Title

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The Metals from the Cenote Sagrado, Chichén Itzá
as Windows on Technological and Depositional Communities

By

Bryan Russell Cockrell

A dissertation submitted in partial satisfaction of the

requirements for the degree of

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in

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University of California, Berkeley

Committee in charge:

Professor Emeritus Steven Shackley, Chair
Professor Rosemary Joyce
Professor Ronald Gronsky

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Abstract

The Metals from the Cenote Sagrado, Chichén Itzá
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Doctor of Philosophy in Anthropology

University of California, Berkeley

Professor Emeritus M. Steven Shackley, Chair

This project is the first to reconcile metals recovered from the Cenote Sagrado at Chichén Itzá, Mexico from three museums in the US and Mexico in which Cenote objects are held. 148 of these metals were characterized through archaeometric studies. Through non-invasive and non-destructive analyses, this project involved the documentation of individual metals, including bells, sandals, and figurines, searched for patterning across the assemblage to identify distinct technological styles, and then compared data to published literature to determine the metallurgical communities in Mesoamerica and Lower Central America indexed by these styles. After performing a visual inspection of each object with a magnifying glass and recording measurements with calipers, optical microscopy with visible, ultraviolet, and infrared light was then employed to comprehensively document object surfaces. Bulk compositions were evaluated with portable-Energy-Dispersive-X-Ray Fluorescence spectrometry. After carrying out these analyses in museum storerooms, with the permission of the Peabody Museum of Archaeology and Ethnology, 15 objects were brought to laboratories in New York for finer-resolution studies, including synchrotron-based X-Ray Diffraction and Rutherford Backscattering Spectroscopy, which permitted the evaluation of artificial enrichments on the metals.

The assemblage consists of copper-based objects, including bronzes of arsenic and/or tin as well as brass, and *tumbaga*, a metal containing gold, silver, and copper. Many show post-fabrication alteration, including indentation, tearing, and wrinkling, practices that may have taken place in ritualized deposition. Two zoomorphic bells were hammered to shape after their lost-wax casting. Two sandals were artificially enriched in silver and gold through electrochemical replacement gilding. Reconciliation of the data with pre-existing literature reveals the contributions of metallurgists in Guerrero and Michoacán (axe-monies), the Tarascan state (tweezers), Veraguas/Chiriquí (anthropomorphic figurines), and Gran Coclé (rolled tubes) to the Cenote deposit. The documentation of sandals in 16th-century literature and the presence of brass suggest that the deposition was developed through connections to the Mexica tributary system and through the working of metal imported from Europe, thus, centuries after the main occupation of Chichén (8th-11th century AD). Experimental lost-wax casting and hammering has allowed for exploration of metallurgy as a performative and fully embodied practice and to recognize that the individuals who altered the objects after their fabrication were themselves metallurgists, enacting technical knowledge.

1

TABLE OF CONTENTS

The Cenote Sagrado at Chichén Itzá is doubtlessly a major component of the public imagination of ancient Mesoamerica and of the practice of archaeology. Besides a nexus for tourism (Casteñeda 2010) and political controversy (Breglia 2005), Chichén and the Cenote itself have been dramatized and romanticized as a focus for ritualized offerings in the past, particularly of humans (Jones 2005; Lerner 2011). Scholars have partially, if not chiefly, augmented this view. The ethnographer Ralph Roys (1933 in Tozzer 1957) writes:

> "We can not but believe that these foreign embassies, which must have travelled for weeks through tropical forests, swamps and waterless wastes to reach a far-off city in northeastern Yucatan, were motivated more by the religious veneration which its famous sanctuary enjoyed than by the political prestige which its rulers enjoyed in such a distant country."

Indeed, the potential of Chichén as a pilgrimage destination enriches the drama. Feeding the public imagination of archaeological practice is the recognition of the uncontrolled excavations of the Cenote in the early 20th century. While archaeologists in the 1960s sought a more rigorous approach to the site's excavation and an interest in the preservation of stratigraphy, *National Geographic* video (1961) records the chaos of archaeological materials spewing out of the Cenote waters through a pressurized airlift and onto a raft, again inhibiting the artifacts' proper contextualizations.

In this project, I have sought to challenge these established imaginaries. Through fine-grained analyses of archaeological artifacts from the Cenote, can I, first, decentralize the deposition and bring into focus the contributions of the craftspeoples who fabricated the materials that ended up in the Cenote? Roys (1933) notes the vast distances that visitors may have traveled to reach the Cenote. I want to turn my lens to these distant places and illuminate the craftspeoples whom the materials in the Cenote deposition index. Can we, second, demonstrate that archaeological rigor can indeed be brought to bear on the Cenote deposition? Through a stepwise set of methods, in concert with the interests of the government of Mexico and museum conservators and curators, I have aimed to comprehensively document individual objects. I have attended to fragmented and poorly preserved objects as much as, if not more, than I have to cleaner materials because these former materials still reveal abundant information about technology and post-fabrication treatment. Furthermore, I have explored the records of all of the 20th century projects to excavate the Cenote for any information about context. While the refined methods of 21st century underwater archaeology were not practiced in these earlier projects, I found that a disciplined archaeometric investigation of the objects opened windows on previously obscured details.

Development of the Project

Metals recovered from the Cenote Sagrado, among other materials, pose a challenge. There is no metallurgical debris at the site of Chichén Itzá, and Yucatán is relatively lacking in deposits of metal sources. The implication is that the metals were imported. Prior studies of the Cenote materials have suggested diverse sources for the metals, primarily emphasizing the Isthmian region of Central America (Costa Rica and Panama), on the basis of their morphological styles (Cobos 1998; Coggins and Shane 1984; Lothrop 1952).

To achieve an interpretation of the Cenote metals more holistic than any of the preceding studies could offer, I collaborated with Edith Ortiz Díaz (Instituto de Investigaciones Antropológicas, UNAM) and José Luis Ruvalcaba Sil (Instituto de Física, UNAM) in the development and implementation of the project. With Dra. Ortiz and Dr. Ruvalcaba, I constructed a clear research design that drew on our prior experiences in archaeometallurgical investigations and shared technical equipment while the research was conducted.

My initial visual inspections of the metals in 2010 and 2011 helped me to further refine my approach: I noted that many of the metals appeared to be heavily altered and fragmented. As all of the project's collaborators had substantial experience in archaeometric research, particularly in the analysis of inorganic materials, I aimed to craft an investigation that would depend on the most contemporary approaches to archaeometry with an awareness of the need for non-invasive and non-destructive analyses, in line with the likely concerns of the government of Mexico, and museum conservators and curators. Through careful consideration of previously published studies, examinations of the metals themselves, and recognition of the analytical resources that were available to me, I developed the following specific research questions:

What range of technological practices are evinced across the metals assemblage? At the same time, what (post-fabrication) alteration practices are evinced by the metals?

What metallurgical communities are indexed by these practices?

Guided by these questions, I realized the project would depend on at least two main datasets: the results of the archaeometric analyses *and* the results of previously conducted studies of metals from the potential 'catchment area' for the Cenote metal fabrications, from Mesoamerica to northern South America. In other words, the analyses would need to be properly situated in the current picture of metallurgy in the Americas in order to make deft identifications of the different metallurgical communities whose works are represented in the assemblage. After careful selection of a sample of objects to study within the larger assemblage (discussed in more detail in Methods), I submitted applications for permission to study the metals to the Peabody Museum of Archaeology and Ethnology at Harvard University and to the Consejo de Arqueología of the Instituto Nacional de Antropología e Historia, Mexico. On receiving permission to study metals at the Peabody Museum and at the Museo Nacional de Antropología and the Museo Palacio Cantón, I continued to discuss the detailed research protocol with my collaborators and began to organize our team and equipment to continue the investigation.

Research Antecedents and Theoretical Orientation

Three prior studies have been conducted of the Cenote metals (Contreras et al. 2007; Franco Velázquez and de Grinberg 2002; Lothrop 1952). Each of these studies focused on the collection of one museum, and each privileged compositional data to other threads of data. My study is the first to reconcile metals from three museums in Mexico and the US in which they are held. While I have undertaken compositional analyses, I also have recognized the important information that can be gleaned from meticulous inspection of the objects' surfaces with relatively low-tech methods, including a magnifying glass and an optical microscope. Building on these three previous studies and contextualizing data through exploration of the records related to each of the 20th-century

Cenote excavation projects, documents that describe the objects' conservation treatments, and, of course, published literature on metals from the Americas, I have intended to perform a highly comprehensive characterization of the metals assemblage. My theoretical orientation leads me directly to consider the peoples who fabricated and re-fabricated the objects.

In the project, I examine the variety of superficial traces of fabrication and alteration on individual Cenote metals in order to create object 'biographies' (or reconstruct their 'itineraries'), categorizing the traces as the products of fabrication decisions, secondary consequences of fabrication, post-fabrication alterations, or ambiguous features that could have arisen from several different actions. I reconcile the characterization of these superficial traces with compositional and microstructural data in order to 'flesh out' these object life histories. By comparing these biographies, I identify patterns across the assemblage in order to ask: what 'technological style(s)' is/are evident among the Cenote bells (Gosselain 1992; Hegmon 1992; Lechtman 1984; Sillar and Tite 2000)? Then, what 'communities of practice' are indexed by each style (Kamp 2001; Lave and Wenger 1991; Sassaman and Rudolphi 2001)?

The life history of an archaeological object is an extrapolation of its chaîne opératoire (Leroi-Gourhan 1964-1965), documenting not only the "physical sequence of operations" involved in the object's fabrication but also the "bodily gestures [of] ancient technicians" (Dobres 2010:106). I expand such a life history to also include post-fabrication alteration, taphonomic effects of deposition, and post-excavation treatment. Object life histories, through emphasis on the gestures of the objects' designers, readily offer a route to the "dynamic social milieus" involved at fabrication and also at use, deposition, and conservation (Dobres 1999:129). A more dynamic conceptualization of archaeological objects arrives with the notion of "itinerary," which emphasizes the ways by which objects enter and exit different social relationships (Joyce 2012, 2013). The "object itinerary" is especially useful for my investigation because it makes room for the reception of the object by modern and contemporary peoples (i.e. post-excavation, including myself as an archaeological scientist).

Technological style is based on the notion that, as Lechtman (1984:32) writes, "technology per se becomes the medium for the expression of message." It is a branch of "style," which, as Hegmon (1992:517) observes, involves "doing things" and making "choices." People who craft select from a "universe of possibilities," according to Lemonnier (1986:153), and the choices they make are inspired not necessarily by functional reasons, but also by cultural contexts (Sillar 1996:260-261, 2000:3,9-10). Objects index their technological style in each new context through which they pass and acquire new styles through the gestures of their users, depositors, excavators, and conservators. If these objects circulated over long distances, retaining the features of their fabrication, they continually communicate their technological style and thus the spatial, temporal, *and* social contexts in which they were made.

A community of practice is a group of individuals who make objects with a shared technological style (Bradley 2004; Lave and Wenger 1991; Minar and Crown 2001; Odland Portisch 2010). While shared practice results from similar access to raw materials and/or geographic proximity to one another, it is also develops from shared learning. Crafted objects, even when deposited in places distant from their site of fabrication, index the community of craftspeople who made them and, in turn, the

communities of users, depositors, excavators, and conservators who enacted their gestures on the objects. These bodily gestures have material consequences, such as particular elemental compositions, microstructures, and superficial traces that can be evaluated.

The Cenote Sagrado

The limestone-rich terrain of Yucatán yields under pressure to form sinkholes into which groundwater seeps, forming *cenotes*, or natural wells. One of the two cenotes at Chichén Itzá, a major Maya political center from the 8th c. to the 11th c. A.D., has been studied repeatedly in the 20th century. Edward Thompson was sponsored by Charles Bowditch to excavate the Cenote. From 1904 to 1911, Thompson led a team to mechanically dredge the Cenote of its artifacts and then employed divers to recover objects. Thompson was unable to properly document the stratigraphy of the finds (Coggins 1992). In visiting the project, Alfred Tozzer stated in 1904 that the dredge brought objects to the surface and any debris would "fall in a pile. This debris was searched for small objects but, unfortunately, not all of it was sifted" (Folan 1968). Thompson's project recovered a diverse array of materials, from jade to ceramics to metal to wood, textiles, and human bone. Eventually, these objects were transferred to the Peabody Museum of Archaeology and Ethnology (PMAE), of which Bowditch was a benefactor.

Thompson suggested that he had recovered less than ten percent of the "cultural material" in the Cenote (Folan 1968). Decades later, Cirerol Sansores (1935, 1940) discovered artifacts, including "copper bells," in the debris from Thompson's project that remained on the Cenote's southern rim. In an effort to more adequately preserve the deposit's stratigraphy, excavations of the Cenote resumed in 1960-1961 and 1967-1968 under the auspices of Mexico's Instituto Nacional de Antropología e Historia (INAH). First using a pressurized airlift and then bringing in divers, this project recovered diverse materials but still struggled with preservation of stratigraphy. In the project's early phase, the airlift would occasionally spew the materials it had swallowed "back into the Cenote" (Folan 1968). The airlift also induced fragile materials to break (Piña Chán 1970). At one point, in order to make the Cenote's contents more visible, copper(I) sulfate (Cu_2SO_4) was added to the water in order to kill algae, but this effort proved unsuccessful (Folan 1968). Clusters of different materials, heavy and light, were recovered together. The field report of Ponciano Salazar Ortegón records the daily tally of finds but does not state whether they were found in groups or describe the extent to which they were associated with other metal and non-metal objects.

In the 1967-1968 project, the excavators first tried to desiccate the Cenote's waters but failed (Piña Chán 1970). Then they worked from the Cenote's edges in three-meter-wide units using picks and shovels. To enable the work of divers, a Purex solution (Cl, K_2SO_4, and Al-salts) was added in order to clarify the Cenote's waters again; this time, they were successful, yielding eight to ten meters visibility. They also revised the airlift so that "no solamente excava sino que retira el lodo de la excavación" ("not only did it excavate but it removed the mud from the excavation"; Arqueología Subacuática Méxicana, Informe 40-86). Combining divers with the airlift, the project recovered materials by quadrants. In quadrant 2, they identified copper-rich bells, rings, carbonized

4

textile, bark, copal balls, blue-painted tripod vessels, jade beads, human remains, animal bones, and Mayapán ware (Piña Chán 1970). In quadrant 3, they recovered gold-rich bells, metal sandals, gold-rich sheet, copper-rich wire rings, copal balls, wooden stools and masks, gourd pieces, jade plaques and beads, Puuc vases, pyrite mirrors, human remains, rubber balls, and textile fragments. The metals from these excavations are now held in the Museo Palacio Cantón (MPC) in Mérida. In 1959, as part of an exchange, the PMAE sent 92 of the Cenote metals to INAH, which were then accessed to the Museo Nacional de Antropología (MNA).

Excavations of Chichén have recovered no archaeological materials indexical of metallurgical operations (e.g. slag, crucibles with metallic residues). This point, taken with the lack of ore or native metal in Yucatan, suggests that the metal objects were imported to Chichén. Like the Cenote jades, for which Proskouriakoff (1974) posited diverse sources from Oaxaca to Pacific Guatemala, the metals may have arrived at the Cenote from multiple geographic locations, as earlier evaluations have suggested with a greater focus on the objects' iconography (Bray 1977; Cobos 1998; Coggins and Shane 1984; Lothrop 1952). These studies emphasize the iconographic influence of Lower Central America (modern Nicaragua, Costa Rica, and Panamá) on the Cenote metals, while Bray 1977 points to associations with a wider Mesoamerican geographic scope.

Despite efforts to maintain stratigraphic control of the finds, the inherently disturbed nature of the deposit—if multiple depositions occurred over time, settling objects may have dislodged previously deposited objects—paired with the excavators' experimental approach to underwater archaeology, using different methods by trial and error, and the poor documentation of methods and finds complicates any effort to deduce a chronology of depositions. Nevertheless, the prodigious and diverse nature of the entire Cenote assemblage and the tentative stylistic dating of jades (Proskouriakoff 1974) and hydration dating of obsidian (Sheets 1992) suggest that the deposit developed over centuries. I propose that the Cenote deposit of metals, jades, obsidian, and other materials is an example of "structured deposition," that is, "ritual action involving formalised repetitive behaviour and the use of material symbols" (Richards and Thomas 1984, 191). Geographically proximate examples of "structured deposition" that also involved diverse materials include Laguna del Manatí (Ortiz C. and del Carmen Rodríguez 1999) and the Templo Mayor at Tenochtitlán (López Luján 2005; López Austin and López Luján 2009).

Metal artifacts have been recovered in other contexts at Chichén, most notably in and around the High Priest's Grave (Thompson 1938; Proskouriakoff 1962). Copper-based bells found in the shaft of the grave were associated with Mayapán ceramics, suggesting a deposition that succeeded Chichén's main occupation.

Within the Cenote, ceramics date from AD 800 to 1550 (Ball and Ladd 1992). An early group (AD 800-1200) consists mainly of water jars and other utilitarian forms, featuring Chichén Unslipped, Slate, and Red ware. A later group (AD 1200-1550) includes tripod dishes and blue-painted bowls that contain copal; these forms tend to be Mayapán Unslipped and Red wares.

Studying the platform around the edifice at the southern end of the Cenote, some of whose stone had fallen into the waters, Piña Chán (1970, 1998) proposed that the worked stone resembles the stone panels that comprise the Great Ball Court at Chichén and thereby dated the depositions at the Cenote to later in Chichén's occupation.

However, the edifice, which he suggests was used as a purification site for the "víctimas destinadas al sacrificio" ("victims destined for sacrifice"), cannot necessarily be tied to the depositions of objects into the Cenote.

Coggins and Shane (1984) divide the depositions into three phases based on the iconography of the objects. In Early Phase I (AD 800-900), objects bear imagery similar to that presented at the Great Ball Court and the Upper Temple of the Jaguars. This phase includes "sheet gold and cast gold alloy figurines" from Lower Central America. In the Early Phase II (AD 900-1150), the objects "reflect the warrior cult of the Toltec" and again include "cast gold" but from Pacific Lower Central America. Sheet gold was "imported" but "worked locally" and over time, cast copper played a larger role. Finally, in the Late Phase (AD 1250-1539), postdating Chichén's main occupation, objects associated with particular deities were deposited and include "gold-foil-covered objects and a lot of cast copper."

Piña Chán (1970) proposed a chronology that grouped metal sandals, bells, and rings in an early phase but included no metal in a later phase. Ball and Ladd (1992) argued that the materials were deposited in a single event, a "termination ritual," at Chichén's abandonment. Nevertheless, visits to the Cenote apparently continued. The *Chilam Balam of Chuyamel* reports that Hunac Ceel, leader of Mayapán, sought a prophecy at the Cenote in AD 1451. De Landa's *Relación* reports that the Xiu unsuccessfully embarked on a visit to the Cenote in 1536 and that people and objects were routinely thrown into the well. The *Relación de Valladolid* (1579) states that men from Valladolid fast and then head to the Cenote, into which they throw women in the hope of "a good year." Purportedly during Thompson's project, a Maya man "en éxtasis" ("in ecstasy") arrived at the Cenote having traveled a long distance (Coggins 1992). Recognizing ambiguities and inconsistencies in prior evaluations, clearly, the geographical provenances of the Cenote metals and the chronology of their deposition(s) need reconsideration.

