objects made use of metal smelted from at least two different ore sources. Objects 69/9b and 91/2a were made from metal derived from a simple copper ore which contained on the order of 0.03% silver as the most significant trace element with occasional signs of nickel and lead. Qualitative analysis data suggest that this ore type was also the source for the metal used in objects 69/8b, 69/8c, 69/9f, 90/8f, and 91/2b. The remaining objects appear to have been smelted from a complex copper ore containing up to 0.1% silver and notable for the presence of up to 0.02% arsenic and traces of antimony, tin, and other elements. These data are presented in Appendix A.

The cast copper objects from the Middle Post Classic fall into four functional types—bells, bell-headed pins, buttons, and rings. For each type, it is reasonable to assume that, though design and stylistic details vary, fabrication methods did not. Accordingly, I will present the metallographic analysis of one prototypical object for each type.

Bells. The first type, of which there are nine, is the ornamental bell. The bell selected for analysis, #69/7, is shown in Figures 3-1 and 3-2. Its upper resonator chamber is conical, with wirework reinforcement or decoration encircling the top and bottom. The surface of the cone is decorated with a pattern of lines running parallel and normal to the curvature of the cone.

The lower resonator chamber of the bell is spherical. One side is decorated with a relief pattern in the image of a face, including eyes, eyebrows, and nose. The other side is undecorated, but numerous cloth fragments adhere to it. The resonator chamber of this bell is 3 cm in height and varies from 0.075 to 0.15 cm thick.

The clapper, a round metal bead, was functional until the object was sampled. The suspension ring, oval in cross-section, rises smoothly from the flat top surface of the upper resonator chamber.

The metallographic and chemical analysis samples were removed from the resonator chamber as shown in Figure 3-3. Chemical analysis showed that the metal in this particular bell was smelted from a complex copper ore, containing 0.1% Ag, 0.01% Pb, and 0.02% As.

In the as-polished state, one can see (Figure 3-4) that the portion of the section corresponding to the surface of the object is heavily layered with corrosion products. These products are a natural result of the object's extreme age, and consist primarily of cuprous oxide (Cu_2O), which is identifiable by a color change from blue to red under polarized light. Corrosion products appeared on all of the objects, except where noted.

The etched structure of the bell exhibits large primary copper dendrites surrounded by eutectic microconstituent (Figure 3-5). Since chemical analysis did not reveal significant alloying elements (see Table A), and since the eutectic microconstituent is similar in color to the accumulated corrosion on the surface of the object, it was concluded that this material is

Cu_2O. Since the Cu-O eutectic point (Figure B-2) is at 0.39% O_2 and the overall structure is hypoeutectic, an oxygen concentration somewhat lower than 0.39% is indicated.

Some of the dendrites, as shown in Figure 3-6, show signs of coring due to microsegregation. This evidence indicates that the molten metal, once cast, cooled slowly enough to allow significant diffusion of oxygen from the solidifying dendrites to occur.

The dendrites extend across protrusions in the design of the bell, indicating that the object was cast in one piece rather than assembled from individually cast parts. However, a sharp indentation in the surface of the bell (Figure 3-6) suggests that the lines on the upper resonator chamber were incised into the surface. Corrosion of the grains around the indentation has obliterated any unequivocal evidence to support or refute this suggestion.

The hollow design and continuous structure of the bell indicate that it was probably cast using a lost wax technique. In this technique, practiced throughout the region and described in detail by [12], a wax model of the object to be cast was built around a moist clay and charcoal core. For a bell, the clapper must have been embedded in the core material. The wax model was then surrounded by further layers of the charcoal and clay mixture and the whole was sun dried. Next, the wax was melted out of the mold and the molten copper poured in. It is probable that the high levels of oxygen observed in this object were introduced at this point, possibly as steam from moisture accumulation in the mold.

After the metal had cooled, the outer and inner molds were broken away, leaving the bell and its enclosed clapper behind. If the decorative patten on the upper resonator chamber was indeed incised, the incision was probably done at this point.

Bell-headed Pins. Only two objects of the next type, bell-headed pins, were found, both in the same context (a burial). One of two very similar artifacts was sampled, #91/2a, and it appears in Figure 3-7. Although, as will be discussed, metallography of this object indicates that it was cast in one piece, it is convenient to describe the design as consisting of three distinct parts. The first, the bell proper, is spherical and covered with green corrosion product. Mineralized cloth fragments adhere to both sides. The mouth of the bell bisects the lower half of the sphere, which is 1.7 cm in diameter and 0.13 cm thick. The clapper, an irregularly shaped piece of stone, was still functional when the object was sampled.

The second part of the design obscures the fact that the resonator chamber is conical in shape. This complexly decorated collar appears solid, but is actually hollow. Its thickness ranges from 0.26 to 0.39 cm. The design is best described as a cluster of folded leaves from which the bell itself rises like a bud. The cluster gradually tapers toward the tip of the underlying cone, where the third part of the bell begins. The third part of the bell is a 4.6 cm long pointed stem, 0.35 cm in diameter and thus slightly smaller than the tapered end of the resonator chamber. It is circular in cross-section and essentially straight.

Samples were taken for chemical and metallographic analysis as shown in Figure 3-8. The results of the chemical analyses show that the artifact was made using metal smelted from a simple copper ore containing 0.03% silver, with no other significant trace elements (see Table A).

Two metallographic sections, 91/2a.A and 91/2a.B, were taken. The first section was cut through the bell itself and the decorative collar, including part of the leaf design. The conical internal shape of the resonator chamber was revealed when this section was cut. Upon etching, the grains in this section are seen to be quite large, being visible with the naked eye. In the portion of the section corresponding to the lower resonator chamber, few inclusions or pores are seen within or between the grains (Figure 3-9). In the section corresponding to the collar, on the other hand, lines of Cu_2O inclusions which appeared to outline copper dendrite arms are visible (Figure 3-10). The grain structure is continuous across details of the design, indicating that the object was cast in one piece. A black and gray material was observed along the inside wall of the bell, and is shown in Figure 3-11. The porous, cellular structure of this material indicates that it is probably charcoal, which would suggest that some fragments of the original mold broke loose during casting and remained embedded in the finished bell.

The second section was cut through the region where the decorative collar and the stem meet. After etching, this section is also seen to contain extremely large grains. The grains in this section appear to have grown along the longitudinal axis of the sample as shown in Figure 3-12. The entire section contains small inclusions which appeared to be Cu_2O. In the portion of the section nearest the resonator chamber, these inclusions lie along dendrite arms as in section 91/2a.A. However, in the portion of the section corresponding to the stem of the pin no such ordering is visible.

As mentioned above, the continuity of the grain structure indicates that the object was cast in one piece. The continuous grain structure, together with the hollow design and embedded pieces of charcoal, indicates that a lost wax technique was used. The increase in density of inclusions in the stem of the bell and the dearth of inclusions in the lower resonator chamber suggest that the casting sprue, where metal entered the mold, was at the tip of the stem and that the bell solidified from the lower resonator chamber up, with the stem being last to solidify. The large grain size indicates that cooling was extremely slow, allowing trapped gas bubbles, now visible as Cu_2O inclusions, to float to the upper part of the bell and thence into the stem.

Buttons. The third object type, buttons, is represented by thirteen artifacts of two distinct styles. The object analysed here, #69/9b, is a wirework button and is shown in Figure 3-13. The other button type is hemispherical and is shown in Figure 3-14.

Button #69/9b has an ellipsoid dome shape and is formed from a number of wirework S-curves which connect to form an open pattern. The dome rests on an elliptical band with two crossing straps and its thickness ranges from 0.14 to 0.4 cm. It is heavily corroded and some portions are completely mineralized.

The object was sampled for chemical and metallographic analysis as shown in Figure 3-15. Results of chemical analysis showed that it was made from metal smelted from a simple copper ore containing 0.04% silver.

The metallographic section shows an extremely porous cast structure with grains appearing to extend radially from several large voids in the material (Figure 3-16). Grain size is quite large, but is substantially smaller than in either 69/7 or 91/2a, which suggests that this object cooled more rapidly than either of the other two.

There are traces of the same gray material observed in object #91/2a—believed to be part of the fabrication mold—wedged between two of the spirals making up the design, as shown in Figure 3-17. Though the design of the button alone would indicate that it was cast by the lost wax method, this evidence would tend to strengthen that argument. The extreme porosity of this object could be attributed to the complex nature of the design or to rapid cooling and resultant shrinkage. It should be noted that the design of this button has a much larger surface area relative to the total volume of metal present than either of the two previously discussed objects, which would tend to result in more rapid radiational cooling.

Rings. The final object type is represented by two nearly identical rings. One of the two, object #68/3, was examined by me in a project separate from my thesis work [13], and those results are presented here.

The ring appears in Figure 3-18. Like that of the button, #69/9b, the design of the ring is made up of several wirework S-curves. They lie parallel to the circumference of the ring, between two bands of metal. Both of the bands are grooved, so that each looks like a double ring. The ring is 1.9 cm in diameter and 0.147 cm thick.

Samples of this object were taken for chemical and metallographic analysis as shown in Figure 3-19. The chemical analysis results show that this artifact was made from metal smelted from a complex copper ore containing 0.08% silver, 0.01% arsenic, and 0.01% lead (see Table A).

Examination of the metallographic section after etching shows that the grains are large, though not so large as in the two bells. The structure is shown in Figure 3-20. This object is less porous than the button, and contains very few inclusions. As with the other objects in this group, we may conclude that a lost wax casting technique was used and that cooling was quite slow.

So, to summarize briefly, those cast objects made from unalloyed copper were universally fabricated using a lost wax technique. Several of them, in fact, still contain pieces of the mold used in their manufacture.