Methods

All three collections were visited in 2010 and 2011 in order to make an initial study of the objects by recording macroscopic observations, photographing particular objects, and considering which objects would merit further analysis. In selecting such objects, the goals were: (1) to examine a wide range of the object forms (*e.g.* bells, sandals, figurines) represented in the assemblage, while ensuring comparability of forms in the final sample; and (2) to study those objects whose fabrication and alteration signatures were most visible macroscopically through superficial traces such as porosity, fracture, and tearing at edges. Throughout the entire project, non-invasive and non-destructive analyses were employed.

In the first stage of analysis, in spring and summer 2012, 148 objects were studied through portable instruments brought to the three museums (the PMAE, MPC, and MNA). With Dra. Ortiz, Dr. Ruvalcaba, and their students, Mayra Manrique, Valentina Aguilar, and Edgar Casanova, I: (1) performed a visual observation of each metal specimen with a magnifying glass, evaluating the artifact in light of pre-existing typologies and taking measurements with calipers; (2) documented the object with optical microscopy, employing visible light for initial evaluation, ultraviolet light for detection of

6

organic residues and surface defects, and infrared light for observation of impressions left behind by fabrication tools; and (3) qualitatively characterized the elemental composition of the object with X-Ray Fluorescence spectrometry. At each step, I narrowed the focus, reviewing my notes from the prior step to select regions of individual objects that merited further analysis, such as an area with a patina representative of a larger region of the object or an area with a fracture.

At the PMAE, step (2) was performed with a Dino-Lite AD413T-12V portable microscope, with digital photography capability, 20 to 200x magnification, and LEDs tuned to 395 nm (UV) and 940 nm (IR). Higher-resolution visible light study was conducted with a Zeiss OPMI 1 optical microscope with a Lumenera 1-2C digital camera at PMAE Conservation. The latter setup offered slightly higher resolution (2.0 MP) than the Dino-Lite (1.3 MP). At the MPC and MNA, this study was performed with an Edmund E-Zoom6V stereoscope with a Nikon Coolpix 4300 digital camera. UV radiation was applied through a 60-W lamp attached to the stereoscope (254 nm) or with freestanding ultraviolet lamps UVGL-55 or UVGL-58, offering short- and long-wave UV (254 and 365 nm). IR microscopy was undertaken using a Sony NightShot video camera with IR filter for 700-1000 nm detection.

At the PMAE, step (3) was performed with a Bruker Tracer III-SD (40 kV; 12.30 µA; 12 mil Al + 1 mil Ti filter; beam at object surface: 5x6.75 mm). A Fundamental Parameters method was used for calibration, and the measurements were subsequently standardized with three certified reference materials from Xcalibur XRF ((1)14-kt Au L020; (2) Ag-Cu L115; and (3) brass NIST SRM 1107) and the steel 2205 standard sent with the Tracer and then normalized to 100 wt% (Figure 2c). Multiple points were analyzed on each Cenote metal, probing several faces whenever possible. Each point was analyzed twice, and each analysis lasted 180 live-seconds. At the MPC and MNA, pXRF was performed with SANDRA (Sistema de Análisis No Destructivo por Rayos X), developed at IF-UNAM, with a laptop (beam size=1-1.5 mm diam.; heavy elements: 45 kV; 0.05 mA; 200 live-seconds for each point; 20 µm Al + mylar filter; light elements: 35 kV; 0.1 mA; 300 live-seconds for each point; no filters). An adjustment in the XRF parameters was made for the MNA metals, which were by and large Au-rich (45 kV; 0.05 mA; 120 live-seconds for each point; mylar filter). Besides SRM 1107, a Cu-Au-Ag reference (585-40) was used to standardize SANDRA. Recognizing the potential conflation of As Kα and Pb Lα in pXRF spectra, the relative intensities of As Kb and Pb Lb were studied as indications of elemental presence or absence.

The PMAE allowed me to undertake a series of finer-resolution analyses of selected metals. I chose objects with especially heterogeneous surfaces and with the potential for artificial superficial enrichment, a practice detected on many other *tumbaga* objects from Mesoamerica. Collaborating with scientists at two laboratories in New York, I developed experiments that would be especially suitable for probing these two issues, allowing me to examine the distributions of elements on surfaces and to compare the composition of the bulk metal to that of the surface. At the Cornell High Energy Synchrotron Source (CHESS), ten objects were analyzed with synchrotron radiation-XRF (SR-XRF) (17 keV; beam at object surface = 0.5 mm^2) at beamline F3 to produce elemental distribution maps. Spectra were fit with PyMCA software, which uses Fundamental Parameters. Ten objects (only partial overlap with those analyzed by SR-XRF) were analyzed with transmission SR-XRD (59.3 keV; λ=0.207 Å; sample-to-

detector distance $\approx$ 843.9 mm; beam size = 0.5 mm^2 or 1 mm^2; collection time = 4, 40, or 400 live-seconds) at beamline A2. Diffraction patterns were calibrated with CeO_2 powder and analyzed with Fit2D software.

Thirteen PMAE objects were analyzed with RBS (H$^+$ and He^{++} beams, 3 MeV, beam at object surface $\approx$ 2 mm^2) at beamline 30 of the Ion Beam Laboratory at SUNY Albany. The total dose applied during each analysis was 2.5 μC. A Pt target was used for calibration. The aforementioned L020 and L115 were employed as standards. Spectra were processed with RUMP and SIMNRA software.

The chapters that follow present the results and interpretations of the research tied to three particular groups of Cenote metals: bells, hammered objects, and figurines. Each, of course, is only a sample of the sub-assemblages of bells, hammered objects, and figurines in the larger Cenote metals assemblage, and, together, they represent approximately half (75) of the 148 specimens that I studied. But, I propose that these three object groups are especially useful representative windows into the larger assemblage for the variety of technological practices they index and for their relative comparability to metals recovered from other locations in Mesoamerica.

BELLS

Today a person walking towards the Cenote Sagrado at Chichén Itzá, Mexico will hear tourists speaking Spanish, English, German, and Arabic, children emitting loud whistles with small jaguar toys, and raindrops gently patting the dense vegetation. But what did this walk sound like in AD 1000? What did it sound like at the Cenote's edge when jade plaques were broken and copal was burned in earthenware containers before they were thrown into the well? It may have been just as cacophonous as the site is today. The metallic bells that were physically altered en route to or at the Cenote and then deposited into the well would have added to this visually and sonically exciting scene.

Of the 494 Cenote metals in three museums in Mexico and the US, 148 (including fragments) have been studied by the authors (Figure 1). This paper explores traces of fabrication and alteration on lost-wax cast bells to create object 'biographies'. We reconcile these traces with compositional and microstructural data to 'flesh out' these biographies. We identify patterns across the assemblage to ask: what 'technological style(s)' (Lechtman 1984) is/are evident among the Cenote bells? Then, what 'communities of practice' (Lave and Wenger 1991) does each style index?

Noting prior evaluations (Coggins and Shane 1984; Piña Chán 1998) and drawing on our initial inspection, we hypothesize that multiple technological styles are present, and these styles index metallurgical communities in Mesoamerica and lower Central America. Recognizing traces of post-fabrication alterations, from indentations to wrinkles, and such traces among other Cenote materials, such as chipped stone (Sheets et al. 1992), jade (Proskouriakoff 1974), and wood (Coggins 1992), we propose that the communities that 'created' the metals include the metallurgists who fabricated them *and* the peoples who brought them to the Cenote, altered them before deposition, and excavated and conserved them, lending the metals their present appearance. Compared to earlier studies of the metals (Lothrop 1952; Franco Velázquez and de Grinberg 2002; Contreras et al. 2007), ours reconciles compositional data with other threads, such as evaluation of superficial traces and determination of phases, drawing on complementary, non-invasive, non-destructive analyses. Furthermore, ours is the first to compare Cenote metals across the three museums that house them: the Peabody Museum of Archaeology and Ethnology (PMAE), the Museo Palacio Cantón (MPC), and the Museo Nacional de Antropología (MNA).

To properly contextualize the bells, we explored the diagnostic features of the metallurgies of different regions of Mesoamerica. One fundamental challenge we encountered was that the lack of production contexts impedes the attribution of finished metals to particular 'technological styles'. Exchanges of metallurgical knowledge and materials were fluid. Lead isotope analyses indicate that West Mexico exported metals to eastern Mexico and Belize (Hosler and Macfarlane 1996). Iconographic characterizations of Colombian, Panamanian, and Costa Rican metals show "shared themes" across metallurgy into stonework (Graham 1996). Given the objects' portability and the recognition that metallurgists may modify their technological style over time and imitate other communities' styles,

our task is complex.

Provenance and Chronology

The limestone-rich terrain of Yucatán yields under pressure to form sinkholes into which groundwater seeps, forming *cenotes*, or natural wells. The Cenote Sagrado at Chichén Itzá, a major Maya political center from the 8th c. to the 11th c. AD, was studied in the 20th century. In 1904-1911, Edward Thompson led a team to mechanically dredge the Cenote of its artifacts and employed divers to recover objects, which were sent to the PMAE. Thompson was unable to properly document stratigraphy (Coggins 1992). Excavations resumed in 1960-1961 and 1967-1968 under Mexico's Instituto Nacional de Antropología e Historia (INAH) (Piña Chán 1970). First using a pressurized airlift and then bringing in divers, this project recovered diverse materials but still struggled with stratigraphy. The airlift spewed materials it had swallowed back into the water and induced fragile materials to break. In the 1967-1968 project, the excavators tried to desiccate the Cenote's waters but failed. Then they worked from the Cenote's edges in three-meter-wide units using picks and shovels. The metals from these excavations are now in the MPC. In 1959, as part of an exchange, the PMAE sent 92 Cenote metals to INAH, which were then accessed to the MNA. Excavations of Chichén have recovered no metallurgical debris. This point, taken with the lack of ore or native metal in Yucatán, suggests that the metals were imported to Chichén.

The inherently disturbed nature of the deposit—subsequent depositions would have dislodged previously deposited objects—paired with the excavators' experimental approach to underwater archaeology and the poor documentation of methods and finds complicate efforts to deduce a depositional chronology. Nevertheless, the prodigious and diverse nature of the Cenote assemblage and the tentative stylistic dating of jades (Proskouriakoff 1974) and hydration dating of obsidian (Sheets et al. 1992) suggest that the deposit developed over centuries.

Conservation

29 of the 38 analyzed bell specimens were excavated in Thompson's project, while the other nine were recovered in the INAH's. Little to no documentation exists describing any immediate post-recovery object treatments. Thompson wrote that dredged mud likely containing artifacts was "washed and passed through a fine mesh sieve" (in Coggins 1992:18). Conservators have proposed that acidic reagents were applied to clean Cenote metals after their recovery (J Contreras, G Peñuelas, D Piechota 2012, pers. comm., 24 April, 2 May). Lothrop (1947) notes that the greenish color on one unidentified metal is the "result of working on the black incrustation with nitric acid."

At the PMAE, at least eight high-Au bells were treated between 1983 and 1985. Besides degreasing the surfaces with acetone and (re-)applying museum accession numbers on all six, one bell was cleaned of "archaeological deposits" with distilled H_2O and another cleaned of Cu-oxides by reduction with Zn and

15% NaOH.

None of the nine MPC bell specimens was conserved, and the state of the MNA bells is uncertain. However, after excavation in 1960-1961, metals would have been brought to INAH in Mexico City for conservation and cleaning (Piña Chán 1970).

Two bells exhibit exceptional losses. B13 consists of two fragments that comprise complete bell, while B19 lacks an entire half.

Prior Analysis

Thompson allowed T.A. Willard (1931) to analyze six bells, presumably by gravimetry. Willard found that one has 20% Au and the others had "less [Au content] but still enough to get a gold reaction." In the present study, the lowest Au content among the bells with major Au content (≥10 wt%) was 81.5 wt% (F2). Beginning gravimetry as early as 1927, Root (1937, 1946-7) noted that between 0.005 and 0.03 g of metal was a sufficient sample. In gravimetry, the sample is introduced into precipitation reactions with solids and solutions of known compositions in order to calculate concentrations of individual elements in the unknown sample. Root noted that the results "are not accurate to more than the nearest 0.5 percent," but concentrations are reported to the nearest 0.1%. He also employed Feré quartz spectrography (λ=2100-5200 Å): 1 mg of the unknown metal was inserted into a graphite electrode, and a 120 V DC arc was struck, irradiating film strips. Standard films were compared to the unknown films in order to identify elements, and concentrations were determined by the "relative intensities of the lines."

Velázquez and de Grinberg (2002) studied six MNA bells, noting a select range of surface anomalies, the conservation state, and certain morphological features. Through XRF, they found Fe, As, and Ag in all six and Pb in three. They sampled the bells for Atomic Absorption Spectrometry, measuring various elements (excluding As) quantitatively. Cu was the primary constituent of all, while Pb (major in one, minor in three) was the only other element that appeared at concentrations ≥1 wt%.

Contreras et al. (2007) analyzed nine Cenote metals, but no bells, with ED-XRF, SEM, and PIXE-RBS.

Methods

In selecting objects for study, the goals were: (1) to examine a wide range of forms, while ensuring comparability of forms in the final sample; and (2) to study those objects whose fabrication and alteration signatures were most visible macroscopically through superficial traces. Throughout the project, non-invasive and non-destructive analyses were employed.

148 objects were studied through portable instruments brought to each museum. We: (1) performed a visual observation of each metal with a magnifying glass, comparing the object to pre-existing typologies and taking measurements with calipers; (2) documented the object with visible light microscopy for initial

evaluation, ultraviolet (UV) microscopy for detection of organic residues, and infrared (IR) microscopy for observation of tool impressions; and (3) qualitatively characterized the elemental composition(s) with portable Energy-Dispersive X-Ray Fluorescence spectrometry (pXRF).

At the PMAE, step (2) was performed with a Dino-Lite AD413T-12V portable microscope, with digital photography capability, 20 to 200x magnification, and LEDs tuned to 395 nm (UV) and 940 nm (IR). Higher-resolution visible light study was conducted with a Zeiss OPMI 1 optical microscope with a Lumenera 1-2C digital camera at PMAE Conservation. At the MPC and MNA, this study was performed with an Edmund E-Zoom6V stereoscope with a Nikon Coolpix 4300 digital camera. UV radiation was applied through a 60-W lamp attached to the stereoscope (254 nm) or with freestanding ultraviolet lamps UVGL-55 or UVGL-58, offering short- and long-wave UV (254 and 365 nm). IR microscopy was undertaken using a Sony NightShot video camera with IR filter for 700-1000 nm detection.

At the PMAE, pXRF was performed with a Bruker Tracer III-SD (40 kV; 12.30 µA; 12 mil Al + 1 mil Ti filter; beam at object surface: 5x6.75 mm). Fundamental Parameters was used for calibration, and the measurements were subsequently standardized with three certified reference materials from Xcalibur XRF ((1)14-kt Au L020; (2) Ag-Cu L115; and (3) brass NIST SRM 1107) and the steel 2205 standard sent with the Tracer and then normalized to 100 wt% (Figure 2c). Multiple points were analyzed on each Cenote metal, probing several faces whenever possible. Each point was analyzed twice, and each analysis lasted 180 live-seconds. At the MPC and MNA, pXRF was performed with SANDRA (Sistema de Analisis No Destructivo por Rayos X), developed at IF-UNAM, with a laptop (beam size=1-1.5 mm diam.; heavy elements: 45 kV; 0.05 mA; 200 live-seconds for each point; 20 µm Al + mylar filter; light elements: 35 kV; 0.1 mA; 300 live-seconds for each point; no filters). An adjustment in the XRF parameters was made for the MNA metals, which were by and large Au-rich (45 kV; 0.05 mA; 120 live-seconds for each point; mylar filter). Besides SRM 1107, a Cu-Au-Ag reference (585-40) was used to standardize SANDRA. Recognizing the potential conflation of As Kα and Pb Lα in pXRF spectra, the relative intensities of As Kb and Pb Lb were studied as indications of elemental presence or absence. Fifteen PMAE specimens were studied at the Cornell High Energy Synchrotron Source (CHESS). One bell was analyzed with synchrotron radiation-XRF (SR-XRF) (17 keV; beam at object surface = 0.5 mm^2) at beamline F3 to produce elemental distribution maps. Spectra were fit with PyMCA software, which uses Fundamental Parameters. Three bells were analyzed with transmission SR-XRD (59.3 keV; λ=0.207 Å; sample-to-detector distance ≈ 843.9 mm; beam size = 0.5 mm^2 or 1 mm^2; collection time = 4, 40, or 400 live-seconds) at beamline A2. Diffraction patterns were calibrated with CeO_2 powder and analyzed with Fit2D software.

Five bells were analyzed with RBS (H$^+$ and He^{++} beams, 3 MeV, beam at object surface ≈ 2 mm^2) at beamline 30 of the Ion Beam Laboratory at SUNY Albany. The total dose applied during each analysis was 2.5 µC. A Pt target was used for calibration. The aforementioned L020 and L115 were employed as

standards. Spectra were processed with RUMP and SIMNRA software.

Typology

Typological parallels were sought, following Bray 1977: fig. 2, Hosler 1988: fig. 1, Pendergast 1962: fig. 5, and Schulze 2008: figs. 8.3, 8.8 (referred to by "B", "H", "P", and "S") (Figure 1d.1). Combined, they depend on objects from sites that transcend the geographic scope of the metallurgical communities that may have contributed to the Cenote deposit. Cenote bell types from Lothrop 1952 ("L") were noted. These typologies do not encompass all of the diversity of the Cenote bells, but approximate parallels are indicate.

21 bells display anthropomorphism or zoomorphism: a canine head (n=2; L: E, B: n/a, P: IE1), an entire animal (turtle (n=3), monkey (n=3); L: n/a, B: r and s, P: IE), or a human or animal figure on a platform attached to the resonator (n=13; L: n/a, B: q, P: n/a). The Hosler and Schulze typologies do not account for such bells.

Metrics

High-Au bells tend to show greater height ($\bar{x}$ = 44.71 mm, 1σ = 14.25 mm, c_v = 0.32) and width (26.18 mm, 1σ = 8.81 mm, c_v = 0.34) than the high-Cu bells (h: $\bar{x}$ = 29.71 mm, 1σ = 7.95 mm, c_v = 0.27; w: $\bar{x}$ = 16.01 mm, 1σ = 3.79 mm, c_v = 0.24) (Figure 1e.1). The monkey and turtle bells, all of which are high-Au, are more similar in height and width (h: $\bar{x}$ = 41.28 mm, 1σ = 8.60 mm, c_v = 0.21; w: $\bar{x}$ = 30.04 mm, 1σ = 12.75 mm, c_v = 0.42) to the other high-Au bells, but they are usually more circularly symmetric; thus, their width tends to be greater than that of the other high-Au bells.

The pear-shaped (n=13) and spherical (n=3) high-Cu bells show similar patterning in maximum height and maximum width to those belonging to these two types in Schulze 2008 (Figure 1d.2). While the range of maximum width of the spherical bells ($\bar{x}$ = 13.93 mm, 1σ = 2.23 mm, c_v = 0.16) falls within that of the pear-shaped bells ($\bar{x}$ = 16.43 mm, 1σ = 4.27 mm, c_v = 0.26), the maximum height of the spherical bells ($\bar{x}$ = 16.31 mm, 1σ = 1.67 mm, c_v = 0.10) is significantly less than that of the pear-shaped bells ($\bar{x}$ = 31.93 mm, 1σ = 5.79 mm , c_v = 0.18).

Superficial Features

The result of visual inspection and optical microscopy was to develop a compendium of surface features for each object (Figure 1f). A feature may represent: (1) a "technological decision," intended by the bell's designer to be present; (2) a "consequence of fabrication" that may not have been intended by the designer(s); (3) a "secondary alteration," that developed after the bell's original fabrication; or (4) an "ambiguous feature" that arose in fabrication and/or post-fabrication.

Technological decisions. A **platform**, a circumferential band of metal

usually at the resonator's top, is present on 16 of the bells, high-Au and high-Cu compositons alike. This platform may have served to reinforce the metal at an abrupt, nearly perpendicularly-angled edge. On one high-Au bell, which coincidentally has the greatest maximum length and width of any bell studied, the presence of two platforms may demarcate the bell as especially elaborate.

A **reinforced lip**, a band that outlines the bell's mouth, is present on 12. This feature may also have stabilized a delicate edge, but at the same time yielded more weakness, as fractures may develop in its vicinity.

A **suspension loop,** present on 34, was fundamental to the bell's emission of sound, whether individually if the bell had a clapper or by striking other bells with or without clappers. Combining several strips of wax to form a loop, metallurgists would have allowed the loop to more ably bear the substantial weight beneath it. Loops consisted of one (n = 10), two (n = 18), or three (n = 6) strips. The mean strip width is 1.71 mm (n = 33 measurable, 1σ = 0.52 mm, c_v = 0.30). The high-Cu bells' strip widths (n = 17, $\bar{x}$ = 1.50 mm, 1σ = 0.32 mm, c_v = 0.22) tend to be lower than those of the high-Au bells (n = 16, $\bar{x}$ = 1.93 mm, 1σ = 0.60 mm, c_v = 0.31). The consistency of the strip's width across different bells is conspicuous to the naked eye. On the high-Au bells, the loop was often 'disguised' as a part of the anthropomorphic or zoomorphic design.

Consequences of primary fabrication. Eleven high-Cu bells and one high-Au bell have at least one **sprue**, a tab that solidified at the end of the metal pour. The locations of all suggest that metal was poured into the bells' narrower ends. Those lacking sprues were cleaned of these tabs after removal of the bell from its casting shell. Based on the surface to which the sprue is perpendicular, the Cu-based bells may have solidified vertically, whereas the high-Au bell may have solidified horizontally.

Seventeen bells display other forms of **surface additions**, usually no more than one mm in diameter. This texture likely developed from heterogeneities in the wax model, the ceramic shell, or both.

Voids, sites where metal is entirely missing, are present on 14, and **surface losses**, where there is metal beneath the surface, are evident on ten. Voids and surface losses may be attributable to heterogeneities in the wax model and/or the ceramic shell, but also may arise from shrinkage that occurs during solidification. They are isolated forms of **porosity**. Clusters of pores were noted on thirteen bells, five with more extensive porosity and eight with more localized. Five bells have **sealed lips**: their resonators were completely closed, inhibiting sound emission. Four were high-Au, and one was high-Cu. Given the consistency of the sealing, we assume this feature developed from a complete collapse of the resonator's hollow interior during casting.

Secondary alterations. Eight bells have an **indentation**, and 14 show **flattening.** We identified an 'indentation' as a localized flattening, where there is a clear depression in the metal without any real loss of patina. A 'flattening' covers a broader region of the object.

Eight, all high-Au, display an **embrittled surface**, a type of natural corrosion of the metal. Burnishing actually may have augmented the potential for embrittlement (Scott 1983a).

14

Four show traces of **invasive analysis** in the form of conical depressions produced by a drill. The metal removed would have far exceeded the 0.03 g maximum that Root proposes for gravimetry. At least five of the studied bells were analyzed by Root, but only one of these five showed a drill hole.

The consistent **organic residue** present on the bell's surfaces was related to the application of a museum accession number. In UV light, a residue that fluoresced lime green, potentially an adhesive used for exhibition, was evident on two bells.

Ambiguous features. **Natural mineralization** of the metal was apparent on all of the high-Cu bells but only on six high-Au bells, where we expected greater ubiquity given the dramatic disparity in electrochemical potential of Cu, Ag, and Au (Scott 1983a). But post-excavation cleaning(s) would have removed at least some of this patina. We wonder whether the black patinas also emerged from burning before deposition or from interaction between the metal and **decaying plant matter** in deposition. Evaluating Brazilian placer Au with Fe-rich brown-black coatings two to 25 μm thick, Rapson (1982) concluded that organic matter dissolved the Au through production of "extracellular amino acids."

Discolorations more localized in their distribution take the form of green, white, brown, red, orange, and grey patches or spots, attributable to soil, corrosion products, and/or residues from museum curation procedures.

Ten bells contain a **clapper** in their resonator. When inspection was possible, the clapper was a small, usually gray stone. In cases of absence, the clapper may have fallen out of the resonator in use, deposition, or post-excavation or have been intentionally removed.

Twelve display **cracking,** that is, a surface discontinuity where metal remains below. Aside from the two fragments from the same bell, 12 exhibit **fracturing,** whereby the discontinuity extends into the bulk. Cracking and fracturing could have arisen in casting and post-casting working, in alteration before deposition, during the development of the Cenote deposition, as materials struck one another, or even after excavation. Four high-Au bells display a **loss of surface patina**, attributable to the natural inter- and intra-granular corrosion to which *tumbaga* is prone (Scott 1983b). This feature also could have resulted from attack by the marine depositional environment and/or cleaning treatments after excavation.

Four of the Cu-based bells and 13 of the high-Au bells display linear **striations** in dense clusters. They may have arisen in natural embrittlement, during polishing of the metal after casting, a practice Fleming (1992b) correlates with artificial gilding, or after excavation in cleaning.

Fourteen are **asymmetric** on their long axis. This asymmetry could have developed in casting, in post-casting shaping, or in later alterations, such as indentation and flattening, before deposition.

Composition, Distribution, and Enrichment

Half of the bell specimens studied are high-Cu (n=19) and the other half are high-Au, commonly referred to as *tumbaga*, whose Cu concentration is highly

variable (Fleming 1992a proposes a lower limit of 2% Cu, and Scott 1983a proposes a range of 10 and 90% Cu) (Figure 2).

Following Shackley (2011) and Schulze (2013), we recognize that individual points analyzed through pXRF may be compositionally diverse from segregation that has occurred during solidification, particularly an issue with Cu alloys with As and/or Pb, and to internal corrosion. We do realize, however, that, when destructive and/or invasive analyses are not permitted or when surfaces cannot be cleaned, these varied patinas may be the only option for study. Through careful documentation of multiple points and their visual and compositional comparison, it should be possible to work with 'dirty' surfaces. Furthermore, conservatively evaluating the data in a quantitative fashion—comparing multiple analyzed points and noting the locations and appearances of those points and calibrating the data with certified reference materials—can offer insight on the range of compositions present. Comparing the quantitative results obtained by Root with the results of pXRF analysis shows remarkable agreement in the case of one high-Au bell (B3) and far less agreement in the concentrations of minor elements (*e.g.* As, Sn, Pb) in the high-Cu bells.

Among the high-Cu bells, three are nearly pure Cu (>99 wt%) (Figure 2b). All contain minor-trace concentrations of As, ten contain trace concentrations of Pb, and four contain minor-trace concentrations of Sn. In all of the cases when Pb is present in the high-Cu bells, its concentration is lower than 0.5 wt%, but even these trace levels could potentially represent intentional acts of alloying. The presence of Fe most likely relates to superficial soil (Figure 3).

In B11, the Pb concentration may be overestimated because of mineralization on the bell's surface (Figure 3c). Drawing on an SR-XRF map of the As distribution in B11 and an RBS profile of the same bell, we infer that As is present in the bulk, presumably in the Cu-rich α-phase (since its concentration is less than the solid solubility limit of As in Cu, 6.83 at%) and less present in any superficial, mineralized patina, which is the case for Sn and Pb (Figure 3c). Recognizing that metallurgists were not necessarily interested in the optimization of certain material behaviors, we can still point to the effects of alloying on these behaviors, such as the general reduction in melting point they achieve, and propose that facilitating certain behaviors *may* have guided these metallurgical practices. Alloying Cu with As improves hardness, and Hosler (1994, 109) proposes that a concentration of 0.5 wt% As makes a difference in the metal's "working properties." But, As also may be present as an unintentional artifact of smelting, if Cu-sulfides were used, often yielding As-sulfides in reduced metal (Torres et al. 1996). When metals exceed the solid solubility limit of As in Cu (6.83 at%), they become increasingly difficult to work (Lechtman 1981, 114). No bell among those studied exceeded 7 at% As. Alloying Cu with Sn enhances the strength and castability of the metal (Lechtman 1988, 359). No Cenote bell surpassed the solid solubility limit for Sn in Cu (15.8 at%). But, Pb is highly prone to form insoluble phases in Cu at room temperature. Still, alloying Cu with Pb enhances the flow of the metal in casting and the solidified metal's machinability.

Among the high-Au bells, Ag is consistently present between 3 and 6 wt%

and is presumably an artifact of the Au source (Figure 2a). Scott (1983a) proposes a broad range of Ag (5-45 wt%) and Cu (0.1-5 wt%) concentrations in native Au. Under this classification, nine of the 19 high-Au bells (i.e. those with Cu ≤5 wt%) could be the products of unprocessed native Au deposits. Au alone could be advantageous because of its resistance to corrosion and its softness (Fleming 1992a). Cu alloyed with Au lowers the metal's melting point by as much as 134°C (m.p. = 910°C at ≈21 wt% Cu) (Okamoto et al. 1987). The alloy is thus easier to cast than either metal alone and facilitates the "[reproduction of] fine decorative detail more accurately" (Bray 1979). Au-Cu alloys are harder than either metal alone, and whether this hardness is important to metallurgists making bells (who may want to finish shaping by hammering, as SR-XRD has illustrated for two Au-Cu bells) is uncertain (Figure 3b).

Diffraction patterns show the texture expected from cast, polycrystalline materials. Phases identified in B3 and B4 include auricupride ($AuCu_3$) and tentatively Pt (Figure 3b). At high concentrations of Au, $AuCu_3$ would not be expected. For the compositions of representative points on B3 and B4, the ternary Au-Ag-Cu diagram (Prince et al. 1990) indicates that only the disordered α-phase should be present at equilibrium at 300°C. However, $AuCu_3$ was identified only for a point whose detector-facing side is an interior surface of the bell that is potentially Cu-rich. While we did not expect to detect Pt as a pure phase in SR-XRD, we had identified Pt in variable concentrations on both bells by pXRF. Alternatively, pure Au is a strong candidate for the Pt-labeled phase if the bell was subjected to uniform compression, translating all of the Au peaks to lower d-spacings (B3: $\Delta\delta \approx$ -4.6%; B4: $\Delta\delta \approx$ -5.7%), although we recognize a similar observed effect could be achieved with a small change in sample-to-detector distance. The elongated diffraction spots seen in both bells' patterns suggest post-casting hammering, useful especially on the intricate zoomorphic finials. On B11, Cu and Cu_2O were consistently identified together by SR-XRD (Figure 3d). RBS analysis of two high-Au bells (B3, B4) shows no signs of enrichment in any element (Figure 3a). Oxidized edges for Cu, Ag, and Au were detected with both a He^{++} beam (≈2-3 μm penetration) and a H^+ beam (≥10 μm). The golden color of these bells is the result of alloy selection rather a distinct artificial surface enrichment.

Replication

Cockrell replicated bells through lost-wax casting at The Crucible in Oakland, CA. The goals were to: (1) acquire a multi-sensory perspective of the process of lost-wax casting; (2) consider the range of choices that a person engaging in this process may have made; and (3) identify material traces of the casting that may be irrecoverable or may go unnoticed archaeologically. The first bell was fabricated with an alloy of 80 wt% Cu and 20 wt% Sn and the second with an alloy of 98 wt% 80/20 Cu-Sn and 2 wt% Pb. In both cases, P was added as a deoxidizer.

While we recognize the inexact correspondences with ancient practices (e.g. alloy composition, bell diameter), we do not see them as inhibiting

limitations but embrace their potential to lead us to new questions. First, noting the ease with which wax can be re-melted and re-shaped, facilitating ready revision during the design process, how much time did metallurgists in Mesoamerica spend working with wax for each bell they made? Second, a patina of $Fe(NO_3)_3$ was applied to the bell's surface, generating a red-black color, and a clear wax sealant was applied to inhibit corrosion. Has pervasive Cu-based corrosion obfuscated the vestiges of intentionally applied, diversely colored patinas on Mesoamerican bells? Thirdly, certain tasks, such as the preparation of the core and the pour of molten metal, necessitated group involvement and, in the latter case, rehearsal with an empty crucible. How many Mesoamerican metallurgists worked simultaneously on an individual bell? Did they rehearse certain actions before fully undertaking them?

The Contributions of Metallurgical Communities

Through hierarchical cluster analyses with SPSS (squared Euclidean distance with average linkage then, separately, with Ward's linkage), we identified bell clusters in one analysis through eight features related to the bells' primary fabrications—zoomorphic design (presence (and form)), number of suspension loop strips, presence of clapper, presence of reinforced lip, and presence of Zn, As, Sn, or Pt as minor elements ($\geq$1 wt%)—and another analysis through three features related to the bells' secondary fabrications—striations linked to burnishing, presence of flattening, and presence of indentation. High-Cu bells and high-Au bells formed distinct clusters. Four high-Cu bells are anomalous, clustering with the high-Au bells. These four bells are the only high-Cu bells that lack As and/or Sn as a minor element (three are nearly pure Cu, and the fourth is Cu-Zn); and they are among only six high-Cu bells that lack reinforced lips. In fact, three of the four have nearly identical proportions of As K-α intensity to Cu K-α intensity (0.007) in pXRF analysis, and two of these three are spherical rather than pear-shaped. While we cannot necessarily determine correlations between, for instance, a particular As content and the lack of a reinforced lip, we can start to illuminate new clusters of features through SPSS. The analyses of features related to secondary fabrications show three high-Cu bells as anomalies in the high-Au cluster; they are related through the presence of flattening or indentation. Much like the inclusion of morphologically similar suspension loops and reinforced lips on high-Cu bells *and* high-Au bells shows the 'compositional inclusivity' of certain primary fabrication practices, the presence of flattening/indentation makes us wonder if a similar cross-compositional range of actions was applied after casting.

We identify a broad chronological spectrum for the development of the Cenote deposit. In the 'early' realm, the high-Au zoomorphic bells align with the "International Group" (ca. AD 400-900) of metals from Lower Central America (Cooke and Bray 1985). While these bells bear similar compositions to bells found in Oaxacan contexts, their designs differ, in that the latter are usually included in composite pendants and/or involve designs (e.g. pyriform, rows of false filigree spirals) nearly identical to their Cu-based counterparts from West

Mexico (Peñuelas 2008; Ruvalcaba Sil and Ortiz Díaz 1999). The Cenote high-Au zoomorphic bells align more closely in form to bells ascribed to Chiriquí and Veraguas metallurgists in the collections of the National Museum of the American Indian and the Metropolitan Museum of Art. As no artificial gilding was detected on the two high-Au bells studied with RBS, we cannot necessarily relate the high-Au bells to metallurgical practices of the Oaxaca Valley or Lower Central America and Colombia, where various methods of artificial gilding (including depletion and electrochemical replacement) were undertaken. It is possible that the high-Au bells were burnished, as suggested by their superficial striations, leading to a degree of dissolution of Cu and Ag from their surfaces that would not be detectable with RBS. Camacho-Bragado et al. (2005:24) have proposed that certain high-Au objects from Monte Albán's Tomb 7 (whose Mixtec influence dates between AD 1300 and 1524) were burnished once and were not subjected to a gilding process that would have finely segregated the metallic constituents.

If the separation suggested by Hosler (2009) into phases of unalloyed Cu metallurgy (AD 600-1200) and alloyed Cu metallurgy (AD 1040/1200-1521) in West Mexico was to be applied, we would place the three nearly pure-Cu bells (B17, B18, B20) in this first phase and the remaining high-Cu bells in this second phase. But this inference would deny the potential for anachronistic production of unalloyed bells in later periods and would ignore the possibility that the bells were fabricated outside of West Mexico. Indeed, many of the chronological indicators among the Cenote bells would date their original fabrications to late in the main occupation of Chichén or even after the site's main occupation (ending ca. AD 1050). Any correlation between the pear-shaped and spherical bells deposited at the Templo Mayor, Tenochtitlán and proposed by Schulze (2008) to be manufactured in the Valley of Mexico and those of the Cenote would situate these bells' fabrications in the 15th and 16th centuries. The three spherical high-Cu Cenote bells, all with single-strip suspension loops, may have been produced at Mayapán (AD 1050-1440), where archaeologists have recovered metallurgical ceramics, including a possible bell mold and crucibles containing bell production debris (Paris and Peraza Lope 2013; Meanwell et al. 2013). Approximately half of the Mayapán bells (n=306) are button-shaped, but one-fourth of them are spherical; nearly 90% of all have a suspension loop consisting of a single strip. Some of the high-Cu bells also may have been produced at Lamanai, where miscast bells along with casting 'reservoirs' and prills have been dated to AD 1350-1700 (Simmons *et al.* 2009). The presence of Zn as a minor element in a globular high-Cu bell (B15) is indicative of Colonial-period importation of European metal. Evidence of pre-Colonial Mesoamerican brass production is unknown. Certain needles and aglets from the Colonial-period Maya occupation of Tipu (AD 1544-1707) consist of brass (Cockrell et al. 2013).

In addition to technological styles, we must identify 'depositional styles,' the products of treatments by different communities that used and deposited the bells, a set of practices distinct from but intimately related to the objects' original fabrications, again following Lave and Wenger (1991). Among metals from funerary contexts in Veraguas, Lothrop (1950, 25) identified cast, high-Au

figurines that were crushed and bent, ultimately resembling some of the Cenote bells that were indented or flattened. Some depositional practices evinced on the metals extend to other Cenote materials, such as burning/heating (obsidian tubular beads (Sheets 1992, 174-175)) and cutting (wooden artifacts (Coggins 1992, 339)).