Grain size was quite large in all of the objects, indicating generally slow cooling rates. In general, grain size appeared to increase with increasing feature size, suggesting that the grain size depended on the area available for radiational cooling relative to the mass of material present—the surface/volume ratio—rather than on a deliberate variation in cooling conditions by the responsible smiths.

Cu-As alloys. Of all the cast objects sampled for chemical analysis, only one, #69/6, contained significant amounts of an element other than copper. Analysis of that bell is summarized here.

The resonator chamber of the bell is smooth, spherical and undecorated, with a smooth-edged mouth bisecting the lower hemisphere. It is 2 cm in diameter and ranges from 0.09 to 0.15 cm thick. Its thick round double suspension ring merges with the body of the bell in an uneven manner, with irregularly shaped metal surrounding the meeting point. However, the metal does not change color in this region, as would be expected if some form of solder were used. Furthermore, since it is possible to produce this design without facing the difficulties of two-piece construction, the suggestion that the stem was added to the bell after casting rather than fabricated simultaneously with it was rejected as unlikely. The artifact is pictured in Figure 3-21.

The bell had a round metal bead clapper, which was functional until samples were taken. It is much less heavily corroded than other objects found in the same context (notably 69/7 and 69/9b) and is a dark, almost black color, suggesting that it may have been chemically cleaned following excavation.

Samples for chemical and metallographic analysis were taken as shown in Figure 3-22. Results of the chemical analysis show that the object is a Cu-As alloy with traces of silver and lead. Arsenic concentration is 1.33% by weight.

The metallographic sample, taken from the resonator chamber adjacent to the mouth, broke during sampling and was mounted in two pieces, 69/6.A and 69/6.B. The outer surfaces of both sections and the fracture surface between the two were covered with an unusual pink material (Figure 3-23) which was identified as residue remaining from the application of a cleaning agent [7]. Since the material appears on the fracture surface between the two sections, it was concluded that the crack responsible for the fracture existed prior to sampling and had corroded with the rest of the object.

The metallographic sample has a cast dendritic structure, with primary copper dendrites surrounded by a material which, based on compositional data, may be assumed to be arsenic-rich (Figure 3-24). The second phase is heavily cored and ranges in color from silver near the dendrite arms to green near the center of the second phase region. The color change indicates that the second phase, identified from the phase diagram (Figure B-1) as copper + γ, cooled slowly enough to allow microsegregation of the arsenic-rich γ phase. However, the high density of second phase observed indicates that equilibrium cooling did not occur, as the arsenic content of the sample is less than the 7.8% solid solubility limit for arsenic in copper at ambient temperature, and the arsenic would thus be completely dissolved in the copper matrix under equilibrium cooling conditions.

The bell was almost certainly cast using the lost wax method. The high degree of microsegregation in the second phase indicates that the casting cooled rather slowly, producing regions in which the arsenic concentration approached the eutectic concentration of 29%.

3.1.2 Worked Objects

Cu-Sn Alloys. *Tweezers.* Of the two worked objects from the Middle Post Classic Period, only one, a tweezer, was found to be a Cu-Sn alloy. This object (#557/3) appears in Figure 3-25. Viewed in profile, the tweezer exhibits three-dimensional curvature: both blades are somewhat dome-shaped, arcing away from the hinge before curving back to meet each other along a semi-circular blade edge. The blade thickness tapers from 0.105 cm at the longitudinal axis to 0.025 cm at the blade edge.

The tweezer was sampled for chemical and metallographic analysis as shown in Figure 3-26. Chemical analysis showed that the artifact contained 8.99% Sn by weight. Such a high percentage of tin produces an alloy that is subject to substantial work-hardening and embrittlement.

Examination of the etched metallographic sections reveals small grains, some of which contain randomly oriented slip bands (Figure 3-27). Many Cu_2O inclusions and several pools of a material which, considering the phase diagram (Figure B-3) and the composition of the artifact, can be identified as Cu-Sn eutectoid are visible (Figure 3-28). Both the inclusions and the eutectoid are elongated along the longitudinal axis of the sample. The material etched preferentially, revealing flow lines which also parallel the longitudinal axis of section 557/3.B. Some annealing twins are visible. Several fissures, shown in Figure (3-29), can be seen along the inner surface of the tweezer blade.

In addition to metallographic examination, section 557/3.B was tested to determine the Vickers Hardness Number (VHN) at various points along the blade. The data obtained is shown in Figure 3-30. Measured values range from 176.0 at the tip of the blade to a low of 126.2 at the inner end of the section.

The combination of flow lines, elongated inclusions, elongated eutectoid microconstituent, and hardness values indicates that the object was extensively worked, with the degree of working increasing toward the edge of the blade.

The presence of slip bands randomly within the material–rather than at the edges–and the elongation of the eutectoid indicate that a hot working method was used, rather than a series of cold working and annealing steps. In the latter process, slip bands and elongation of grains are produced by plastic deformation of the material but are subsequently removed by grain growth during annealing. In hot working these ancient objects some work continued as the metal cooled below the recrystallization temperature (about 350°C, see Figure B-3. Eutectoid regions are elongated along with the grain structure as a whole, but remain elongated after the surrounding metal recrystallizes [3, p. 177].

The fissures along the inner surface of the blade may indicate brittle failure of the metal during the fabrication process.

It is likely that the symmetrical tweezer shape was fabricated from a blank of some sort, and that the hinge was then bent to finish the object. Though metallographic studies of the hinge were not performed, the properties of the alloy used suggest that the object was heated during the hinge-bending process because it would otherwise have become brittle due to work-hardening.

Cu-As alloys *Axes.* The other Middle Post Classic worked object, an axe, was previously examined by Elise Berliner [1]. The object is nearly identical in form to a number of axes from the Historic period. This axe, object #557/2, is made from copper with a significant (though unknown) amount of arsenic. Though the axe was cast, the blade was subsequently cold-worked to a peak hardness of 229 VHN. This hardness indicates a probable composition in the 5-10% As range [3, p.273].

3.1.3 Summary of Middle Post Classic Metallurgy

Cast Objects. As noted above, the Middle Post Classic objects exhibit relatively complex designs, bell #69/6 being the exception. Since eutectic solidification of an alloy is more gradual than solidification of a pure metal, these designs would be more easily fabricated from an alloy. The improved strength possible with alloys was not, however, necessary to the successful execution of these designs. So, the slow cooling rate resulting from lost wax casting was apparently sufficient to compensate for the deficiencies of unalloyed copper, producing objects with minimal porosity.

Worked Objects. Though compositionally and functionally different, both worked objects are notable for the use of alloying elements to achieve desired properties. In the case of the tweezer (object #557/3), computer simulation studies have shown that unalloyed copper is not strong enough to withstand the stresses inherent in this design when the blade thickness is less than 0.05 cm, as it is in this object [4]. This design can only be fabricated from an alloy, and an alloy was indeed used. Extensive work-hardening of Cu-Sn results in embrittlement of the material and possible subsequent cracking, but the problem can be eliminated by hot working or annealing. So, since this object was hot worked, the fabrication method chosen compensated for the properties of the material.

In the axe from this period, object #557/2, arsenic was used to produce an alloy with greater hardenability than that of unalloyed copper. From a material properties standpoint, this object was hard enough to serve as a functional cutting or splitting tool [6].

Conclusions. To conclude, Middle Post Classic metal objects can be divided into two groups on the basis of either chemistry or fabrication. In the first group are cast objects, made almost exclusively from copper. In the second group are worked objects, made from bronze alloys. In both groups, design was adapted to the properties of the material being used. Or, looked at another way, the materials to be used were selected based on design constraints. It is impossible to determine which view is correct without additional information concerning the materials available to the Maya smiths.

3.2 The Late Post-Classic, 1300-1544 AD

3.2.1 Cast objects

Of the three cast objects from the Late Post Classic, two, a ring and a bell, were made from copper, while the third was a Cu-Sn alloy containing 1.89% Sn by weight. Only the third object, a bell (#774/23), was metallographically analyzed.

The bell dates to the later part of the time period (1400-1544 A.D.) and is illustrated in Figure 3-31. The resonator chamber is rhomboidal in shape, and highly symmetrical, measuring 2.2 cm in height and 2.2 cm wide at the axis. The suspension ring rises smoothly from the top corner of the bell. The upper portion of the resonator chamber is decorated with concentric circular grooves running parallel to the edge that divides the upper and lower resonator chambers. The mouth, which bisects the lower resonator chamber, is embellished with a slightly flattened lip, which is 0.13 cm wide. The resonator chamber is 0.11 cm thick, and the lip adds an additional 0.075 cm to that thickness. It is not known whether the lip serves a reinforcing function or is entirely decorative. A metal bead, functional until the object was sampled, served as a clapper.

The object was sampled for metallographic and chemical analysis as shown in Figure 3-32. It was found to be an alloy of copper and 1.89% tin, with 0.30% arsenic and traces of other elements.

After etching, a cast dendritic structure consisting of primary copper dendrites surrounded by a second phase which, based on composition, must be tin rich eutectoid is observed. The grains are very large, and grain boundaries are indistinct. The structure is illustrated in Figure 3-33.

Indentations corresponding to the decorative grooves on the upper resonator chamber, are visible in the section (Figure 3-34). As there are no slip bands or deformed dendrites near these indentations, they were probably part of the original casting.

A line of corrosion is clearly visible between the lip and the body of the bell. The structure of the lip itself, shown in Figure 3-35, is distorted, with slip bands and deformed dendrites. The structure is continuous wioth that of the body of the bell.

Based on this evidence, it may be concluded that the object was cast in one piece by the lost wax method. All aspects of the design, both the indentations around the upper resonator chamber and the lip around the mouth of the bell, were part of the original casting. Subsequent to casting, the lip was flattened somewhat by hammering.

3.2.2 Worked Objects

All four of the worked objects from this period—two tweezers, an awl tip, and a piece of sheet metal—were found to be Cu-Sn alloys. Only one, a tweezer from the early subperiod (1300-1400 A.D.), was analyzed.

The tweezer, object #614/1, is illustrated in Figure 3-36. The blades are circular in shape and flat, 0.04 cm thick. A hole with ragged edges has been punched through both blades. The two circular blades are joined by a rectangular piece of metal, folded over to form a hinge. There are no apparent seams between the blades and the hinge, and no reason to suspect that the object was not formed in one piece.

Samples for chemical and metallographic analysis were taken from the tweezer blade as shown in Figure 3-37. Results of chemical analysis showed that the object was made from an alloy of copper with 4.3% tin (see Table A.5).

Upon etching, the structure is seen to consist of large primary copper grains with interspersed regions of Cu_2O and tin-rich eutectoid. The non-metallic inclusions are elongated along the length of the section. The grains are relatively large, with numerous annealing twins. The structure is illustrated in Figure 3-38.

Microhardness testing was also performed on this section, with the results illustrated in Figure 3-39. The hardness ranges from 130.0 to 82.86 VHN, with the lowest values occuring at the outer edge of the blade.

From the elongated inclusions it can be concluded that the tweezer blade was worked radially, away from the center. However, the annealing twins, the grain size, and the relatively low hardness of the blade indicate that the object underwent annealing following the last work-hardening fabrication step.

3.2.3 Summary of Late Post Classic Metallurgy

Relative to the Middle Post Classic, the variety of object types in the Late Post Classic is sharply diminished. Only tweezers, bells, and rings appear in both periods and, as the relevant photographs (referenced above) show, the Late Post Classic representations of those object types were stylistically different from their Middle Post Classic equivalents.

In the Late Post Classic, unalloyed copper is superseded as the predominant material by Cu-Sn alloys. Both decorative objects—bells—and utilitarian objects—tweezers—were made from Cu-Sn.

As a fraction of the total, there are more utilitarian objects from the Late Post Classic (2 out of 7) than from the Middle Post Classic (2 out of 25). However, both of the utilitarian Middle Post Classic objects were found in burials, while neither of the Late Post Classic tweezers was.

This suggests that the cultural function of tweezers in particular and perhaps of metal in general changed during the Late Post Classic.

3.3 Figures

Figure 3-1: Photograph of object #69/7, top view.

Figure 3-2: Photograph of object #69/7, side view.

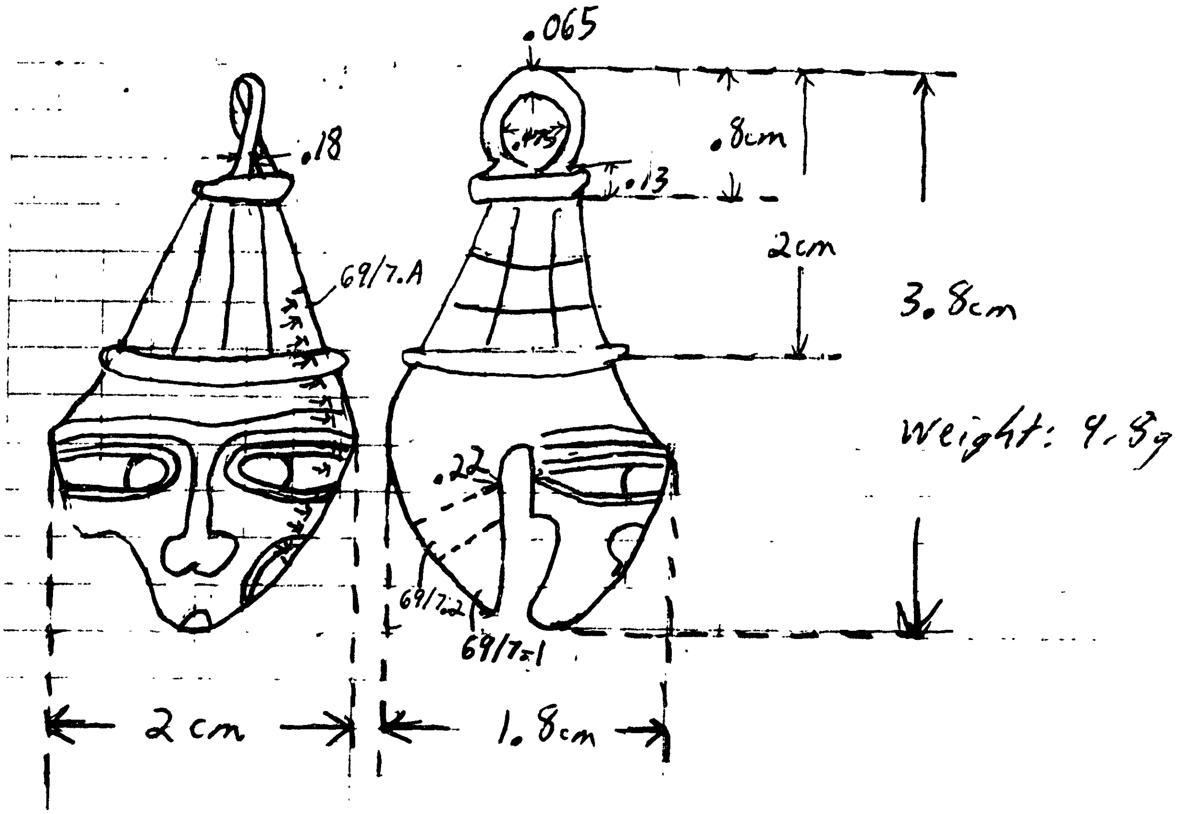


Figure 3-3: Samples taken from object #69/7.

Figure 3-4: Section 69/7.A. 50x. As polished, showing surface corrosion.

Figure 3-1: Photograph of object #69/7, top view.

Figure 3-2: Photograph of object #69/7, side view.

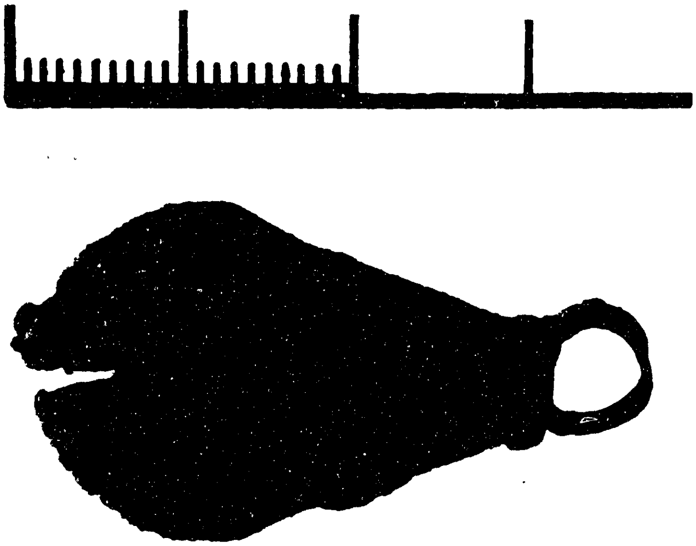


Figure 3-5: Section 69/7.A. 50x. $K_2Cr_2O_7$ etch, showing dendritic structure.

Figure 3-6: Section 69/7.A. 100x. $K_2Cr_2O_7$ etch, showing coring, possible incision.

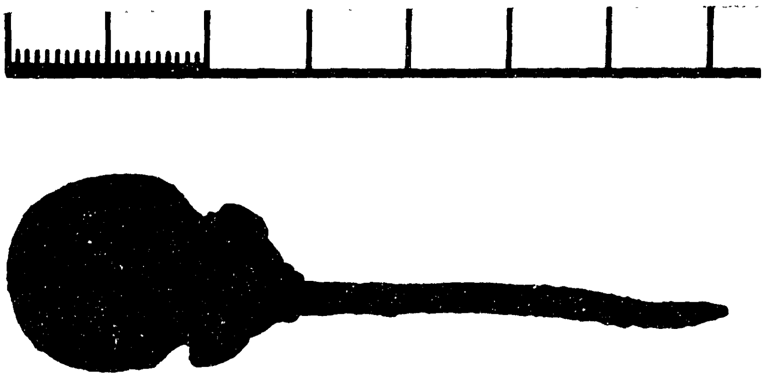


Figure 3-7: Object #91/2a, a bell-headed pin

Figure 3-8: Samples taken from object #91/2a.