Ultimately, peoples must have brought metals to the Cenote through land (West and Central Mexico) or sea (Costa Rica-Panama) routes or a combination of both. We cannot ignore the possibility that the metals underwent successive re-fabrications at different locations between their places of original fabrication and the Cenote. Stemming from this and, fundamentally, from transport between these places, the temporal gap between the bells' fabrication and deposition may be significant. Perhaps the Zn-containing globular bell most vividly expresses this potential for transformation: the brass may have been imported from a European source and then melted and cast into a more familiar Mesoamerican form.

Conclusions

The Cenote deposit is an expression of inclusivity. A high-Au zoomorphic bell was an equally valid contribution as was a high-Cu false filigree bell. Acceptance to the community of depositional practice was achieved through gestures such as indenting, flattening, or burning or even the act of making sound. Following Hoffman (1999) that post-fabrication alterations are examples of "technological agency," we recognize that the depositional practitioners at the Cenote were themselves metallurgists, ceramicists, and lapidary workers performing re-fabrications of metals, pottery, and stone. The ambiguity of the indented and flattened bells, similar in appearance to the misshapen bells from Lamanai and Mayapán. labeled as evidence of recasting, makes us wonder: could production debris also have been a valid contribution to the Cenote deposit? Furthermore, could finished bells have been reshaped to mimic production debris and index the entire life history of the bell in preparation for its deposition? Similarly, the presence of slag in an offering in Templo Mayor's Stage 5 suggests a material-based ritualization of Mesoamerican metallurgy (Schulze 2008, 331). Above all, we recognize that analyses—particularly of compositionally heterogeneous objects—must yield complementary, not only supplementary, data. We want to expand our sample size, if only to apply the metric and qualitative studies to a wider range of bells, enhancing the representativeness of our inferences. We also intend to apply XRD and RBS to other high-Au bells to more broadly probe the relationships among superficial and internal composition. Following Hosler and Macfarlane (1996, 1819), lead isotope analysis of Cenote metals could be an important tool for further correlation of the objects with particular metallurgical communities.

HAMMERED OBJECTS

Like the conspicuous loops on the metal bells from the Cenote Sagrado at Chichén Itzá in Yucatán, Mexico, the presence of small circular and rectangular holes on metal sheet objects from the Cenote suggests that the metals were attached to other materials. The bells were suspended, swaying, and emitting sounds. The sheets were covering, concealing, and presenting lustrous surfaces. Occasionally, the materials to which some sheets were connected, such as yucca fiber and wood, have been preserved with the metal. Otherwise, we only can surmise the variety of colors and textures that would have become apparent to participants in and observers of Cenote depositional events through the physical juxtaposition of different materials.

Sheet objects are far less common than bells in Mesoamerican archaeological contexts. Nevertheless, a wide array of sheet metals was recovered from the Cenote. On initial inspection, given the diversity of forms and surface appearances of the sheet specimens and the fact that sheet was manufactured in several regions of Mesoamerica, we inferred that multiple metallurgical communities fabricated the sheet that was found.

After study of 148 Cenote metals in the Peabody Museum of Archaeology and Ethnology (PMAE), the Museo Palacio Cantón (MPC), and the Museo Nacional de Antropología (MNA), we present characterizations of 19 sheet objects, including six sandals, two-axe monies, and ten objects that escape easy formal categorization, spanning all three museum collections. Two additional objects that are not sheet per se but were primarily hammered are presented at the end as important diagnostic objects. Seventeen of the 21 are *tumbaga* (typically Au-Cu but some have substantial Ag content). The four other objects discussed are Cu-based alloys. Native or smelted metal would have been hammered and then chiseled with metal or stone to achieve an appropriate size for the sheet object, then hammered and potentially annealed to thickness and shape. Embossing on four objects would have been undertaken with metal, stone, and/or bone tools; the minimal depth of the embossed designs suggests to a modern smith that a pitch-like foundation was not employed (B Heras 2013, pers. comm., 18 November). In this paper, we intend to draw attention to an overlooked class of metal—sheet—that circulated in Mesoamerica and evaluate materials whose 'function' is not immediately obvious. Following our approach to the Cenote bells, we aim to: (1) develop biographies of individual objects, drawing on multiple threads of data; (2) identify particular technological styles (Lechtman 1984) within the assemblage based on the patterning across these object biographies; and (3) evaluate the metallurgical communities of practice (Lave and Wenger 1991) that these technological styles index through comparison with data gleaned from published metal corpora (Figure 4).

Provenance and Chronology

The Cenote Sagrado is a water-filled limestone sinkhole at Chichén Itzá, a major Maya political center from the 8th c. to the 11th c. AD (further context in Bells paper). Two primary projects in the 20th century recovered metals along with jade, ceramics, and various organic materials: Edward Thompson's dredging and diving project from 1904 to 1911, from which objects were sent to the PMAE and later to the MNA as part of

exchanges, and INAH's use of a pressurized airlift and divers in 1960-1961 and 1967-1968, from which objects were sent to the MPC. Both projects struggled with preservation of stratigraphy. The lack of metallurgical debris at Chichén and of ore and native metal in Yucatán suggest that the metal objects were imported to the Cenote. Indicative of the insufficient documentation in Thompson's project is the identification of artifacts in the debris pile left by earlier excavators (Cirerol Sansores 1940). These artifacts included "fragments of pure gold—rolled and stamped" (our translation). To achieve limited stratigraphic control, Piña Chán (1970:38) excavated the Cenote in quadrants and identified sheet metal (Au-rich sheet and sandals) only in quadrant 3, where he also recovered rings and Au-rich bells. Ceramics from the Cenote date to AD 800 to 1550 (Ball 1992). In their chronologies, Coggins and Shane (1984) propose that sheet metal was deposited between the mid-8th century and the mid-12th century AD and that, later, objects covered with "gold foil" were deposited from the mid-13th century AD to the Spanish arrival, while Piña Chán (1970:56) includes metal sandals in an early depositional phase. We agree with these authors' proposal of successive depositions but seek to refine the chronological details.

Conservation

The objects' post-recovery treatments are discussed more widely in the Bells section. Marks left by brushes are evident on one sandal. At least two PMAE sandals were cleaned with acetone. The conservator noted that, even with delicate application of the solvent, the "thin patina and charred areas" were affected on one sandal; an attempt was made to "even" the surface, but ultimately it became difficult to discern what was an "original discoloration" and what was "degraded lacquer." After localized application of acetone, the entire sandal was degreased with acetone, and on both sandals, the museum accession number was applied. For the other sandal accession number, it is noted that this number was written in ink on a barrier layer of Acryloid B-72. Other PMAE sheets were typically degreased with acetone, but it was not always were surface deposits fully removed. Oxidation on sheet masks was removed through reduction with a solution of Zn + 15% NaOH. Accession numbers were typically applied in India ink on Acryloid. We are uncertain of any treatments applied to the MPC and MNA sheet metals. Three sheets presented here (L9, L11, L12) were conserved. The conservation of L9 occurred at ENCRyM in 2004. This object is especially fragile and is supported by a piece of plastic cut in the amorphous shape of the sheet.

Prior Analysis

As he did with bells, Root analyzed Cenote sheet objects as early as 1927. He employed both gravimetry and Feré quartz spectrography. The locations of invasive analysis are far less noticeable on the sheet objects than they are on bells. Root analyzed at least five sandals, two of which can be correlated with sandals presented here. For sandal S1, there is a major discrepancy between the Ag concentration determined by Root and that identified in the present study and, for sandal S2, there is a potentially more minor discrepancy between the Au concentrations (Figure 5c).

Franco Velázquez and de Grinberg (2002) studied six Cenote bells, but not sheet objects, through visual inspection, ED-XRF, and AAS.

Contreras *et al.* (2007) analyzed nine Cenote specimens, all sheet objects, including sandals, earflares, and axes. Comparing results of ED-XRF, SEM and PIXE-RBS analysis for two sheet specimens—a sandal and an earflare—they concluded that both Au enrichment and that the thickness of this enriched layer (0.4-0.5 μm on the sandal and 0.3-0.4 μm on the earflare) indicated that electrochemical replacement gilding was employed.

Methods

Detailed discussion of the current methodology is presented in the Bells section. All sheet objects were studied with the same fundamental approaches: visual inspection with a magnifying glass, measurements with calipers, study with an optical microscope (visible-UV-IR), and bulk compositional analysis with portable ED-XRF spectrometry. Among the finer resolution analyses, four sheets (L2, L3, S2, and S3) were analyzed with RBS and SR-XRD, while the same four except L3 were evaluated with SR-XRF.

Typology

Sheet objects receive little attention in published typologies of Mesoamerican metals. Bray (1977) states that the sandal form is unique to the Cenote Sagrado context. The identification of six objects as sandals is aided by the preservation of a presumed ankle strap attached to one sandal (S1), joined to the sole by the tab-and-slot method. Owing to the recovery of textiles with shapes nearly identical to those of the metallic sandals, it is assumed that the sandals were actually composite textile and metal objects. On at least one of the studied sandals (S4), textile impressions are preserved. Many of the more ambiguous sheet objects, similar to others from the Cenote, may have been attached to wooden substrates. Bray cites the existence of "sheet metal strip, foil, overlay or sheathing," potential analogs to some of these Cenote sheets, at the sites of Mayapán, Zuuk, Nebaj, Chipal, Zaculeu, Guaytan/S. Agustin Acasaguastlan as high-Au forms and at the sites of Mayapán, El Cedral, Lamanai, and Tajumulco as high-Cu forms. He also identifies "diadems" from Iximché, "plumes" and "panaches" from the Cenote Sagrado, and "belts" and "bracelets," both of which he only specifically ascribes to the Cenote but which he then labels as "widespread" in their distribution. Pendergast (1962) and Hosler (1988) presented typologies of sheet objects, but, in most cases, the forms do not appear in the excavated Cenote assemblage. The exceptions are the axe-monies mentioned but not illustrated in Hosler (1988); these objects are presented in greater focus in Hosler et al. (1990). Two Cenote sheet specimens (L11 and L12) display formal similarities to Type 1a of axe-monies, fabricated in West Mexico (Guerrero and Michoacán) and Oaxaca (Figure 4e).

Metrics

Thickness was measured at between two and four points on individual sheet objects, except one case (Figure 4h). When thickness was below the detection limit of the

calipers (0.01 mm), the measurement was recorded as <0.01 mm, and, for the purpose of calculations, it was treated as 0.01 mm.

The average thickness of the high-Au objects (n=8) is 0.11 mm (1σ=0.12 mm, c_v=1.11), that of the high-Cu objects (n=8) is 0.24 mm (1σ=0.10 mm, c_v=0.44), and that of the other objects (n=4) is 0.08 mm (1σ=0.11 mm, c_v=1.39). Recognizing the high standard deviations for the thicknesses of the high-Au and intermediate sheets, their lower average thickness, compared to the high-Cu sheets, is conspicuous. The non-sheet objects U2 and U3 are significantly thicker: their bridges are, on average, 0.44 mm thick, while their spirals are 0.67 mm thick.

Five of the six sandals have an average maximum length of 144.20 mm (1σ=18.26 mm, c_v=0.13) and an average minimum width of 66.60 mm (1σ=7.72 mm, c_v=0.12). The sixth sandal is an outlier: its maximum length and width are less than half of those of the other sandals. Potentially smiths designed it for an infant to wear and the others for adolescents and adults. Besides similarities in shape, the two object pairs (axe-monies L11 and L12; hollow tubes L13 and L14) each show striking similarity in their maximum lengths and widths.

SUPERFICIAL FEATURES

In our characterizations, the features that follow may represent: (1) a "technological decision" of the metalsmith(s); (2) a "consequence of fabrication" that the smith(s) did not intend; (3) a "secondary alteration" that developed after fabrication; or (4) an "ambiguous feature" that arose in fabrication and/or post-fabrication (Figure 4g).

Technological decisions. All six sandals and six ambiguous sheets display **punched holes** presumably designed for threading, to facilitate attachment to another material and/or to enable suspension of the metal. The holes' symmetry and their occurrence in areas that do not show obvious stress suggest intentional design. The holes are always found at the sheet's edges and are carefully aligned with each other. They are circular except in the case of sandal S1, which displays rectangular holes, and sandal S2, which has rectangular and elliptical holes. One circular hole on sandal S4 may have been dramatically deformed in subsequent hammering, use, deposition, or post-recovery handling. On all sheets, except one, the holes have been punched from the same side, identified by the direction of the metal at the holes (curving inward or outward).

Five ambiguous sheets were **embossed**, creating a geometric design in low relief. On three (L5, L9, and L15), the design was applied on one side, but, on the other two (L1 and L2), there are raised and depressed areas of the design on a single side, indicating chasing *and* repoussé were performed. The instruments applied to make embossed circles are distinctive: one sheet (L1) was embossed with a double-pronged tool, another with a single-pronged tool (L5), and another with a single-pronged but beveled tool (L15). Occasionally, the relief is not entirely symmetric but deformed, suggesting that insufficient pressure was applied to that point during the original embossing.

One sandal (S1) and five ambiguous sheets (L2, L3, L4, L13, and L14) have an **incised guideline** near their edge that would have been used as a guide for the metalsmith to follow while cutting the sheet. This guideline is never preserved for the entire perimeter of the object, suggesting that, for the most part, smiths carefully followed it, thereby leaving only 'clean' metal in their wake.

Consequences of primary fabrication. Some superficial features may be unintentional products of fabrication. One such feature is **porosity**, small depressions that developed through the trapping of gas molecules as the metal cooled after melting or annealing. Porosity is highly localized on one sheet (L5) but more widely distributed on five sandals (S1, S3, S4, S5, and S6).

Extraneous metal is present on two objects as a tab at an edge (L2, S5), or on three as a fine superficial addition (L1, L3, L16). These tabs and additions could have resulted from imprecise cutting or may represent vestiges of metal attachments that have not preserved, such as ankle attachments to sandals. **Ridges** are present on the edges of the two axe-monies and of four ambiguous sheets. These features developed from hammering the interior regions of the sheets; as these regions thinned, metal spread to edges, thickening them. One ridge developed differently; it represents the metal that was displaced when a cutting tool (whose impressions are preserved) was applied to the other side's edge, forming a depression and causing metal to curl over the edge.

Examination of **cut edges** suggests that varied cutting tools and/or cutting intensities were applied to different objects. Relative assignments of "smooth," "rough," and "very rough" edges were given to each object. Six objects were consistently "smooth" (including L12) while one sandal (S4) showed "very rough" edges. Interestingly, different edge areas of individual objects (S5, S6, L9, L11) had regions of varying degrees of roughness. This variation may be attributed to preservation or to a decision to cut the object at a later time, applying a cutting tool or intensity different from that originally applied. Tubes L13 and L14, which display smooth edges on their long sides but rough edges on their short sides, may have been cut and rolled and then, at a later time, cut in a different fashion.

Secondary alteration. **Torn edges** are evident on one sandal (S3), both axe-monies, and five ambiguous sheets (L2, L3, L6, L13, and L14). Intentionality in tearing is suggested by the regularity of tears on the sandal and the depth of the tears on one of the other sheets. Tearing may have occurred when the object was removed from the material with which it was juxtaposed. The less frequent and less conspicuous tears on other sheets may have developed during their original outlining by cutting, if the metal was especially thin.

Two sandals, one axe-money (L11), and seven ambiguous sheets have **curled edges.** These features could have emerged in the application/removal of the object to/from its substrate. Their presence suggests that the metal overlapped the substrate and perhaps light hammering or burnishing was performed in these curled regions to secure the materials' attachment.

Indentations, isolated and amorphous, appear on two sheets (L6 and L13), neither of which is embossed. These features are reminiscent of depressions on cast high-Au bells.

Ambiguous features. Seven ambiguous sheets (L2, L4, L6, L9, L13, L14, L15) and one axe-money (L12) have **wrinkles** on their surfaces. These features may be byproducts of hammering and/or embossing, but more likely developed if the sheet was crumpled after fabrication. Conservators unraveled wrinkled balls of metal in order to study their interiors, potentially adding wrinkles to the sheet in the process of unraveling it (D Piechota 2012, pers. comm., 2 May). Two ambiguous sheets have thin parallel **creases** that extend across their long side (three creases on L3 and two creases on L4),

and one sandal (S3) has a single crease parallel to its short side. The metal may have been rolled at one time and then flattened before deposition or after recovery.

Two sandals (S4 and S6) display **cracking,** which developed during thinning of the metal, in use, induced by the pressure of the foot, in the deposit as the metal was compacted by other materials, and/or in cleaning and conservation. One sheet showed cracking that coincided with a circular design element and would have arisen during the embossing process. Three ambiguous sheets (L4, L9, and L13) and the two axe-monies display **voids**, which are asymmetric and located adjacent to areas of stress, such as wrinkles. The voids emerged during hammering of the metal or when the metal was being wrinkled or unwrinkled

All six sandals, the two axe-monies, and six ambiguous sheets (L1, L4, L5, L13, L14, and L16) show **incisions** or **striations.** These depressions are isolated or clustered. Unlike the preparatory lines, these lines are not parallel to cut edges *and* localized at edges. While the vastness of some striation clusters may be associated with fundamental hammering of the metal, with the lines following the direction of working, others have developed in the process of embossing geometric designs. The dense cluster of deep incisions on one sandal's ankle strap itself may have served as a 'guideline', potentially made on the sheet before it was cut as a way to approximate the area required for the strap.

Three sandals, the two axe-monies, and ten ambiguous sheets (L1-L6 and L13-L16) display **localized discoloration.** Some are fine green circular discolorations that may have arisen in post-excavation cleaning; Thompson noted this discoloration as a possible consequence of a nitric acid solution applied to one unidentified Cenote metal. Other discolorations—pink, orange, and black on the Au-Cu specimens and a friable grey-white on the Cu-based specimens—are likely products of corrosion.

Composition, Distribution, and Enrichment

Mindful of its limitations, we drew on p-ED-XRF data in a limited quantitative extent to form broad compositional groups (Figure 5). Among the *tumbaga* sheet, there are clusters of high-Au (90+ wt%) (n=7) and high-Cu (85+ wt%) (n=6) objects (Figure 5a). Following Scott (1983 SiC), all eight of the high-Au sheets have Cu content (approx. ≤5 wt%) that could have arisen as a natural impurity of the Au source. Sandals fall in the high-Cu cluster, but one (S6) shows highly variable composition across the Au-Cu spectrum across multiple points. Unlike the *tumbaga* bells, whose Ag content never exceeded 5.5 wt%, three *tumbaga* sheets have notably higher Ag content, 8.4 wt% (L15), 25.2 wt% (L6), and 25.5 wt% (L5) (in the Au-Ag-Cu normalization), but these values fall within the range of naturally-occurring Ag (5-45 wt%) in native Au (Scott 1983 SiC). Among other elements, Fe (n=17), Zn (n=at least 9), Pt (n=at least 7), and Bi (n=at least 6) were frequently present. Fe is prominent particularly in L2, where it is more concentrated in reddish areas. Sn is present at significant trace concentrations in L5 and L6. The seven high-Au objects are not ideal for hardening because their compositions fall in the single-phase solid-solution region of the Au-Ag-Cu phase diagram (ASM Handbook 1990: 705-706). Indeed, the three most heavily embossed sheets (L5, L9, and L15) have significantly lower Au concentrations. The significantly higher Ag content of the two rolled tubes increases their hardness, drawing the ternary alloy into the two-phase

region. The two axe-shaped sheets are primarily Cu with trace As (0.3 wt% in one case and 0.5 wt% in the other) (Figure 5b). As yields a noticeable enhancement in the strength and hardness of Cu starting at concentrations of 0.5 wt%; its concentrations in these two objects fall in the range of low-As Cu-As alloy (approx. 0.1-0.5 wt%) (Hosler et al. 1990, n. 2).