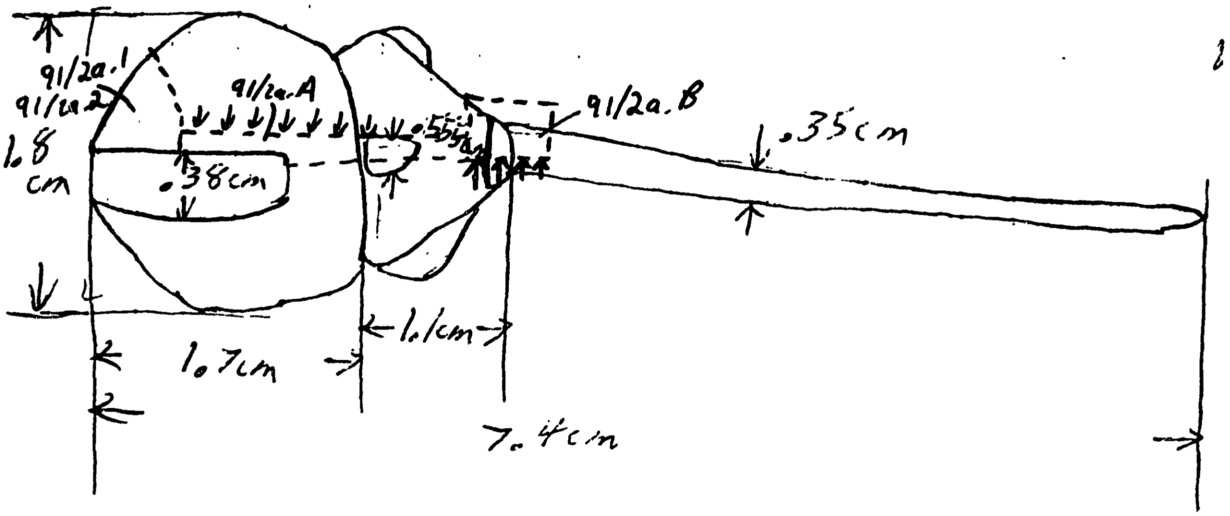
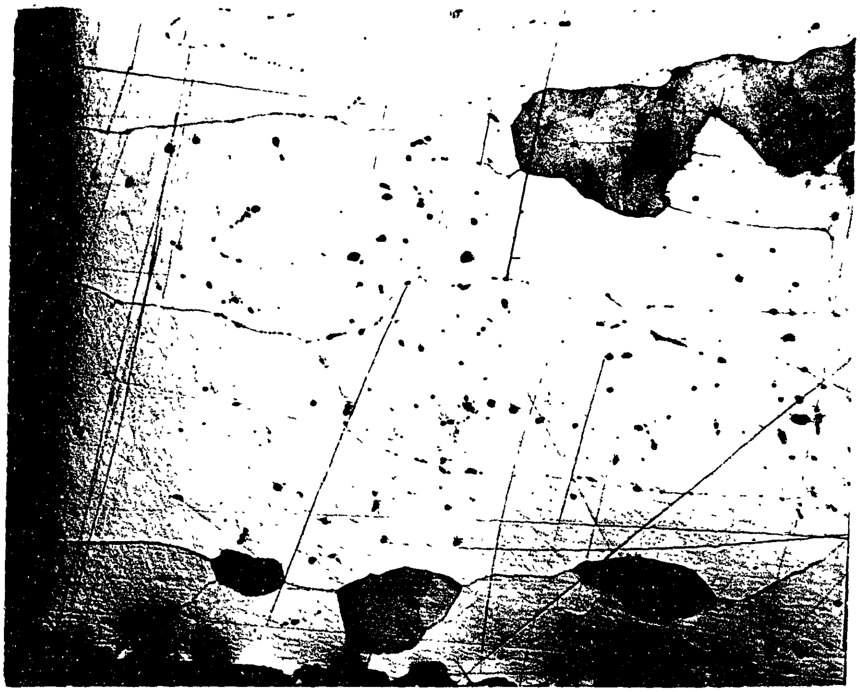


Figure 3-9: Section 91/2a.A. 50x. $K_2Cr_2O_7$ + HCl etch, showing grains in lower resonator chamber.

Figure 3-10: Section 91/2a.A. 50x. $K_2Cr_2O_7$ + HCl etch, showing grains in collar of bell.

Figure 3-11: Section 91/2a.A. 100x. $K_2Cr_2O_7$ etch, showing mold material trapped in bell.

Figure 3-12: Section 91/2a.B. 50x. $K_2Cr_2O_7$ + HCl etch, showing oriented grains along bell stem.



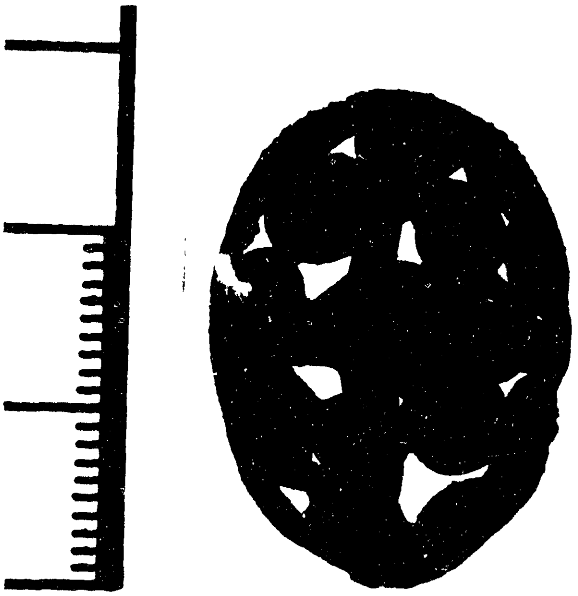
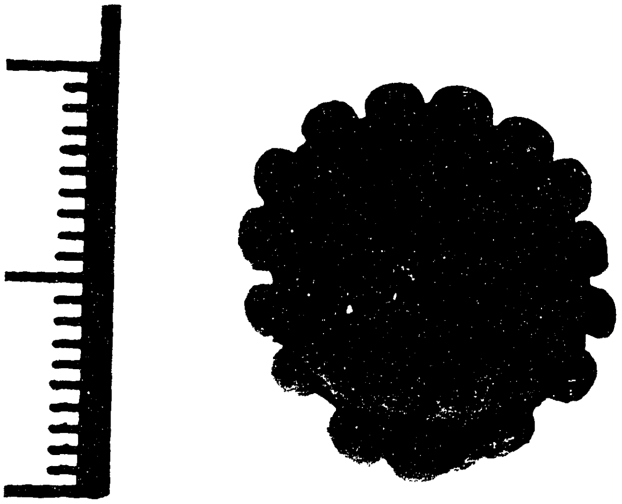


Figure 3-13: Object #69/9b, photomacrograph.

Figure 3-14: Object #90/8c, photomacrograph.



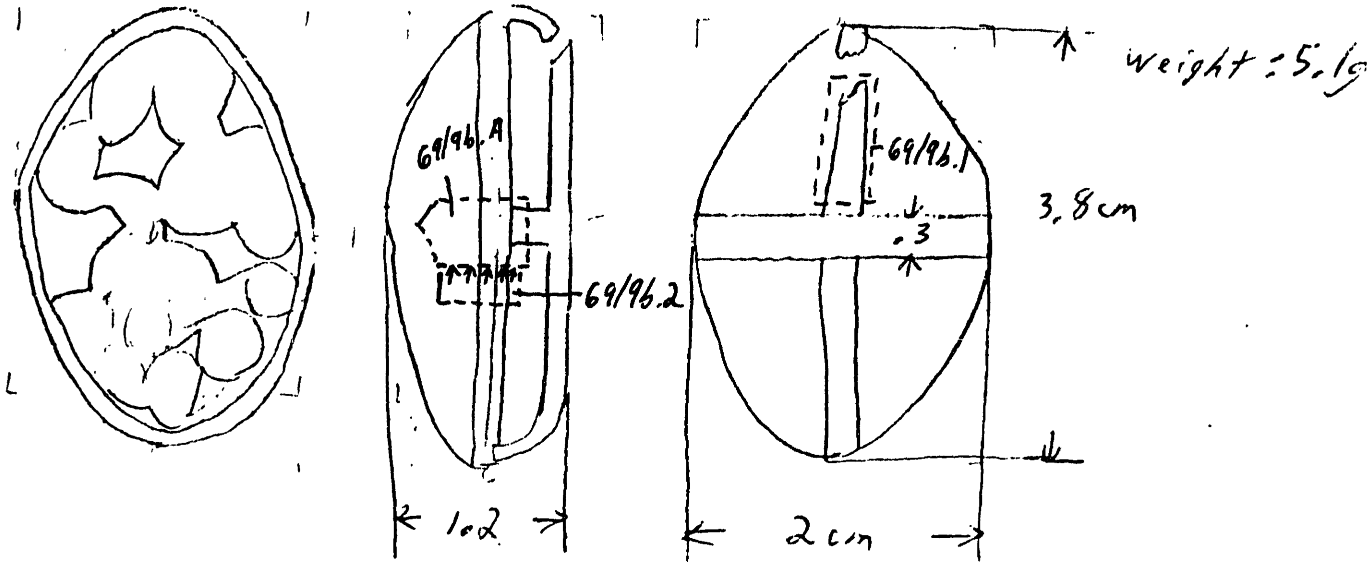


Figure 3-15: Samples taken from object #69/9b.

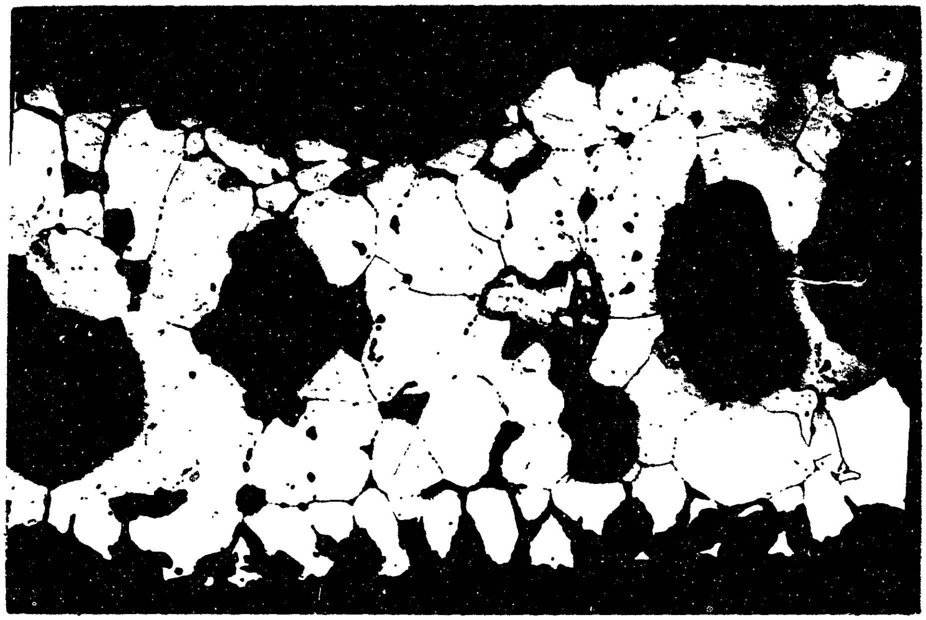
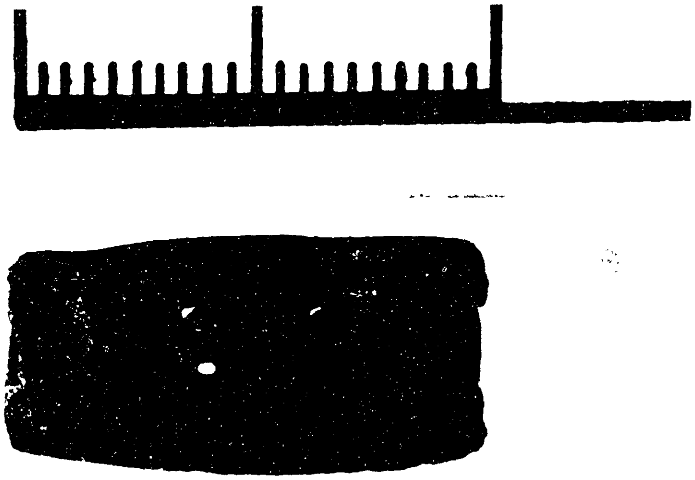
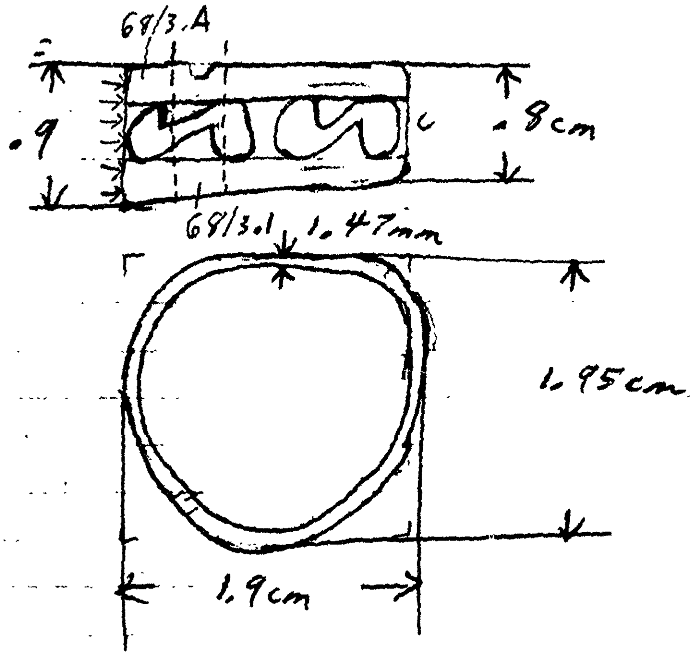


Figure 3-16: Section 69/9b.A. 50x. $K_2Cr_2O_7$ etch, showing radial orientation of grains around pores.

Figure 3-17: Section 69/9b.A. 50x. $K_2Cr_2O_7$ etch, showing fragments of mold material.

Figure 3-18: Object #68/3. Middle Post Classic ring.





Weight: 2.9g

Figure 3-19: Samples taken from object #68/3.

Figure 3-20: Section 68/3.A. 50x. $K_2Cr_2O_7$ etch, showing grain size.

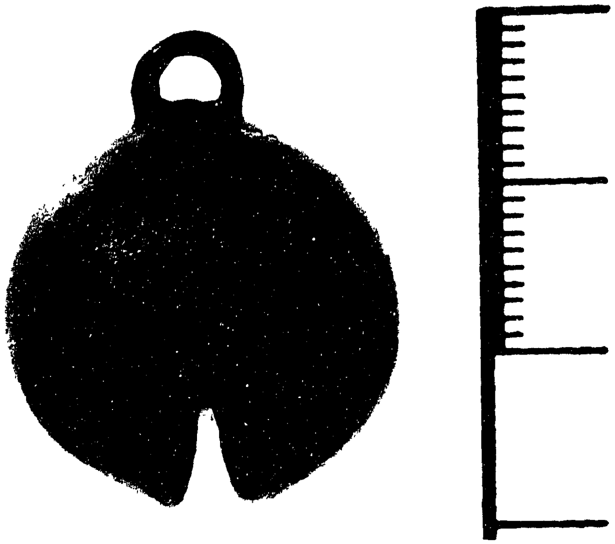
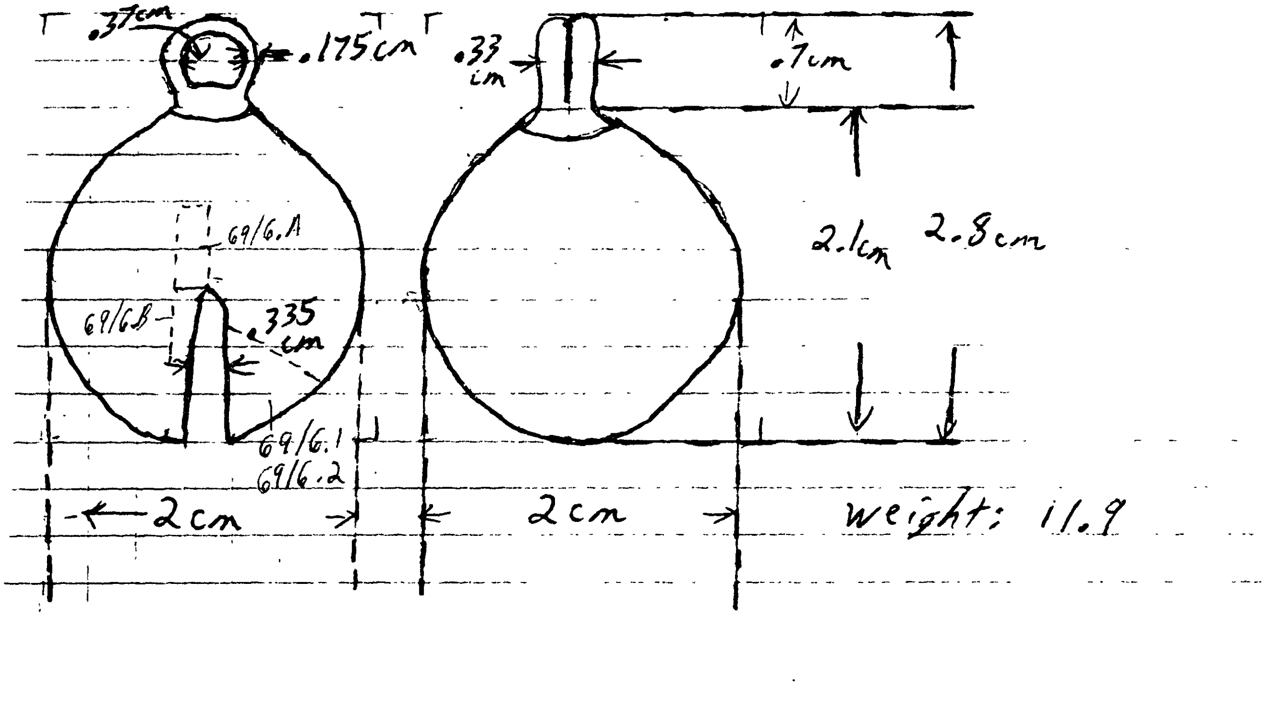


Figure 3-21: Bell #69/6-4, Middle Post Classic.

Figure 3-22: Samples taken from object #69/6.



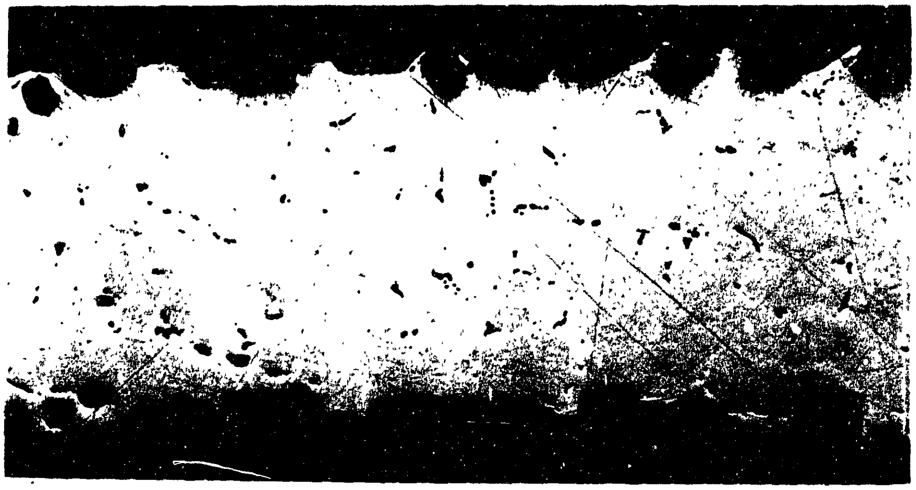


Figure 3-23: Section 69/6.B. 50x. As polished, showing surface coating.

Figure 3-24: Section 69/6.B. 50x. $K_2Cr_2O_7$ etch, showing second phase.