SR-XRF revealed the potential for compositional heterogeneity in sheet objects that was less evident using solely p-ED-XRF (Figure 6). The distribution of Au is consistent across the surface of sheet L2, but Fe and Cu are concentrated at the center and depleted at the edges (Figure 6i). These latter elements were gradually oxidized and peeled away from the metal through annealing and subsequent cleaning, especially if such cycles of hammering and annealing were concentrated at the object's edges, where embossed designs feature. Sandal S2 was subjected to a surface-wide SR-XRF scan (Figure 6c). While Cu is relatively consistent across the sandal surface, Ag and Au are more concentrated along the edges. The difference between Au's concentration at edges and at the center is dramatic. Where Ag and Au are prevalent at the edges, Cu is depleted. In more localized scanning of sandal S3, the concentrations of Cu and Ag tended to be on the middle-to-high range for each element, while the concentrations of Au tended to be on the low end of its range.

Diffraction patterns recorded for four of the sheet objects (L2, L3, S2, and S3) are consistent with fabrication by hammering, given the presence of fine, continuous rings (Figures 6d.1, 6d.2, 6f.1, 6f.2, 6g.1, 6g.2). As anticipated for high-Au objects L2 and L3 and high-Cu objects S2 and S3, the phases identified for each object pair are pure Au and pure Cu, respectively. Comparing diffraction patterns from edge and more interior points on L2, we noted increasing texture, indicating the presence of larger grains near the object's center. This difference in grain size correlates with the fact that the edges are embossed while the center of the object is not. Mapping the diffracting X-ray beam's transmission revealed thinner metal in embossed regions than in non-embossed regions. RBS revealed enrichment in Ag and Au on sandals S2 and S3 (Figures 6b.1 and 6b.2). While all phases that emerged in diffraction experiments were indexed as pure Cu for both sandals, we propose that Ag and Au are not internal to the sandals' bulk metal.

Using SIMNRA, we simulated superficial enriched layers each of whose thicknesses is 0.7 μm. These thicknesses fall within the 0.5-2 μm enriched layer thickness that Lechtman et al. (1982) attribute to electrochemical replacement gilding, where Au (and Ag) from an external source is/are deposited onto a substrate whose pitted surface serves an anodic role. Although those authors observed gilding that covers entire surfaces of archaeological objects, the substantial corrosion on the sandals and our inability to remove samples for metallography impeded any determination of the precise consistency of the enriched layers across the sandals. We did recognize, however, in our SR-XRF scan of sandal S2, a major discrepancy between the concentration of Au at the sandal's edges and that at its center, which was less true of Ag. In gilding, the Au and Ag were likely deposited together, so we assume that the variance in Au concentration across the surface was not developed at this stage. While the cause of depletion is more likely natural corrosion, following the observation of Scott (1983a) of a black powder containing Au in Cu_2O and potentially AgCl on gilded *tumbaga* objects, we should consider that people wearing and/or carrying these sandals may have witnessed these

corrosion-induced transformations in color and luster and not render them 'invisible' by treating corrosion as solely a depositional phenomenon.

On the high-Au sheet objects L2 and L3, we detected superficial Au-based mineralization and, on L2, we encountered Cu-based mineralization with RBS. These features are again consistent with the findings of Scott (1983a) that Au may be particularly subject to corrosion through interaction with certain plants and microorganisms, especially in marine environments, and that, in *tumbaga* objects, Cu-containing (anodic) constituents are prone to corrosion, though more likely in the presence of superficial enrichment in Au/Ag, due to the drastic differences in electrochemical potential among Cu, Ag, and Au.

Replication

To become more cognizant of the technological decision-making that may not be archaeologically recoverable, experimental sheet fabrication was undertaken. A 20-gauge ($\approx$0.8 mm thick) pure-Cu sheet was hammered to achieve the geometric design evident on a particular embossed sheet from the Cenote. While the experimental sheet was compositionally different from the Au-rich Cenote sheet whose design we replicated and was hammered over pitch, when the Cenote sheet may not have been supported, the smithing experience generated new questions. First, while we detected preparatory lines on particular Cenote sheets, what was the extent of preparation for cutting and design implementation that Mesoamerican metalsmiths employed? In experiments, we inked our design with marker and then, aware it would dissolve in later cleaning, we stippled the design with a steel punch (struck by a hammer) to provide a more permanent map. As we smoothed the initial stippling with continued hammering, we wondered the extent to which the guidelines used by ancient smiths were preserved or were subsumed into the design in the hammering process. Second, while annealing may have been undertaken by ancient smiths to soften metal for further hammering, to what degree did they anneal the sheet and clean its surface of oxidation products? Applying a propane-oxygen torch, we looked for color changes on the sheet (entirely dark red) as an indication of sufficient annealing. We quenched the sheet and cleaned the surface of oxidation first in a pickling solution and then under cold water, scrubbing with pumice powder. Did Mesoamerican smiths clean the sheet in a similar fashion, leaving little to no traces of superficial oxidation? Finally, what methods did they employ to counteract their own fatigue? The steel tools we used were wrapped with cushions to support our tiring hands, and we were vigilant of posture as well as space for our legs and feet to rest while we were sitting and hammering.

The Contributions of Metallurgical Communities

Diagnostic features. The lack of metallurgical evidence related to sheet production in Mesoamerica and Lower Central America impedes our ability to place a chronological and geographical frame on the fabrication of the Cenote sheet. The paucity of detail about sheet finds, including qualitative characterizations of attributes like the degree of wrinkling of the sheet or the roughness of its cut edges, poses an additional challenge. However, by identifying patterning across the sheet assemblage and

28

comparing these patterns to known metallurgical traditions, we can begin to evaluate the contributions of different metallurgical communities to the Cenote deposit.

Hierarchical cluster analyses with SPSS (squared Euclidean distance with average linkage then, separately, with Ward's linkage) offered one organization of the sheet assemblage: clusters of sheet objects were determined by one analysis through five features related to the sheets' primary fabrications—elemental composition (high-Cu, high-Cu, or intermediate), relative roughness of cut edges, presence of embossing, presence of guidelines, and presence of suspension/attachment holes—and a separate analysis through five features related to the sheets' secondary fabrications—the presence of: creases, curled edges, indentation, torn edges, or wrinkling (Figure 4i.1 and 4i.2). In the analyses of primary fabrication features, formal groups—axe-monies, sandals, tubes—were maintained at the least, second least, or third least distance with the exception of one sandal, which clustered with the tubes and two other sheets (L3, L4) through the presence of guidelines. Heavily embossed sheets L9 and L15 were tightly clustered, having identical values for four of five variables in the primary *and* secondary fabrication analyses. In the latter, formal groups were less coherent. For instance, high-Cu sandal S3, anomalous among sandals for the presence of creases and tearing, clustered tightly with high-Au sheet L3. As with the bells, we must consider the cross-compositional fabrication and re-fabrication practices among the sheet objects.

Of special note are two hammered, non-sheet objects from the Cenote, which we originally assumed were fragments of anthropomorphic figurines given the similarity of their spiral design elements to those incorporated in the headdresses of certain Cenote figurines (Figure 4f.1). These specimens are actually fragments of spiral tweezers, separated from their blades (Figure 4f.2). Like those that Hosler (1994) studied, the thickness of the spirals is greater than that of the bridge between them, and the width of the bridge is lower closer to the blade (or the blade's presumed location). This latter observation is consistent with the fact that, in fabrication, the metal for the spirals is taken from the blades' metal; indeed, these tweezers are fabricated from one strip of metal. On the other hand, the length of each spiral if it was unwound is nearly half of the length Hosler measured and the compositions of the two corpora are different. Both contain trace As, but, in addition to lower Sn content (1-2 wt% in the Cenote tweezers compared to ≈10 wt% in Hosler's), the Cenote tweezers also contain Zn (2.8 and 4.0 wt%). If ancient metallurgists sought to enhance working properties, the addition of Sn (at concentrations evident in both corpora) improves the metal's springiness, formability, and fatigue resistance; the addition of Zn to Cu would enhance its strength and springiness, and the inclusion of Sn or As with Cu-Zn would inhibit dezincification (Davis 2001: 64-65). These unique objects offer geographical and temporal constraints to the fabrications of the deposited metals. Hosler (1994) ascribes their fabrication solely to Tarascan metallurgists, who worked in the centuries before the Spanish arrival in Mesoamerica. Furthermore, there is no evidence of brass fabrication in Mesoamerica before the arrival of Europeans (Martinón-Torres et al. 2007). Thus, we propose that the tweezers were fabricated in West Mexico as early as the 16th century using a design method that originated in the centuries just before. This low-Zn (and low-Sn) brass would have been more pink than yellow, a contrast to the yellowish spiral tweezers depicted as ornaments worn by priests in the *Relación de Michoacán*, a document written between AD 1539 and 1541 by Friar Jerónimo de Alcalá.

The two axe-monies from the Cenote also were fabricated in West Mexico but at an earlier time, likely after AD 1040, when alloy-based metallurgical practices emerge in the region (Hosler 2009). In form, they are identical to Type 1a in Hosler et al. 1990, a type found in Guerrero, Michoacán, and Oaxaca, but their length is more similar to the lengths of those from Guerrero and Michoacán. Their concentrations of As fall toward the low end of the wide range (0.05 – 6.35 wt%) of As in the West Mexican and Oaxacan Type 1a axe-monies. One of the two shows a corrugated surface, also observed on the published Type 1a axe-monies, a feature that may lend strength to the very thin sheet; raised edges were seen on both, and Hosler et al. (1990) propose that this feature is more common on analogous Ecuadorian axe-monies than on those from Mesoamerica. We noted massive internal voids on both Cenote axe-monies; each void is near the sheet's horizontal axis and closer to its shorter end; a similarly located but less dramatically sized void is seen in a photographed Type 1a axe-money from Guerrero (Hosler et al. 1990: Fig. 6). Could smiths have intentionally created these voids, now exacerbated, in order to thread the axe-monies together, following the surface collection of a stack of 13 Type 1a axe-monies by Weitlaner (reported in Hosler et al. 1990)?

The two rolled tubes (L13 and L14) may be blanks from which other sheet objects, such as beads, were cut, following the hypotheses of Stone and Balser (1958) and Harrison et al. (2010) for assemblages from Panama (Figure 4d). The raised lines adjacent to one open end of each tube served as guides to smiths as they cut metal for the beads. The two parallel creases on flat sheet L3 suggest that it was once a rolled tube (Figure 4a). 'Rolling' L3, we would achieve a circumference of 41.67 mm (its maximum width), while the circumferences of tubes L13 and L14 (underestimated due to overlapping metal in each roll) are 38.87 mm and 38.06 mm, respectively. This similarity, taken with the guideline along one short end of the flat sheet L3, lead us to propose that this sheet was similarly used as a blank for cutting beads or other objects. However, the five Cenote beads that were studied were not hammered, but cast. The tubes are similar in form to objects from Sitio Conte, Panama in the Museum of Fine Arts, Boston labeled as "tubular sheathings," "tubular beads," and "earflare rods"; Grave 74 (ca. AD 900-950) at Sitio Conte contained abundant ear rods (Cooke et al. 2000). The MFA sheathings, beads, and rods are golden and hollow, have two open ends in most cases, occasionally show ridges or guidelines at their open ends that evince cutting, and, most interestingly, show indentations. The presence of these indentations on the tubular beads (shorter in length) and the longer tubes from which the beads were cut implies that indentations were made on the longer tubes and then the beads were cut, or that they were applied post-cutting to blanks and beads alike. We propose that these three sheets (L3, L13, and L14) were fabricated by the metallurgists whose work also has been recovered from Sitio Conte. The presence of cast beads in the Cenote, similar in design and composition to beads from Oaxaca (Camacho-Bragado et al. 2005) reveals that two bead-making traditions are indexed at this unique deposit.

The Cenote sandals lack formal analogues from other regions of the Americas. The enrichment thicknesses on two are consistent with electrochemical replacement gilding, evinced on sheet metals from the Moche site of Loma Negra in Peru (Lechtman et al. 1982, Schorsch et al. 1996). The account of Bernal Díaz del Castillo (1955) of the 16th century Spanish presence in Mexico mentions that provincial leaders from the Río Grijalva (in modern Tabasco) brought "two soles of gold" as tribute (Chapter XXVI) and

that the Mexica leader Montezuma II wore "soles of gold and very precious stonework on top of them" (Chapter LXXXVIII) (our translations). While we cannot assume that golden sandals were necessarily fabricated in the Río Grijalva region, we can propose that sandals, incorporating a technology in use in the Andes in the early-to-mid first millennium A.D. (Lechtman et al. 1982), may have reached the Cenote directly or indirectly by means of the Mexica tributary system. We wonder whether the wider distribution of Ag relative to Au on one sandal's surface (evinced through SR-XRF) could nuance Díaz del Castillo's characterizations of the sandals as "of gold." Turning to other diagnostic features, Au-Pt alloys are characteristic of Tolita-Tumaco metal sheet fabrication (Scott 2011), But, Pt concentrations in such objects far exceed those in the Cenote sheets, where Pt is present between 0.8 and 1.7 wt% (in six objects). As Bray (1974:39) proposes, such concentrations suggest the Pt was an impurity in the Au source. Yet, Ag concentrations could serve as diagnostic tools. The high Ag content ($\approx$25 wt%) of two otherwise dissimilar sheets (L5 and L6) may indicate a shared Au source; compositional data on native Au sources (following Fernández and Quintanilla 2003) is needed.

Stone and Balser (1958) documented "punctate" designs (embossed circles) on sheet objects that they connect (whether they imply the objects' place of production or place of deposition is ambiguous) to metal corpora from the Sinú region (in Colombia) and the Diquís region (in Costa Rica). One object they photographed bears similarities to sheets L5 and L15 in its rectangular shape and embossed design. Considering the SPSS results, L9 also should be grouped with L5 and L15. All three may be parts of larger metal sheets and/or products of experiments with punching tools, particularly L9, which, much like a paper filled with a child's experimental signatures, is covered with varied embossed designs in different orientations.

Hammering in three dimensions. The Cenote sheet objects are not always flat and two-dimensional. Three were rolled (or once rolled) to form tubes. Four other sheets display some degree of concavity, and sandals, considering the preservation of an ankle strap with one sole, were also conceived in three dimensions. Similarly, secondary design practices, such as embossing and hole-forming, gave depth to the sheet. The attachment of metal to a substrate, such as sandal soles to *yucca* fiber, and the practice of superficial enrichment in Au and Ag were other methods by which metal crafters played with layering. Analysis with p-ED-XRF revealed the presence of Cu on three *yucca* sandal attachments (J Jungels 2013, pers. comm., 5 December). Specifically we wonder about the sandals' visual effect: their surface luster must have been partially concealed, in one part by the *yucca* support and in another by the wearer's foot, but still conspicuous enough for Díaz del Castillo to emphasize their gleam.

Crafting parts of wholes. Inherent to the sheets' fabrication is the act of removing a part from a whole through cutting. But, further partitioning of the sheet is apparent in the studied assemblage. The two tubes may have acted as wholes from which parts (hammered beads), whose whereabouts are unknown, were created. Two embossed sheets, whose geometric designs run to the sheets' very edges, may be parts of larger sheets that were sectioned after embossing. Each of these 'cuts' is an act of renovation, in which the designer(s) became newly aware of the metal's plastic properties.

Learning to smith. Besides the two aforementioned sheets whose extensive embossing suggests experimentation with punching, the asymmetry of embossed circles

on one sheet or the shallowness of certain circles compared to others indicates that the designer(s) were exploring the consequences of different degrees of force with one punch or of different tools altogether. On certain sheets, the presence of guidelines for cutting reveals the stepwise character of the fabrication process. Franciscan friar Bernardino de Sahagún's *Florentine Codex* (1577) mentions that featherworkers traced lines into metal sheet that was to be cut. Whether featherworkers made the guidelines on the Cenote sheets, we recognize that, like our experimental smithing illustrated, mapping the design is a crucial first step in smithing. The preservation of these depressions on the archaeological sheets could suggest carelessness, or it could reflect an intentional decision to maintain a signature of labor.

Conclusions

The assemblage of primarily hammered (mostly sheet) metals shows evidence of original fabrication in the Gran Coclé region (in modern Panama), dating to before AD 950, and in Guerrero and Michoacán (in West Mexico) after AD 1040. Sandals may have been fabricated and distributed through the Mexica tributary system into the 16th century AD. Axe-monies, following a Tarascan design, were fabricated after Spanish arrival, given their brass composition. The difference between the objects' fabrication dates and deposition dates may be dramatic and, in that time, they were re-fabricated, whether by indenting, wrinkling, cutting to form beads, or tearing and separating the metal from its substrate. Thus, hammered metal was deposited at the Cenote Sagrado in the centuries after the main occupation of Chichén Itzá (8th – 11th c. AD). Like the bells, the hammered objects show formal similarities that metallurgists achieved through diverse approaches: many have suspension holes, but the holes' shape is varied; many display embossed circular patterns, but the punches used for these designs are not identical; most are *tumbaga*, but Ag concentrations may be drastically different among objects. The Cenote Sagrado became an inclusive ritualized deposition, where hammered metals with analogous features that evinced diverse technological styles were welcome contributions. Post-fabrication alteration of the metals allowed a wider community to participate in the practice of metalsmithing.

Characterization of a wider range of embossed Cenote sheets would be useful to further identify similarities and differences in punches. Further application of RBS and SR-XRD to sheets would be fruitful to investigate whether other sandals *and* other object forms received artificial enrichments. Recognizing that metallographic examination typically requires invasive sampling, we would consider, with clean surfaces, an analysis such as SEM-EBSD as a possible substitute for metallography. This study could then facilitate comparison with assemblages for which metallography has been undertaken, such as foils from Monte Albán, which were cold-worked but lacked signs of a final anneal (Camacho-Bragado et al. 2005:23-24). Although this practice alone may not be uniquely indexical of Mixtec metallurgists, smithing techniques could be one of multiple diagnostics of metallurgical communities.

FIGURINES

As a conduit to the underworld, the Cenote Sagrado was populated with living, or once living, creatures, evinced through the recovery of human and animal skeletal remains, botanical remains, and, the focus of the present paper, anthropomorphic and zoomorphic metal figurines. Through their deposition in the Cenote waters, these materials gained new life, entering this liminal space between the terrestrial world and the underworld. The metallic material of which the figurines consisted was continuously re-animated through casting, hammering to shape, and indenting, before being sent to the underworld (and then later excavated, curated, and conserved).