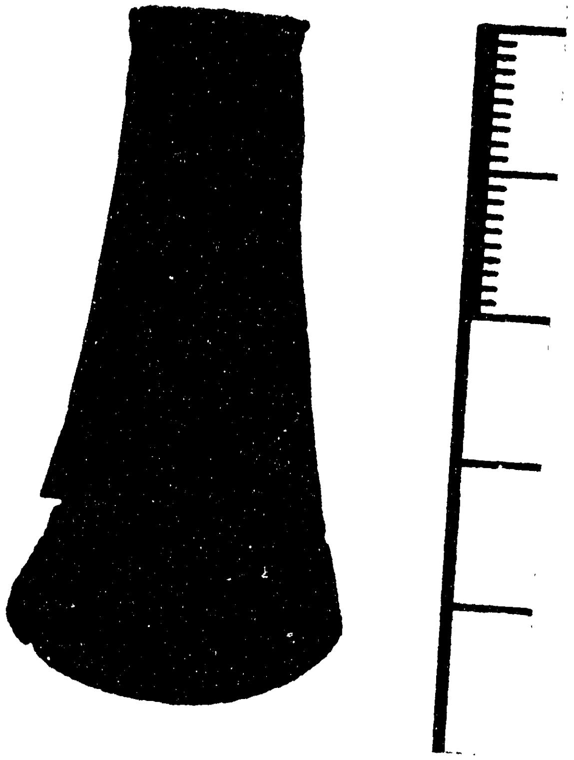


Figure 3-25: Object #557/3, a tweezer.

Figure 3-26: Samples taken from object #557/3.

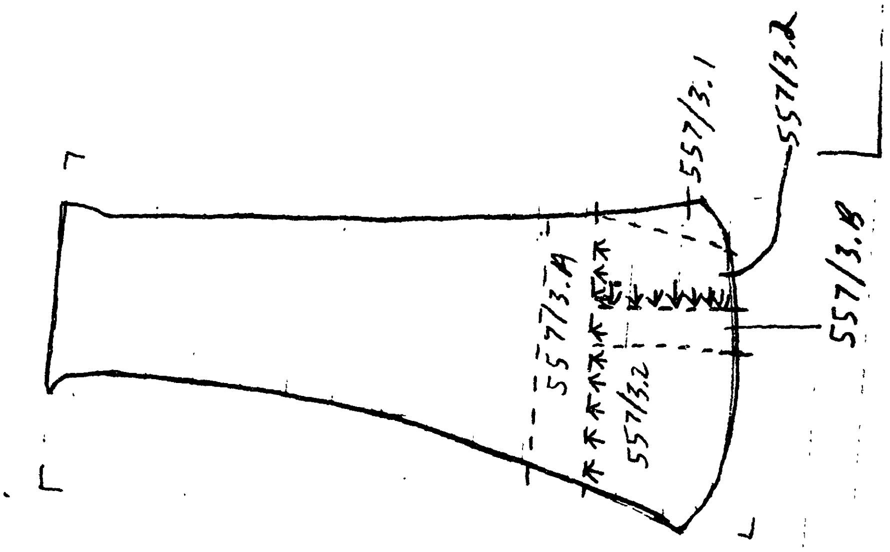


Figure 3-27: Section 557/3.B. 200x. $K_2Cr_2O_7$ followed by $FeCl_3$ etch, showing slip bands.

Figure 3-28: Section 557/3.B. 200x. $K_2Cr_2O_7$ followed by $FeCl_3$ etch, showing Cu-Sn eutectoid.

Figure 3-29: Section 557/3.B. 200x. $K_2Cr_2O_7$ followed by $FeCl_3$ etch, showing fissures in underside of tweezer.

Figure 3-30: Hardness test data for object #557/3.

557/3. A

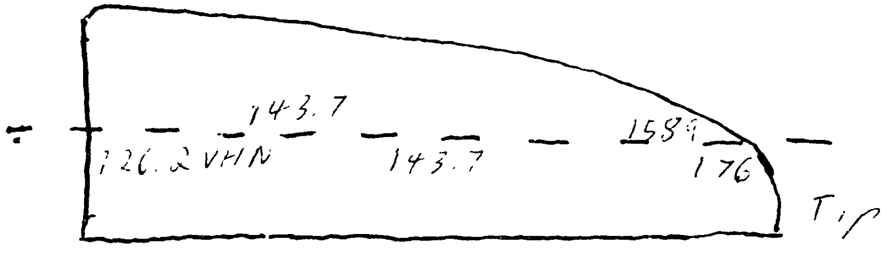


Figure 3-31: Object #774/23, a Late Post Classic bell.

Figure 3-32: Samples taken from object #774/23.

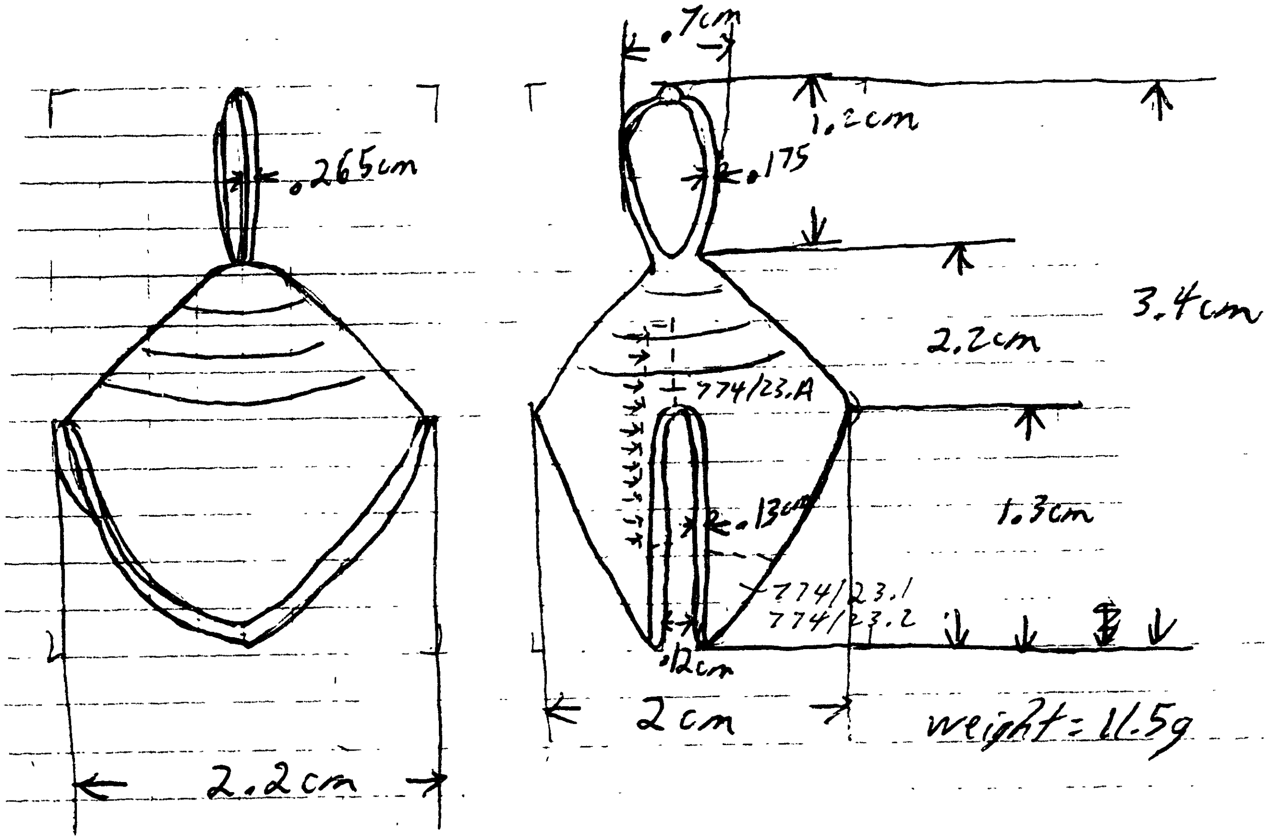


Figure 3-33: Section 774/23.A. 50x. $K_2Cr_2O_7$ etch, showing grain structure.

Figure 3-34: Section 774/23.A. 100x. $K_2Cr_2O_7$ etch, showing decorative grooves.

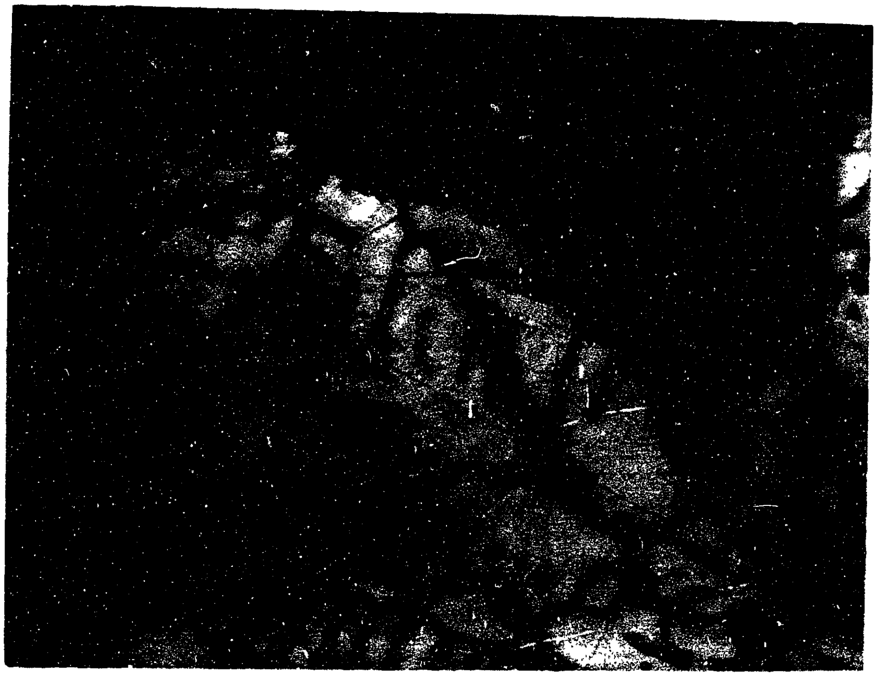
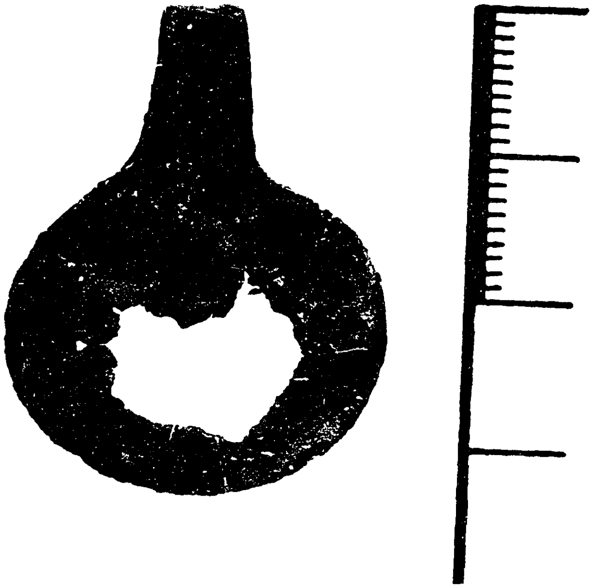


Figure 3-35: Section 774/23.A. 200x. $K_2Cr_2O_7$ etch, showing deformation around bell lip.

Figure 3-36: Object #614/1. Late Post Classic tweezer.



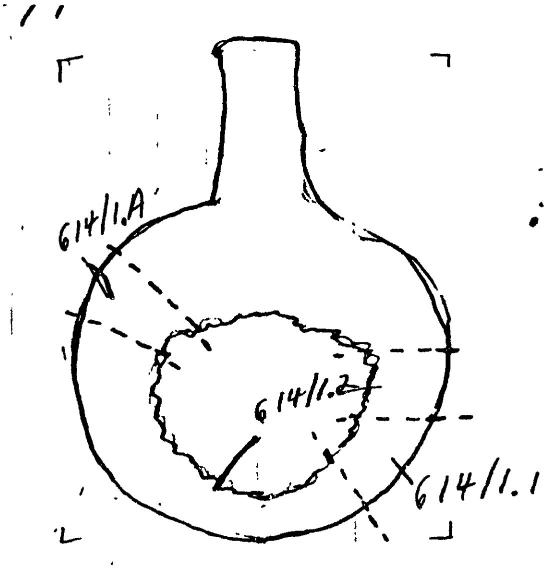


Figure 3-37: Sampling of object #614/1.

Figure 3-38: Section 614/1.A. 200x. $K_2Cr_2O_7$ etch, showing grains, elongated inclusions, and annealing twins.

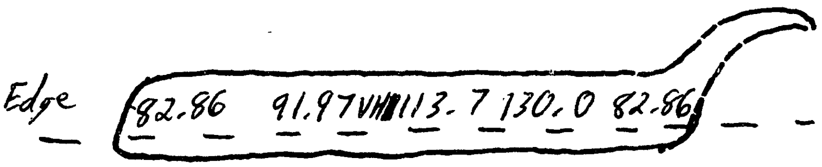


Figure 3-39: Hardness of section 614/1.A.

Chapter 4

Summary and Conclusions

4.1 Summary

4.1.1 Cast Objects.

In both the Middle and Late Post Classic, lost wax casting was the primary casting technique. Other techniques may have been used to form cast blanks for further working. However, the designs of the objects which were left in cast form require that the mold be removable from within the completed object. To remove the mold from inside a cast bell, the mold itself must break apart. A lost wax mold is designed to do exactly that. Furthermore, pieces of material which were identified as part of the original mold were found in several of the objects.

The Middle Post Classic was characterized by complex designs, cast almost exclusively from copper. The exception, Bell #69/6 (discussed on page 27), was a Cu-As alloy and was a much simpler design than was characteristic of the copper bells.

In the Late Post Classic, two of the three cast objects were made from copper, while the third was a Cu-Sn alloy. All three were relatively simple designs, and none of the three was stylistically similar to objects from the earlier period.

4.1.2 Worked Objects.

All four of the worked objects were made from alloys. In the Middle Post Classic, both Cu-As and Cu-Sn alloys were used, while only Cu-Sn appeared in the Late Post Classic.

In the Middle Post Classic, both hot and cold working techniques were applied. This suggests that hot working was used when the degree of working was so extensive that embrittlement of the material was a potential problem, as in the tweezer, object #557/3. Cold working, on the other hand, was used when only surface hardening was required.

In the Late Post Classic, it is difficult to generalize about the fabrication methods used. The single data point is a tweezer (object #614/1) which was cold worked and annealed.

4.2 Conclusions

In the Middle Post Classic, two metallurgical traditions appear to be present. One tradition used unalloyed copper to cast complexly decorated bells, buttons and rings. Most (24 of 27) of the Middle Post Classic artifacts appear to belong to this tradition. The other metallurgical tradition used both Cu-As and Cu-Sn, for both decorative and utilitarian purposes.

Metal objects from both traditions appear to have been symbolically important to the Maya, as all of the objects from this period were found in burials. There is no evidence to show that either of the two metallurgical traditions was more culturally important than the other.

Generalizations about the Late Post Classic period are difficult because so few objects are available from this period. It appears that a third metallurgical tradition appeared during this time. This tradition was marked by both differences in style and by the use of Cu-Sn as the dominant material. Cu-As was not used during the period.

Cultural generalizations about the position of metal in the Late Post Classic society are further complicated by the division of the objects into two temporal subgroups. The early objects, dating between 1300 and 1400 A.D., were all found in rubbish heaps, suggesting that metal was a disposable commodity to be thrown away when no longer needed. The later objects, dating between 1400 and 1544 A.D., were all found in burials, indicating that metal was an important symbol of wealth, status, and power.

The apparent contradiction between the two groups may represent a discontinuity—such as a temporary abandonment or a civic upheaval—in culture at the site or merely an unintentional sampling bias during the excavation. Absent other evidence, the metal objects do not allow us to judge.

4.3 Suggestions for Future Work

It would be extremely desirable to complete the compilation and presentation of data from the Historic Period objects. Those data would allow a more complete discussion of the changes in metallurgy at Lamanai.

More detailed measurements of grain size and porosity in cast objects would allow determination of approximate cooling rates and might allow the researcher to theorize about the characteristics of mold materials.

Appendix A

Chemical Analyses

Symbol	Meaning
M	major
m	minor
v	barely visible
?	questionable
-	not observed
ND	not detected
NA	not analysed

Table A.1: Symbols used in chemical results.

Number	Type	Ag	As	Au	Bi	Cr	Ga	In	Ni	Pb	Sb	Sn	Zn
557/2	Axe	v+	m-	-	v	-	-	-	m	v	v	v	-
61/13	Bell	m	-	-	-	-	-	-	?	v	?	?	-
69/6	Bell	v	m-	-	?	-	-	-	?	v	-	?	?
69/7	Bell	v	-	-	-	-	-	-	?	v+	?	-	-
69/8b	Bell	v+	-	-	-	-	-	-	?	v	-	-	-
69/8c	Bell	v+	-	-	-	-	-	-	?	v	-	-	-
91/2a	Pin	v	-	-	-	-	-	-	?	v-	-	-	?
91/2b	Pin	v	-	-	-	-	-	-	?	v-	-	-	?
69/9b	Button	v	?	-	-	-	-	-	?	v	?	?	-
69/9c	Button	v+	?	-	-	?	-	-	?	v+	-	?	-
69/9f	Button	m	-	-	-	-	-	-	-	?	-	-	-
90/8a	Button	v+	-	-	-	?	?	-	?	?	-	-	v-
90/8c	Button	v+	-	-	-	?	?	-	?	?	-	-	v-
90/8f	Button	m	-	-	-	-	-	-	-	?	-	-	-
68/3	Ring	-	v	-	-	-	-	-	?	?	-	?	-
118/11	Ring	v	?	-	-	v-	-	-	?	v+	-	?	v-
557/3	Tweezer	m	v	-	m+	-	-	v	?	v	?	m++	-

Table A.2: Middle Post Classic objects—qualitative chemical analysis.

Number	Type	Ag	As	Au	Bi	Pb	Sb	Sn
69/6	Bell	0.06	1.33	ND	NA	0.002	ND	ND
69/7	Bell	0.10	0.02	ND	NA	0.01	ND	ND
91/2a	Pin	0.03	ND	ND	NA	ND	ND	ND
69/9b	Button	0.04	ND	ND	NA	ND	ND	ND
90/8a	Button	0.03	0.004	ND	NA	ND	ND	ND
68/3	Ring	0.08	0.01	ND	0.03	ND	0.01	ND
557/3	Tweezer	0.11	0.01	0.006	NA	0.04	0.10	8.99

Table A.3: Middle Post Classic objects—quantitative chemical analysis.

Number	Type	Ag	As	Au	Bi	Cr	Ga	In	Ni	Pb	Sb	Sn	Zn
774/20	Bell	v+	?	-	?	-	-	-	?	?	?	m-	?
774/23	Bell	v+	v-	-	v-	?	-	v-	?	v+	?	m+	?
774/3	Ring	m	v	-	?	-	-	-	?	v+	v	v+	?
614/2*	Sheet	-	v+	-	m	-	-	v	v	m	m-	M	-
614/1*	Tweezer	m	m-	-	v+	-	-	v	v+	m	v+	M	-
905/1	Tweezer	v	?	-	?	-	-	v-	v-	m-	?	m+	-
922/2	Awl Tip	m	v	-	?	?	-	-	?	m	v-	m++	?