This paper presents the analysis of 16 figurine specimens in complete or fragmented form (Figure 7). Twelve are identified as anthropomorphic in design and two as zoomorphic, while two cannot be readily deciphered as anthropomorphic or zoomorphic. Many of the bell specimens evaluated in an earlier paper contain anthropomorphic and/or zoomorphic designs, usually present atop the resonator or comprising the entire bell. In two other cases, high-Cu bells were designed in the form of canine heads. All specimens presented here were lost-wax cast and primarily consist of Au, Ag, and Cu, a metal often referred to as *tumbaga*. While several show an ambiguous form and display soil and/or corrosion-covered surfaces, which may impede ready analysis, we believe their study can still offer information about technological practices and facilitate a more comprehensive understanding of the material world of the Cenote waters.

Identical to our approach to the Cenote bells and hammered specimens, we have: (1) created biographies of the figurines that encompass not only their fabrications, but also their post-fabrication and even post-recovery lives; (2) compared object biographies to determine the technological styles (Lechtman 1984) present within the assemblage; and (3) evaluate these styles in light of published data to consider the metallurgical communities of practice (Lave and Wenger 1991) that the specimens index.

Provenance and Chronology

The Cenote Sagrado is a water-filled limestone sinkhole at Chichén Itzá, a major Maya political center from the 8th c. to the 11th c. AD (further context in Bells paper). Two primary projects in the 20th century recovered metals along with jade, ceramics, and various organic materials: Edward Thompson's dredging and diving project from 1904 to 1911, from which objects were sent to the PMAE and later to the MNA as part of exchanges, and INAH's use of a pressurized airlift and divers in 1960-1961 and 1967-1968, from which objects were sent to the MPC. Both projects struggled with preservation of stratigraphy. The lack of metallurgical debris at Chichén and of ore and native metal in Yucatán suggest that the metal objects were imported to the Cenote. Thompson's notes in the PMAE Archives do not mention metallic figurine finds. The 1961 project report by Salazar Ortegón lists one "chest ornament in the shape of a human bust" without specifying whether the object is metallic, recovered on March 17 (authors' translation). To achieve limited stratigraphic control, Piña Chán (1970:38) excavated the Cenote in quadrants and reported the patterning in finds from each quadrant, but does not mention metal figurines. Ceramics from the Cenote date to AD 800 to 1550 (Ball and

33

Ladd 1992). We follow the proposals of Piña Chán (1970) and Coggins and Shane (1984) for successive depositions of materials at the Cenote; the former author only mentions wooden anthropomorphic figurines in a late depositional phase, while the latter include "cast gold alloy figurines" in an early phase (mid-8th century to AD 900) and then the wooden anthropomorphic figurines in a later one (mid-13th century AD to Spanish arrival).

Conservation

The only figurine specimen whose conservation treatment is documented (F5) was "mechanically cleaned with a wood pick" and "washed with ethanol" at the PMAE. Other cast Cenote metals at the PMAE were usually degreased with acetone, and their accession numbers were then applied in India ink on an acryloid base. Any treatments applied to objects at the MNA are unknown. While Thompson noted in 1904 that dredged mud likely containing artifacts was "washed and passed through a fine mesh sieve" (in Coggins 1992:18), museum conservators have proposed that acidic reagents may have been applied to clean Cenote metals after their recovery (J Contreras, G Peñuelas, D Piechota 2012, pers. comm., 24 April, 2 May). Lothrop (1947) notes that the greenish color on one unidentified Cenote metal is the "result of working on the black incrustation with nitric acid." Comparison of a PMAE archival photograph presumably taken at the time of compositional analysis and a drawing in Lothrop (1952) to our present observations shows that the headdress of one figurine (F8), now in the MNA, became dramatically fractured after its excavation; the location of its detached part is unknown.

Prior Analysis

As he did with bells and sheet, Root analyzed Cenote figurines (at least six of which are presented here) as early as 1927. He employed both gravimetry and Feré quartz spectrography. In spite of the confusing nature of the analytical documentation, some comparison was possible between our results and those that Root obtained. Occasionally, dramatic discrepancies were apparent and, aside from experimental differences, may be attributed to the metal's heterogeneity: the Cu and Au concentrations of one figurine (F5) are almost literally inverted (Figure 8b). In other cases (F11, F15), greater agreement arises particularly for major elements. When possible, we used pXRF to analyze the regions of invasive analysis, though we realized that the geometry of these sites (conical voids) was not ideal for the method and that corrosion and dirt may have accumulated between the times of Root's analysis and ours.

Franco Velázquez and de Grinberg (2002) studied six Cenote bells, but not figurines, through visual inspection, ED-XRF, and AAS. Contreras *et al.* (2007) analyzed nine Cenote specimens with ED-XRF, SEM, and PIXE-RBS, but all were sheet objects.

Methods

Detailed discussion of the current methodology is presented in our Bells paper. All sheet objects were studied with the same fundamental approaches: visual inspection with a magnifying glass, measurements with calipers, study with an optical microscope

(visible-UV-IR), and bulk compositional analysis with portable ED-XRF spectrometry. Among the finer resolution analyses, one figurine (F6f) was analyzed with RBS and SR-XRD while two figurines (F4, F5) were studied with SR-XRD and SR-XRF.

Typology

Most of the analyzed figurines (F3, F4, F5, F8, F9, F10, F11, F15) would belong to "human figures of Isthmian type" defined by Bray (1977). In the typology of Pendergast (1962), these specimens belong to Type VIIIA2, named "realistic anthropomorphic figurines," in contrast to VIIIA1, which he names "stylized anthropomorphic figurines." Two specimens (F6f, F12) belong to Bray's "cast animal figurines" (F12 is sub-type "b", "frog pendants of gold or copper," which apparently are found from Michoacan to Panama) and Pendergast's VIIIB ("zoomorphic figurines") (F12 is sub-type "2", but the only recovered objects of this sub-type are copper-based and from Zacualpa (Lothrop 1936)). The other five specimens (F6a,b,c,d,e) may belong to the human/anthropomorphic or animal/zoomorphic types noted in Bray (1977) and Pendergast (1962). Four open-back cast anthropomorphic figurines (made of Cu or bronze) with less obvious morphological similarities to the Cenote figurines are found in the Museo Regional de Guadalajara and a parallel figurine has been recovered from Teotihuacán (Hosler and Cabrera 2010).

Metrics

Recognizing the fragmentary nature of many of the specimens, one comparison that was feasible for most objects was between maximum height of the figurine and width of the foot, which shows a direct relationship (Figure 7d). Among the anthropomorphic specimens (n=7) with handheld objects, there is minimal variation in the objects' length: the average length of the left-hand objects is 11.99 mm (1σ=1.25 mm; c_v=0.10), that of the right-hand objects is 12.34 mm (1σ=1.35 mm; c_v=0.11), and that of all left- and right-hand objects is 12.17 mm (1σ=1.18 mm; c_v=0.10). Six of the figurines have suspension loops; some figurines have two loops. The average width of the metal strips that form the eight suspension loops, present on six figurines, is 1.95 mm (1σ=0.98 mm, c_v=0.50). The mean strip width of the high-Au bells with measureable suspension loops (n=16) is almost identical: 1.93 mm (1σ = 0.60 mm, c_v = 0.31). The strip widths for the two loops on zoomorphic figurine F12 (3.20, 3.58 mm) are notable outliers: each is greater than that analyzed on any bell (the closest is B2's strip width of 3.10 mm).

Superficial Features

In our characterizations, the features that follow may represent: (1) a "technological decision" of the metalsmith(s); (2) a "consequence of fabrication" that the smith(s) did not intend; (3) a "secondary alteration" that developed after fabrication; or (4) an "ambiguous feature" that arose in fabrication and/or post-fabrication (Figure 7c).

Technological decisions. Superficial features of the figurines index their original fabrications. Lost-wax casting may involve a non-metallic **core** (to help shape and

35

support the metallic form), and this core may be fully or partially removed after metal solidification. The core may be hidden during the molten metal pour, or it may be partially exposed; in the latter case, the occluded half, in contact with the wax model, would lend the metal its shape and support. By adding charcoal to the ceramic in core fabrication, Stern (1939, in Root, PMAE Archives, 969-42, Box 3) found that "the occlusion of gases in the finished castings" was inhibited and greater recovery of surface detail in the cast metal was achieved. Five specimens (F6f, F9, F11, F12, F15) have no core preserved and show cavities on their backs of variable depths, suggesting that the core wax partially exposed during the pour and the core easily removed after metal solidification. Three of them (F6f, F19, F12) display one continuous cavity on their backs except for their appendages, which are solid. Each of the other two has four distinct cavities (head, abdomen, each leg) on its back separated by regions of solid metal; and thus four distinct cores would have been removed from each figurine. We infer that 10 specimens that they are composed of hollow metal with (F3, F5, F6a, F6b, F6c, F8) or without (F4, F4f (the foot of F4) F6d, F6e) a core preserved; in all, the core was fully hidden during the metal pour. One specimen (F10) displays a combination of the two main casting approaches: a core was placed at the back of its head as a support for the shape, but otherwise its head-neck region is solid; we infer that a core was present in the figurine's abdomen where there is a shallow semi-rectangular depression suggesting that metal was added to fill the cavity once occupied by the core (Figure 7a.1 and 7a.2).

Chaplets—wooden pins—may be added to the wax model, formed around the core, to support the core as the wax melts out and the molten metal is poured. The location of chaplets, typically unpreserved, can be indexed by voids in the metal. One specimen (F3) shows a chaplet void on the back of its left foot; this void is filled, actually overflowing, with ceramic material. Another specimen (F5) has multiple voids on the front and back. In some cases of the voids, ceramic (presumably core) material is visible just beneath the metal surface; in at least one other case, the void, evinced by a thin circular depression is filled with metal, even with the rest of the metallic surface. All of the chaplet voids of F5 are circular, highly symmetric, and have diameters consistently between 2 and 3 mm.

Like the bells and certain sheet specimens, the figurines may have been suspended or worn, as indicated by the presence of **suspension loops** on seven specimens (F5, F8, F9, F10, F11, F12, and F15). All of the loops identified are on the back side of the figurines. While the exact original location of the loop on F5 is unclear, given the figurine's intense deformation, it appears to be attached at the neck. Similarly, the loop is attached at the neck on three specimens (F9, F11, F15), encroaching on the head's core cavity; two of these loops are fully intact (not deformed), while that of F11 shows consistent flattening. The loop on another specimen (F8) is attached at the head (closed and hollow) and is completely flattened; the loop on F10 spans the head's core cavity and is partially flattened. Like the bells' loops, there is variety in the number of metal (formerly wax) strips that comprise each loop. Of the nine loops on the seven specimens that have loops, five have one strip each, three have two strips each, and one has three strips. The two loops on the frog (F12) are disguised, comprising the frog's two front hands; several bells with zoomorphic finials also featured loops disguised as part of the animal (Figure 7b.1 and 7b.2). While the Cenote bells have at most one loop each, the Cenote sheet specimens typically display multiple punched holes and two figurines (F11,

F12) have two loops each; the movement of these sheet objects and two figurines would have been more constricted than that of the bells and most other figurines.

Consequences of primary fabrication. Several features arose as unintentional consequences of the figurines' original fabrications. As the molten metal fills the space formerly occupied by the wax and contacts the ceramic/charcoal core, it reproduces the texture of these components. Thus, any roughness of the wax and/or core would have induced fine metallic **surface additions** (F8), or, inversely, **surface losses** (F3, F4, F6b, F8, F15). **Voids** (F3, F4's body and leg/foot, F5, F10), fine areas where no metal remains throughout the object's entire depth, and **localized porosity** (F5, F6f, F8, F11, F15) appearing in clusters of superficial depressions, emerged through uneven cooling of the molten metal and/or compositional segregation. **Cracking** (F6f, F15), a superficial separation of the metal, and **fracturing** (F5, F6f), a complete separation of the metal, besides a development in solidification, may have emerged in post-casting hammering.

Secondary alterations. Other features developed after the objects' original fabrications. Surface roughness (F5, F8, F10, F11, F12, F15)—dense clusters of circular pock-marks—may be attributed to mechanisms of **corrosion** as outlined by Scott (1983a). These rough golden areas may have been cleaned of the Cu-based corrosion compounds that once covered them. Indeed, such corrosion is evident in wide, smooth patches on other objects (F3, F4's body and leg/foot, F9). The likelihood of intensive cleaning is confirmed by the golden surface of one object (F6f) where only corrosion on one foot has been preserved and by the presence of thin, linear, diversely oriented depressions, attributable to polishing, on three of the most uniformly golden objects (F11, F12, F15). Some objects showed **superficial erosion** of the metal or a "peeling" effect (F3, F4's body, F5, F6a, F8, F9) likely related to the natural dissolution of Cu-based components, spurred by the wide gap in electrochemical potential among Cu, Ag, and Au. Besides processes internal to the metal, corrosion may be induced on Au-containing objects from interaction with organic matter (Rapson 1982; Scott 1983a). These mechanisms should not be ignored as the observation of the cross-section of one fragmented specimen (F6a) reveals the lack of diffusion of the brown-black superficial patina into the bulk metal. Conical **drill holes**, from the removal of samples for analysis likely undertaken by Root, are conspicuous on four figurines (F9, F10, F12, F15), and two additional specimens are noted to have been analyzed in the records of Root and in Lothrop (1952) (F8, F11). Under UV light, one figurine (F15) revealed a bright green fluorescence on the back of one leg, presumably from an **organic adhesive** once applied to the specimen for museum display. **Local discolorations** were noted (F4's body and leg/foot, F6f, F10); while most (black, grey, white, olive, red, yellow) may have emerged in deposition, a green mark on one, similar to those on other Cenote metals, may have arisen in museum conservation or curation.

Ambiguous features. While **cracking** and **fracturing** may have emerged in solidification or post-casting hammering, these features could be related to stress corrosion, following Scott (1983a), for objects typically with less than 70 wt% Au (cracking and fracturing: F4's body and leg/foot, F6a; only fracturing: F3, F6b). The loss of one part of figurine F8's headdress, likely to have occurred after excavation, is a significant fracture, as is the missing head of figurine F3: the cleanliness of the separation suggests that this loss indexes an intentional action potentially undertaken in ritualized deposition. **Flattening,** similar to that seen on some Cenote high-Au bells, was noted.

37

While the consistently flattened appearance of three figurines (F3, F10, F12) may be a product of their original design, other flattening is more localized and more curious because of our expectation that these features would not be intentionally designed as compressed: suspension loops (F11, F12) and hands holding rattles (F3, F4).

Indentations, localized depressions in the metal, potentially made with the application of a blunt tool, were less frequently evident on these figurines (F11, F12) than on the bells that were studied. Almond-shaped depressions on the metallic surface were encountered in one case (F8); these marks are deeper, less linear, and less clustered than the marks attributed to polishing on other figurines and may have emerged in pre-depositional burnishing, as they are embedded in corroded areas.

Composition, Distribution, and Enrichment

All 16 specimens are composed of *tumbaga*, a high-Au metal that also may contain Ag and/or Cu (Figure 8). The Cu concentrations in three objects (F11, F12, F15) are low (<5 wt%) and may have been inherent to the Au source; among the other figurines, Cu was an intentional alloying element. The concentrations of Ag in the figurines are relatively consistent (between 2 and 6 wt% in 14 of 16 objects). The Au-Ag-Cu ternary diagram reveals no obvious object cluster save the high-Au (>90 wt%) group. The Au content of other specimens (F4's leg/foot, F6b, F6c) may be underestimated as a result of intense superficial soil and corrosion, which also could overestimate Fe and Cu contents.

The trace concentrations (<1 wt%) of Pt in three specimens (F5, F6a, F6f) are likely contributions of the Au source.

The diffraction pattern of F6f is consistent with a cast object that shows especially large grains, suggesting the figurine was not hammered to shape after casting (Figure 9). The only identifiable phase in F6 is $AuCu_3$, an ordered phase that developed at an Au concentration lower than that detected by p-ED-XRF; this discrepancy is consistent with the higher depth penetration afforded by XRD (Figure 9c.2). Conversely, the textured pattern featuring continuous rings reveals that figurine F4 was hammered after being cast. The translation of peaks (which we recognize also could develop if the sample-to-detector distance changed slightly) indexed as pure-Cu suggests that uniform tension has been applied to the metal, suggestive of an annealed condition ($\Delta d \approx +1.4\%$). Figurine F5's pattern reveals greater texture but still continuous diffraction rings, indicating extensive hammering (Figure 9f.1 and 9g.1). Phases identified include pure Au and the ordered phase $AuCu_3$; their translations, indicative of uniform compression, are, respectively $\Delta d \approx -1.6\%$ and $\Delta d \approx -1.7\%$ (Figure 9f.2 and 9g.2). $AuCu_3$ is especially concentrated in the highly porous, amorphous middle section of the figurine, possibly a cup or bag held by the person portrayed on the right. Reconciling the diffraction patterns with SR-XRF elemental maps, we propose that, with the ceramic core of F5 supported by chaplets located in the lower half of the double figurine, the metal was poured from the heads to the feet: the thick lower right half, highly concentrated in Au but depleted in Cu, was the last part of the figurine to solidify but was the first part to be filled with molten metal (Figure 9d and 9e). This clot inhibited the metal flow, and the metal available to fill the head region was insufficient.

The RBS profile and simulation of F6f shows a homogeneous composition with no detected enrichments in Au or Ag, an observation that we made for two Au-rich bells (B3, B4) (Figure 9b). The compositions of the three specimens are relatively similar: the Au content of F6f is 75.8 wt% while that of B3 and B4 are, respectively, 83.9 and 84.7 wt%.

The implications are threefold. First, two compositional clusters of the figurines emerge: one of Au alloyed with Cu and one of unalloyed Au. It is only possible to draw such a distinction in alloying practice if the Cu concentrations in the potential Au sources are completely known, but already, we can recognize that the decision to alloy or not cut across morphological groups, given the presence of an anthropomorphic figurine and a zoomorphic figurine in the unalloyed cluster. Second, enrichment in Au and/or Ag may be present and only detectable by comparison of XRD results (approximately, the bulk metal) with those of pXRF and RBS (superficial metal). The enrichment on F6f may have been so thick that it was simply not detected by RBS. Potentially it developed through natural corrosion in which Cu was dissolved; these compounds were later removed from the surface, leaving it golden. Third, XRD reveals that both F4 and F5 underwent post-casting hammering and/or annealing, possibly for shaping of different formal elements, and these processes were not localized. But given the highly cracked and fractured state of F4 and the obscured, mangled upper half of F5, what was the exact series of steps in the development of these objects? We may think of hammering to shape as a finishing technique, a means of honing particular design details. Would a smith have wanted to finish/attempt to salvage a 'miscast' metal by shaping it? We propose that F4 was far more intact just after casting than it appears today, it was hammered to shape, and then it underwent intensive alteration through subsequent intentional breakage and corrosion in deposition. On the other hand, the solidification segregation in F5 prevented the full formation of the figurine's top half in casting; then smiths still hammered different regions to shape. This latter case especially compels us to restructure our interpretations of 'miscastings'.