Table A.4: Late Post Classic objects. An asterisk indicates those objects from the early subperiod.

Number	Type	Ag	As	Au	Pb	Sb	Sn
774/20	Bell	0.14	0.20	ND	0.003	0.07	0.16
774/23	Bell	0.11	0.30	ND	0.06	0.08	1.89
614/1*	Tweezer	0.15	0.39	0.007	0.005	0.13	4.30

Table A.5: Late Post Classic objects—quantitative chemical analysis.

Appendix B

Relevant Phase Diagrams

All phase diagrams are from the current edition of the ASM *Metals Handbook.*

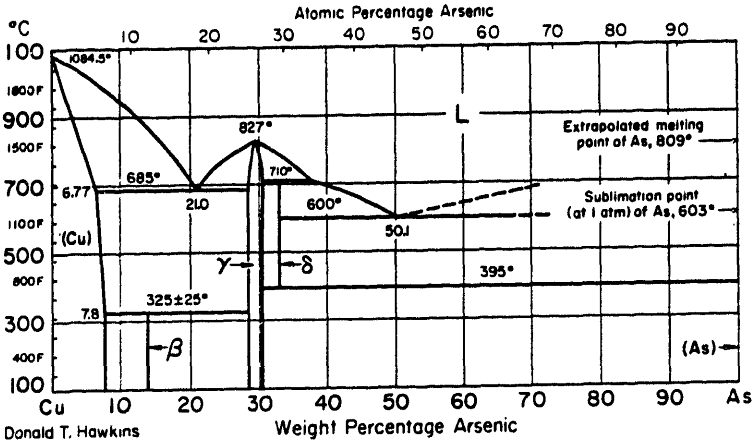


Figure B-1: The Copper-Arsenic Phase Diagram

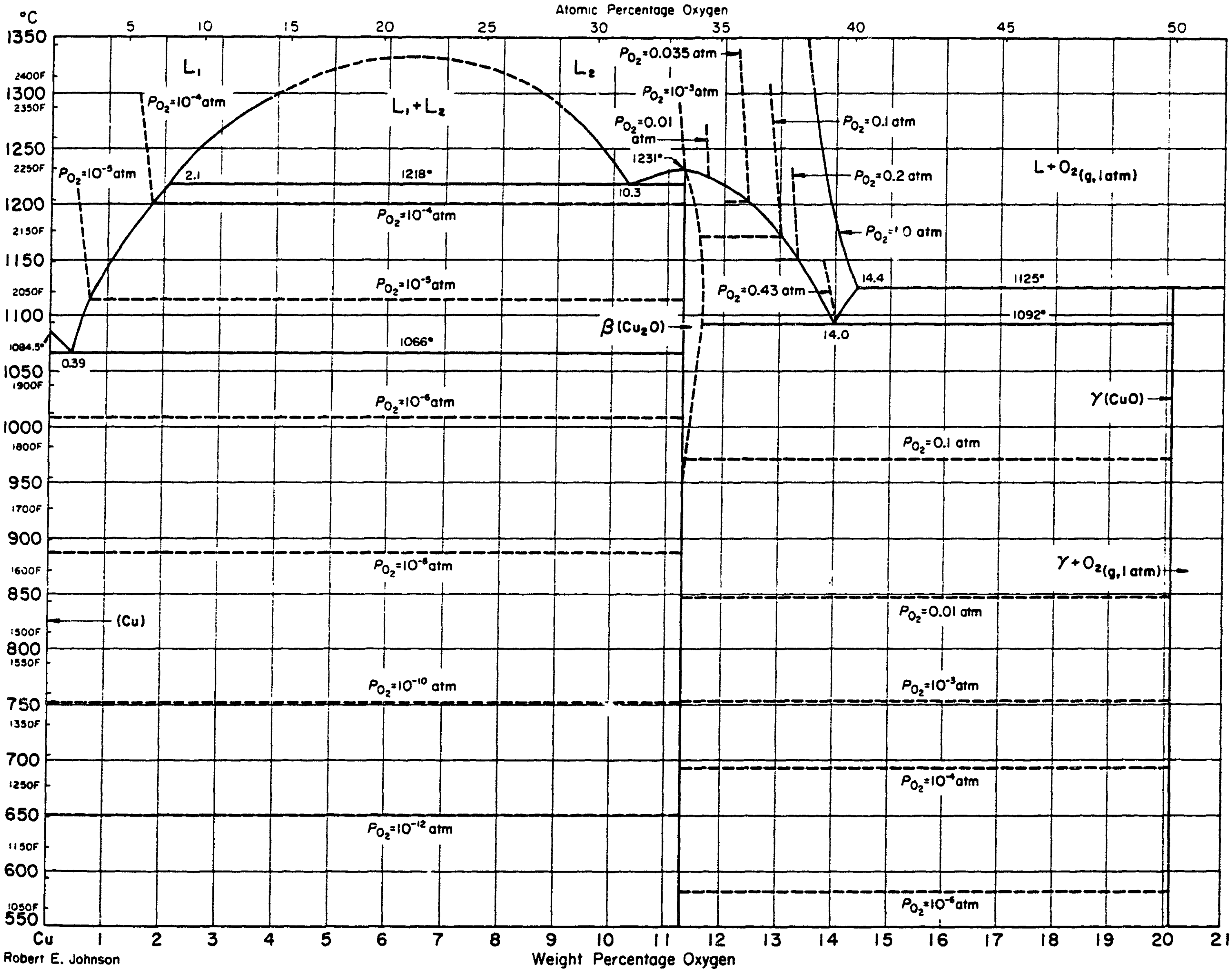


Figure B-2: The Copper-Oxygen Phase Diagram

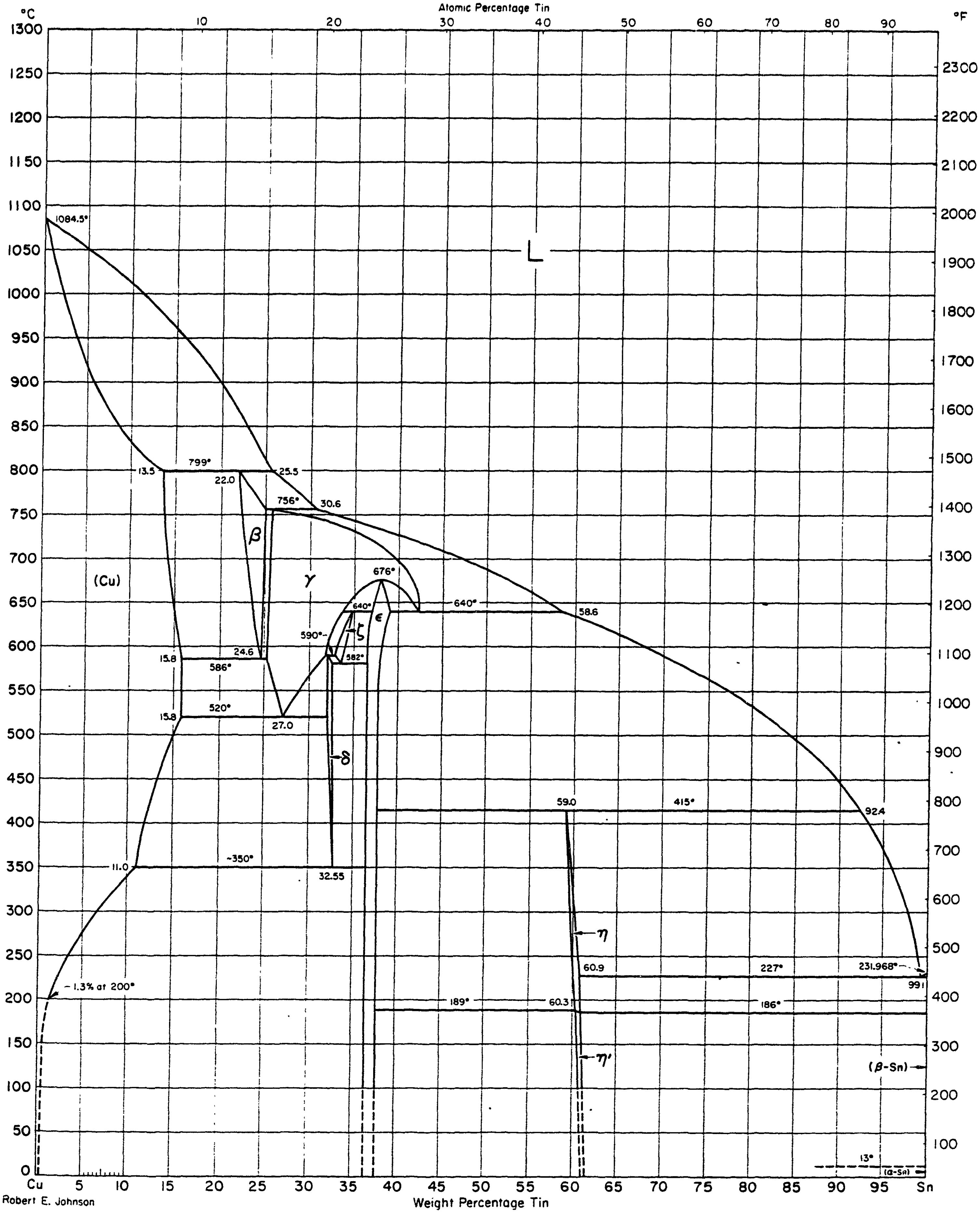


Figure B-3: The Copper-Tin Phase Diagram

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