The Contributions of Metallurgical Communities

Through hierarchical cluster analyses with SPSS (squared Euclidean distance with average linkage then, separately, with Ward's linkage), we explored other ways of organizing the figurines assemblage: clusters were determined by one analysis through five features related to the figurines' primary fabrications—Au concentrations, general casting type (closed or open-back), presence of core, presence of identifiable indices of chaplets, number of suspension loops—and a separate analysis through three features related to the figurines' secondary fabrications—intensive post-fabrication, pre-excavation fracture/loss, the presence of flattening, and the presence of indentation (Figure 7e.1 and 7e.2). In the primary fabrication analyses, there are distinct clusters of closed-back figurines and open-back figurines. Two features—the presence of core and the presence of voids in the locations of chaplets—bundle with the feature of casting type. Does the latter entail the former two? Surely, core removal becomes far easier through open-back casting, but is it necessary? Similarly, is it possible that chaplets would even be useful to support cores in open-back castings? Interestingly, four of the five open-back castings are also four of the five members of the group with highest Au

39

content. Among the secondary fabrication features, we recognized that flattening and/or indentation is evinced both on figurines that have been intensively fractured and on those that have not been. If we envision the fracturing as an intentional action, perhaps, leaving a more dramatic and visible trace, it was an exaggerated form of alteration compared to flattening/indenting or a culminating flourish to a series of modifications.

Considering features related to primary fabrication, the open-back cast figurines tend to have the highest Au concentrations. Potentially a closed-back casting would be less feasible to cast with purer Au and more feasible with increasing Cu content. But, other factors, such as color, may have motivated this decision. On three open-back cast figurines, a suspension loop directly encroaches on the head cavity (where a core would have been situated). While one of these loops is deformed, two appear completely non-deformed. Either the core was very gingerly removed or these loops were added after the figurine was cast. X-radiography would be essential to evaluate this proposal. Attaching, suspending, and/or wearing the figurines through use of their loops inherently facilitates a re-contextualization of the object, and the potential post-casting addition of the loop(s) extends this process of re-contextualization. The lack of detectable artificial enrichment on one figurine was unexpected. One option is that it is enriched, but the enrichment is natural, and the layer, a product of corrosion, enabling depletion of Cu from the surface, was too thick to detect with RBS. Alternatively, if no artificial enrichment exists, we must ask: was the superficial color of the *tumbaga* (pre-corrosion and pre-polishing) a property sought by metallurgists and/or the users of the figurines? While some technicians may have been interested in the object's external revelation of components internal to it à la the proposal Lechtman (1984), others may have conceptualized the external/internal differently: a superficial *tumbaga* color is true to the elemental composition of the metal (and the process of alloying). Here, the internal is the process of fabrication, whereas in Lechtman's formulation, the internal is a physical metallic layer; also, here, the external is iconic and indexical of everything internal, whereas in Lechtman's concept, the external is only iconic and partially indexical of one internal component.

Besides the figurine that lost part of its headdress post-excavation, we propose that other figurines, where the region of separated metal is especially thick (F3, F6a,b,c,d,e), would have undergone fragmentation before their deposition and would have required the application of blunt force to fully separate. The intense disfiguration in the head region of F5, whose size is disproportionately small compared to the lower half, is more a product of its original fabrication than a result of post-casting alteration; we presume that the black-brown discoloration on the upper half would have extended to the lower half before the figurine's documented cleaning by conservators. Yet the traces of post-casting hammering and annealing imply that smiths did not surrender even after the casting operation may not have met their expectations; they continued working the metal. Archaeological metal figurines from the Andes tend to be fabricated from sheet (Lechtman et al. 1975). Cast figurines have been recovered primarily from Costa Rica, Panama, and Colombia (Bray 1974, 1977, 1981; Cooke and Bray 1985; Falchetti 2003; Newman et al. 1991; Plazas and Echeverri 1990; Uribe Villegas 2012). However, others have been found in West and Central Mexico (Hosler and Cabrera 2010), Guatemala (Lothrop 1936), and Belize (Cockrell et al. 2013). We also recognize that metal objects, particularly bells, with anthropomorphic or zoomorphic elements from sites such as

40

Tumba 7 of Monte Albán (Peñeulas Guerrero 2008), the Pescador Treasure (Nahmad and Besso-Oberto 1993), and the Quimistán Cave (Blackiston 1910) can themselves be considered as figurines.

The wide sharing of metallurgical materials and knowledge among Costa Rica, Panama, and Colombia complicates our ability to provenance any Cenote figurines that may be analogous to those fabricated in this geographic region. One set of attributes to consider are those related to primary fabrication, particularly the use of chaplets. Following the proposal of Howe (1986), the double anthropomorphic figurine F5 shows a Quimbaya approach to chaplets but with allusions to Isthmian (Costa Rican/Panamanian) practices. Aligning with a Quimbaya technological style, its 'chaplet voids' are nearly uniform in diameter, and one chaplet void is filled (at least partially) with metal to be even with the surrounding metal. Another chaplet void is plugged with ceramic material, presumably in addition to the core material already present; in Howe's interpretation, Isthmian metallurgists typically covered this additional ceramic by casting metal in place, but this practice is not evident in this location. Indeed, a variety of plugging techniques is apparent across the assemblage. On figurine F3, a chaplet void on its back foot is overflowing with ceramic material but again lacking a metallic cover. On this figurine and two others (F8, F10), larger cavities (for core removal and not related to chaplets) have been filled to the surface with metal; these cavities' perimeters are conspicuous. F10 was cast as partially open-back (its head) and partially closed-back (the remainder). In short, the figurines display traces of Quimbaya practices and allusions to Isthmian practices and show a clear facility for playing with varied casting approaches, even within individual figurines. X-radiography will be necessary to confirm these proposals.

Compositional provenancing depends on a substantial database of analyzed source materials. Fernández and Segura (2004) offer guidance by noting the range of Cu and Au sources (and lack of a Ag source) in Costa Rica: in the hydrothermal Au deposits, Cu is approximately 4 wt%, and, in the alluvial deposits, Cu is not present. Besides the three Cenote figurines with Cu present but less than 4 wt%, if any of the other figurines were fabricated with Costa Rican Au sources, alloying with Cu must have been undertaken. The alluvial rather than the hydrothermal deposits would have been used given the former's significantly lower Ag content (on par with that of the Cenote figurines). Compositional provenancing also will depend on analyses of figurines from documented archaeological contexts. Recognizing the insecure provenances of certain objects, Beaubien, Cullen Cobb, and Harrison (2014, pers. comm., 15 January) note that, on the whole, the Ag content of analyzed Isthmian metals tends to approach 5 wt%, significantly lower than that of analyzed Colombian metals. This patterning suggests an Isthmian source of the metal for the Cenote figurines.

Morphological elements may be an aid in provenancing the metals, but ambiguity again emerges from the ease with which motifs were shared within the Isthmus and Colombia. Handheld objects, present on seven of the eight figurines identified as anthropomorphic, may be one such element to consider. One figurine holds bags, another holds eagles (nearly identical in form to metallic eagle pendants from Veraguas), and the remaining five hold rattles. Drawing on ethnographic cases, Cooke and Bray (1985) note a resemblance between the metallic handheld rattles and the "traditional gourd rattles used by the Kuna" of Panama and Colombia.

41

The secondary 're-fabrications' of the Cenote figurines may find parallels in Isthmian contexts. In Veraguas funerary deposits, Lothrop (1950) encountered Au-rich figurines that were deformed presumably by intense hammering, lending a collapsed appearance even more dramatic than that of certain Cenote figurines. While 'curation' of the figurines in their Cenote deposition is not documented in excavation records, a 1595 document describes how Muisca peoples may group tumbaga figurines with stones, wrap them in textiles, and then bury them in ceramic vessels (in Falchetti 2003).

Temporal provenancing of the figurines is also challenging, but a starting date for their fabrication could be AD 400, aligning with the emergence of the International Group in the Isthmian-Colombian region (Cooke and Bray 1985). Refinement of the potential temporal phasing of closed-back (earlier) and open-back cast (later) figurines, proposed by Cooke and Bray (1985), is necessary, particularly given that casting approaches indexed on the Cenote figurines were more nuanced than these two dichotomous descriptors suggest. Some of the metallurgical knowledge that facilitated the figurines' fabrication may have been put into practice even earlier, in Colombian contexts, particularly in the Quimbaya region (whose metallurgical practices emerged in AD 200) (McEwan 2000). The open-back cast figurines in West Mexican contexts and at Teotihuacán, discussed in Hosler and Cabrera (2010), incorporate morphological elements such as bell necklaces that suggest West Mexican design and show the local preference for Cu and Cu-As compositions for casting rather than *tumbaga*. The fabrications of these figurines may have been inspired by exchanges of metallurgical knowledge with crafters from the Pacific coast of northern South America. Recognizing that certain technological styles may be clearly indexed by these figurines and those from the Cenote based on comparison with figurines from known metallurgical traditions, we also must consider the range of experimentation—the blurring of technological styles—evinced by individual figurines. The combinations of different approaches (to casting setup, to chaplet treatment, to suspension loop design, to post-casting fracture, etc.) may frustrate scholars seeking precise provenances. But, they prove that, in crafting individual objects, metallurgists took risks and played with style. The re-contextualization of the figurines at the Cenote offered a fresh opportunity for play, as the objects, in deposition, came into contact with new materials and were effectively re-fabricated by a different community of metallurgists.

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APPENDICES
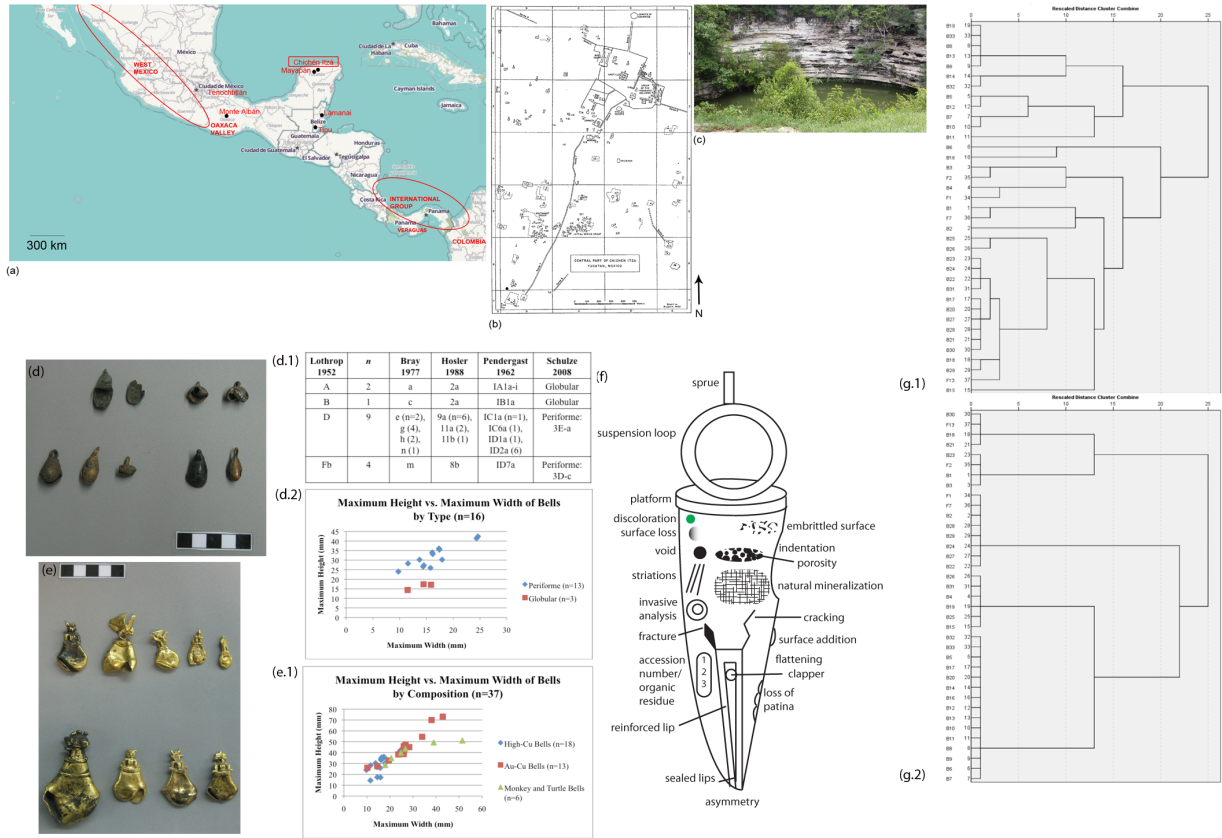
Figure 1. A map of the region is provided with sites and regions mentioned in the text in red (a). The Cenote is at the extreme northern end of the archaeological site and is connected to the ceremonial platform by a sakbe, an elevated path (use of figure pending approval by Peabody Museum Press) (b). The Cenote Sagrado as it appears today (2010) is pictured (c). The high-Cu bells (among which a selection is shown in (d)) were compared to pre-existing typologies of Mesoamerican metals (d.1). On comparison of their maximum widths and maximum heights, the pear-shaped bells (in blue) form a group discrete from that of the spherical bells (in red) (d.2). Comparison of these two metrics across bells of both primary compositions—high-Cu and tumbaga (among which a selection is shown in (e))—reveals discrete groups that align by composition (e.1). An imagined 'Cenote bell' with all of the superficial features mentioned in the paper is presented in (f). Hierarchical cluster analysis with SPSS (squared Euclidean distance; average linkage) is displayed as dendrograms (for 37 bells; the smaller fragment of B13 was excluded), where variables are features of primary fabrication (g.1) and features of secondary fabrication (g.2).

(a) Ternary diagram — axes labeled Ag, Au, Cu

(c)

Bell	Analysis	Fe	Cu	Zn	As	Se	Ag	Sn	Sb	Pt	Au	Pb	Bi
B1	Root		ND				ND				100		
	Current	0.4	3.5	P	ND	ND	3.4	ND	ND	ND	92.1	ND	0.6
B2	Root		10.9				5.5				83.6		
	Current	0.5	11.1	ND	ND	ND	4.5	ND	ND	ND	83.3	ND	0.6
B3	Root		5				5				90		
	Current		12.2	P	ND	ND	3.6	ND	ND	1.6	82.1	ND	0.5
B9,10,11?	Root	0.01	99.1*		0.2		0.1	0.1	0.01		0.0001	0.5	0.005
B9,10,11?	Root	0.1	96.6*		0.4		2.0	0.4	0.05		ND	0.5	ND
B9,10,11?	Root	0.1	95.8*		0.1		2.0	>2.0	0.001		ND	0.01	ND
B9	Current	0.1	96.0	P	2.4	ND	P	ND	ND	ND	ND	1.4	ND
B10	Current	0.2	91.5	ND	6.0	ND	P	ND	0.4	ND	ND	1.8	0.2
B11	Current	0.3	87.0	ND	5.0	0.1	P	6.2	0.3	ND	ND	1.0	0.1

(b)

Bell	Fe	Ni	Cu	Zn	As	Se	Ag	Sn	Sb	Pb	Bi
B5	t		M		m		t		t	t	t
B6	t	t	M	t	t		t	m	t	t	t
B7	t	t	M	t	m	t	t	t	t	t	t
B8	t	t	M	t	m	t	t		t	t	
B9	t	t	M	t	m		t			t	
B10	t		M		m				t	t	t
B11	t		M		m			m	t	t	t
B12	t	t	M		m		t	t	t	t	t
B13	t		M		m						
B14	t		M		m						
B15			M	m	t						
B16			M		t		t				t
B17			M		t						
B18	t		M		t						
B19	t		M		m					t	
B20	t		M		t						
B32	t	t	M		m						
B33	t	t	M		m						t

(d)

p-ED-XRF Analysis of Reference Materials (all values in weight percent)								
Reference	Fe	Ni	Cu	Zn	Ag	Sn	Au	Pb
Naval Brass 1107 (NIST) *Theoretical*	0.037	0.098	61.2	37.3	--	1.04	--	0.18
Empirical (n=5) (Bruker)	0.221 ± 0.003	0.348 ± 0.002	58.8 ± 0	37.2 ± 0	1.15 ± 0			0.17 ± 0.01
Empirical (n=2) SANDRA	0.154 ± 0.020	0.103 ± 0.145	57.4 ± 2.9	42.5 ± 2.7	*			*
High-Silver L.115 (Xcalibur) *Theoretical*	--	--	48	--	52	--	--	--
Empirical (n=5)			44 ± 0		52 ± 0			
14-kt Au (Xcalibur) *Theoretical*	--	--	24.6	3.9	12.9	--	58.6	--
Empirical (n=5)			22.4 ± 0.1	4.5 ± 0	13.3 ± 0		56.5 ± 0.2	
585-40 *Theoretical*			58.5		1.5		40	
Empirical (n=2) SANDRA			59.1 ± 6.2		0.7 ± 0.3		40 ± 6	
Steel 2205 (Bruker) *Theoretical*	66.134	5.396	0.172	--	--	--	--	--
Empirical (n=5)	63.920 ± 0.295	4.868 ± 0.027	0.227 ± 0.005					

"--"indicates the element is not present in the reference.
1σ is provided for empirical values.
* indicates that 1σ exceeded the mean.

Figure 2. A ternary (Au-Cu-Ag) diagram is presented for the high-Au or tumbaga bells (a). Each point represents the p-ED-XRF analysis of one representative location on each high-Au bell (n=19). Also based on the p-ED-XRF analysis of one representative location on each bell, the major (≥10 wt%) (M), minor (10>x≥1 wt%) (m), and trace (<1 wt%) (t) elements of the high-Cu bells (n=18, thus including only one of the two analyzed specimens of bell B13) are presented (b). Comparisons are possible between the compositions (in wt%; ND=not detected; P=present but <0.1 wt%; analysis by p-ED-XRF) of six bells studied in this project (B1, B2, B3, B9, B10, B11) and the data obtained by Root (in Lothrop 1952 and the PMAE archives) for those objects (c) (Root's documentation is not always adequate; the compositions in the dark green rows are probably, but not certainly, related to B9, B10, and B11). It is uncertain whether Root used atomic or weight percents. For his data, blank spaces occur when it is unknown whether the element was not detected or was not tested for. Analyses of certified reference materials used for p-ED-XRF standardization of both the Bruker and SANDRA systems are shown in (d) and compared to their expected compositions.
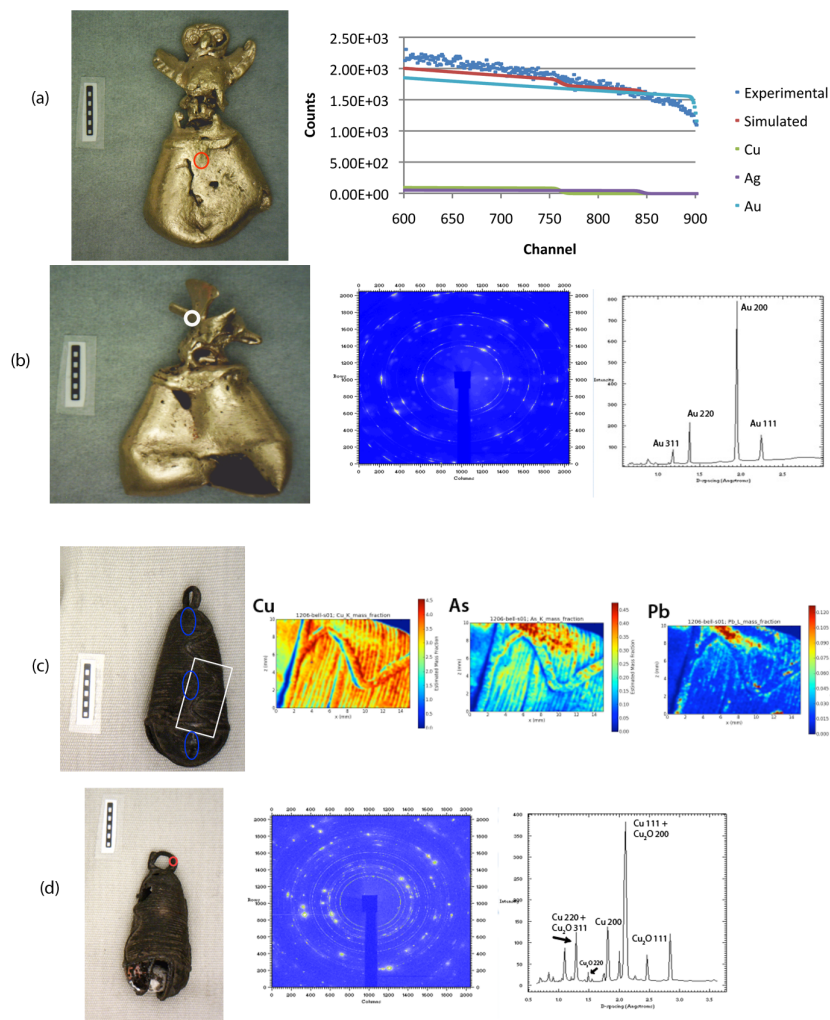
Figure 3. The high-Au bells analyzed with RBS, such as B4 (a) (with the location of RBS indicated by the red circle) showed no superficial enrichment in Au; their surface color was produced from their alloy compositions. The RBS profile simulates a homogeneous layer whose composition is consistent with the p-ED-XRF analysis of a representative location on this bell (Cu 27.3 at%, Ag 5.7 at%, Au 67.0 at%). With SR-XRD, these bells, such as B3 (b) (whose location of SR-XRD analysis is indicated by the white circle) yielded the texture expected from cast polycrystalline materials with post-casting hammering (evinced in the elongation of spots at higher θ), and their phases could be indexed as Pt, or more likely, Au translated because of uniform compression. Preferred orientation in the 100 plane may have facilitated the severe depletion of this peak. SR-XRF analysis of high-Cu bell B11 (c) revealed that As and Pb are less evenly distributed in the bell relative to Cu (red indicates greater concentration and blue indicates lower concentration). Thus, the concentrations of As and Pb may be at least partially tied to superficial corrosion phenomena. The white rectangle shows the region of SR-XRF analysis and the three blue ellipses indicate the locations of p-ED-XRF analysis for comparison. SR-XRD analysis of high-Cu bells, such as B11 (shown in (d) profile with the red circle indicative of the location of analysis) revealed a pattern consistent with polycrystalline materials left in their as-cast state; phases are a combination of pure-Cu and Cu corrosion compounds.
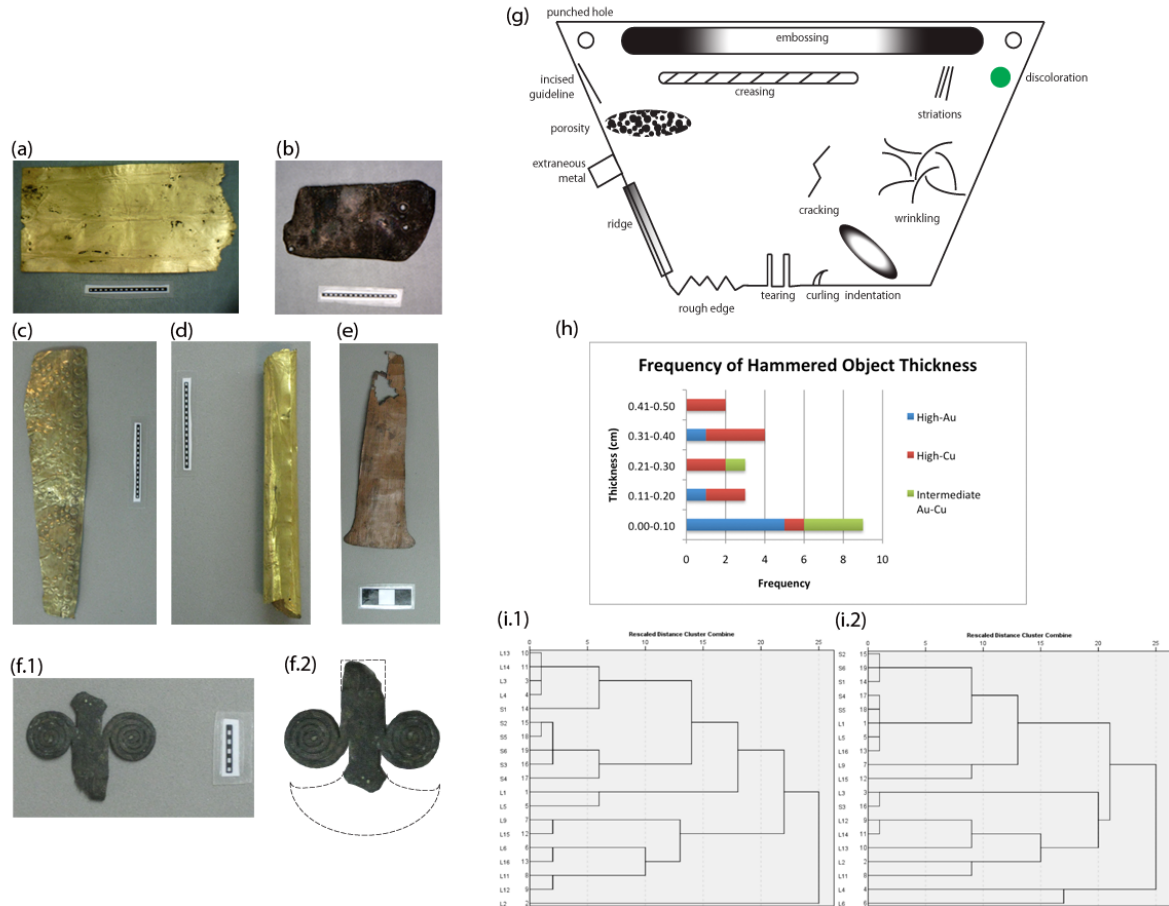
Figure 4. In (a-f.1), a selection of hammered objects from the Cenote are shown: (a) sheet L3; (b) sandal S3; (c) sheet L15; (d) tube L13; (e) axe-money L11; and (f) tweezer fragment U2 (an interpretation of U2 as a complete spiral tweezer is presented in (f.1)). An imagined 'Cenote sheet' with all of the superficial features mentioned in the paper is presented in (g). The thicknesses of the hammered objects (n=21) are presented in terms of their frequency in (h). All thickness values represent the averages of at least two measurements, except in the case of L15. The only two objects in the 0.41-0.50 thickness range are the tweezer fragments. "High-Au" indicates Au values between 90 and 100 wt%; "intermediate Au-Cu" indicates Au values between 30 and 70 wt%; and "high-Cu" includes not only tumbaga (0-20 wt% Au) but also non-tumbaga objects (axe-monies and tweezer fragments). Hierarchical cluster analysis with SPSS (squared Euclidean distance; average linkage) is displayed as dendrograms (for 19 sheets; tweezer fragments are excluded), where variables are features of primary fabrication (i.1) and features of secondary fabrication (i.2).

(a) Ternary Au-Cu-Ag diagram.

(b)

Object	Cu	Zn	As	Sn
L11	M		t	
L12	M		t	
U2	M	m	t	m
U3	M	m	t	t

(c)

Object	Analysis	Fe	Ni	Cu	Zn	As	Se	Ag	Sn	Sb	Pt	Au	Pb	Bi
S1	Root			L		T		L	S	T		S	S	X
	Current	0.1		92.3	T	0.4	ND	0.3	ND	ND	ND	6.9	ND	ND
S2	Root			95.9				2.0	0.1			2.0		
	Current	0.2	T	87.6	T	T	ND	0.9	ND	ND	ND	11.2	ND	ND

(d) p-ED-XRF Analysis of Reference Materials (all values in weight percent)

Reference		Fe	Ni	Cu	Zn	Ag	Sn	Au	Pb
Naval Brass 1107 (NIST)	Theoretical	0.037	0.098	61.2	37.3	--	1.04	--	0.18
	Empirical (n=5) (Bruker)	0.221± 0.003	0.148 ± 0.002	58.8 ± 0	37.2 ± 0		1.15 ± 0		0.17 ± 0.01
	Empirical (n=2) SANDRA	0.154 ± 0.020	0.103 ± 0.145	57.4 ± 2.9	42.3 ± 2.7	*			*
High-Silver L115 (Xcalibur)	Theoretical	--	--	48	--	52	--	--	--
	Empirical (n=5)			44 ± 0		52 ± 0			
14-kt Au (Xcalibur)	Theoretical	--	--	24.6	3.9	12.9	--	58.6	--
	Empirical (n=5)			22.4 ± 0.1	4.5 ± 0	13.3 ± 0		54.5 ± 0.2	
585-40	Theoretical			58.5		1.5		40	
	Empirical (n=2) SANDRA			59.1 ± 6.2		0.7 ± 0.3		40 ± 6	
Steel 2205 (Bruker)	Theoretical	66.134	5.396	0.172	--	--	--	--	--
	Empirical (n=5)	63.920 ± 0.295	4.868 ± 0.027	0.227 ± 0.005					

"--"indicates the element is not present in the reference.
1σ is provided for empirical values.
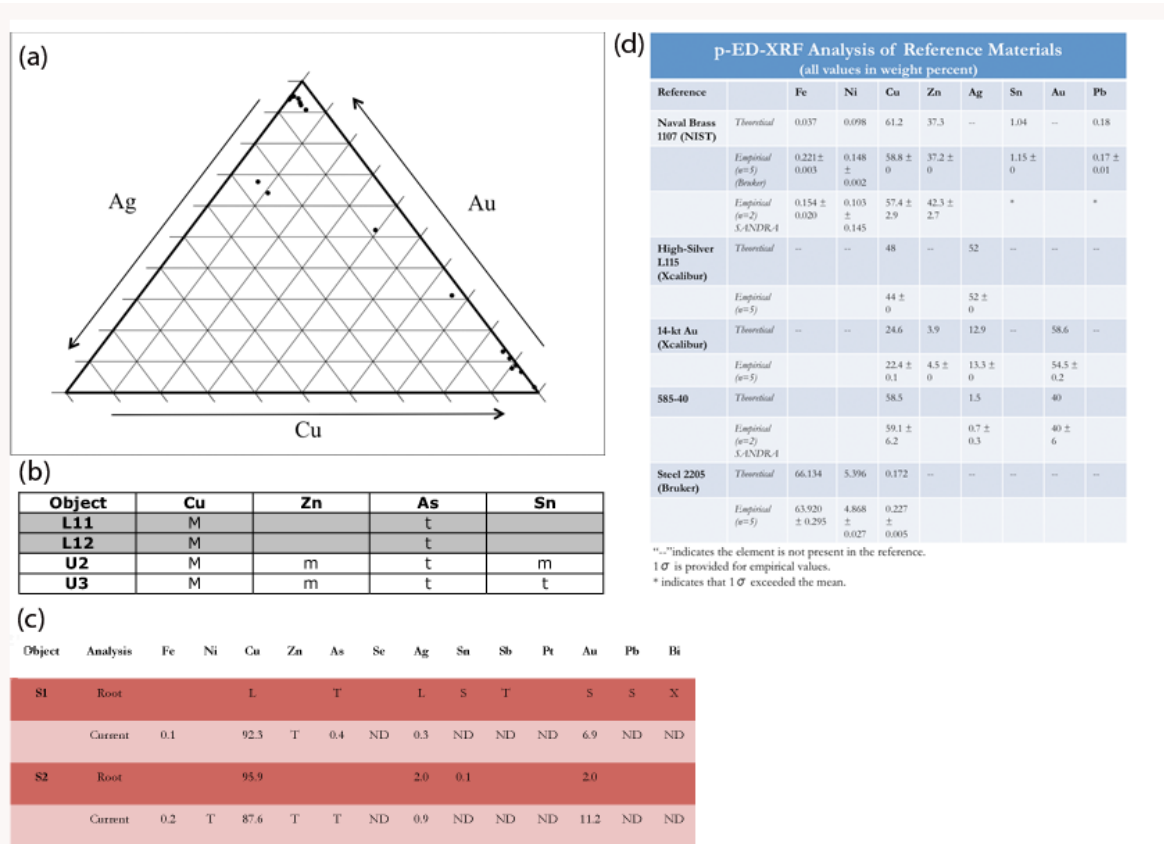* indicates that 1σ exceeded the mean.

Figure 5. A ternary (Au-Cu-Ag) diagram is presented for the tumbaga sheet (a). Each point represents the p-ED-XRF analysis of one representative location on each sheet (n=17). Also based on the p-ED-XRF analysis of one representative location on each bell, the major (≥10 wt%) (M), minor (10>x≥1 wt%) (m), and trace (<1 wt%) (t) elements of the high-Cu objects (two axe-monies (L11, L12) and two tweezer fragments (U2, U3)) are presented (b). Comparisons are possible between the compositions (in wt%; ND=not detected; analysis by p-ED-XRF) of two sandals studied in this project (S1 and S2) and the data obtained by Root (in Lothrop 1952 and the PMAE archives) for those objects (c). It is uncertain whether Root used atomic or weight percents. In his study, L=20%+, S=1-20%, T=0.01-1%, but the meaning of "X" is uncertain; blank spaces occur when it is unknown whether the element was not detected or was not tested for. Analyses of certified reference materials used for p-ED-XRF standardization of both the Bruker and SANDRA systems are shown in (d) and compared to their expected compositions.
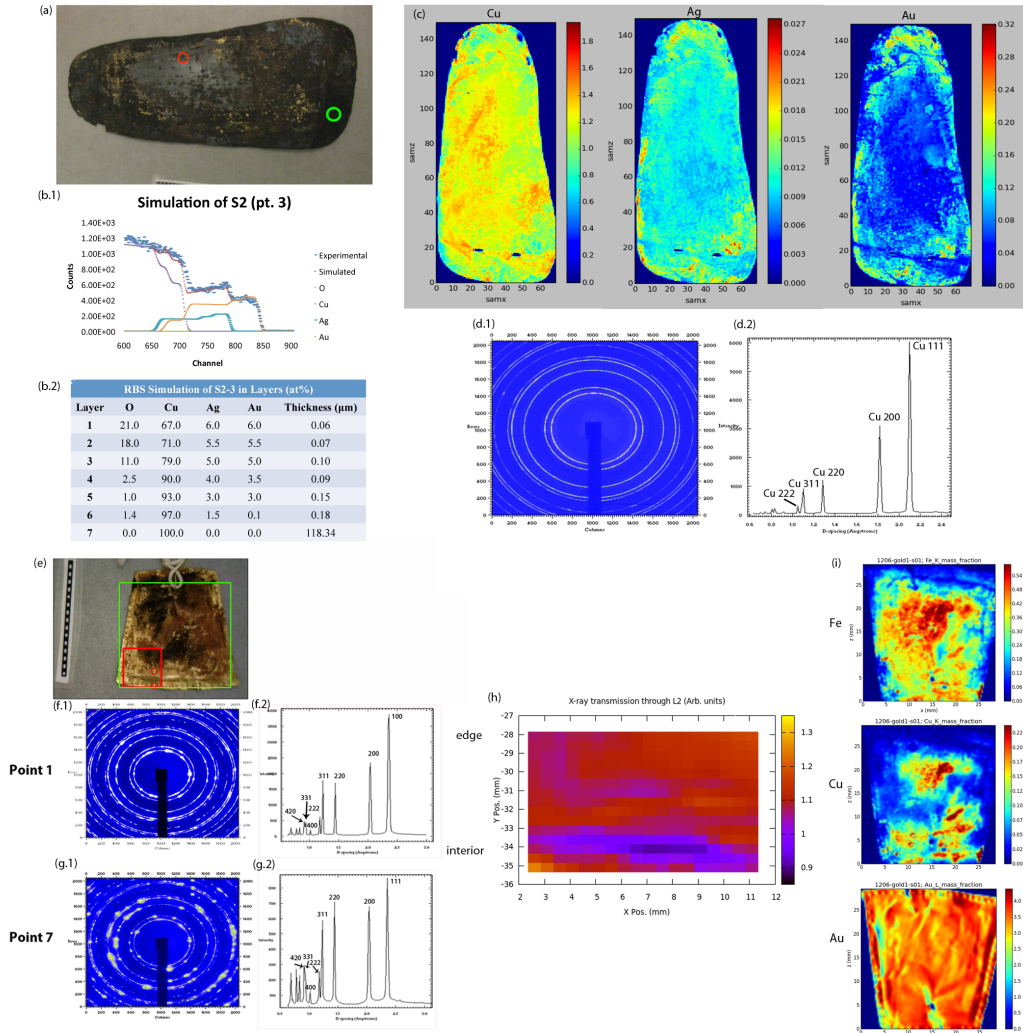
Figure 6. Sandal S2, shown in (a), was analyzed with RBS (He++, 3 MeV) (point represented by the green circle) yielding the data presented in (b.1) that was modeled with SIMNRA, revealing superficial enrichment in Ag and Au and a pure-Cu substrate (modeled layer compositions and thicknesses are shown in b.2). SR-XRF analysis yielded distribution maps (c) for, from left to right, Cu, Ag, and Au in S2 showing concentration of the noble metals, particularly Au, on its edges. SR-XRD (of the point represented by the red circle) revealed a pattern consistent with a hammered object (d.1) and phases all indexed as pure Cu (d.2). Trapezoidal, embossed sheet L2, shown in (e), was evaluated with SR-XRD (point 1 at edge and point 7 at interior, shown by red circles), yielding patterns (f.1 and g.1) consistent with hammering, but with greater texture (and thus less hammering) for more interior points (g.1); phases were indexed as pure Au (f.2 and g.2); the beam transmission map (for the region encompassed by the red rectangle in (e)), compiled by Dr. Jacob Ruff, showed greater transmission on L2's edge, indicative of thinner metal (and consistent with the presence of embossing in this region). SR-XRF of the region in the green rectangle in (e) yielded distribution maps for Fe, Cu, and Au (shown in (i)), revealing a potential superficial correlation between Fe and Cu.

63
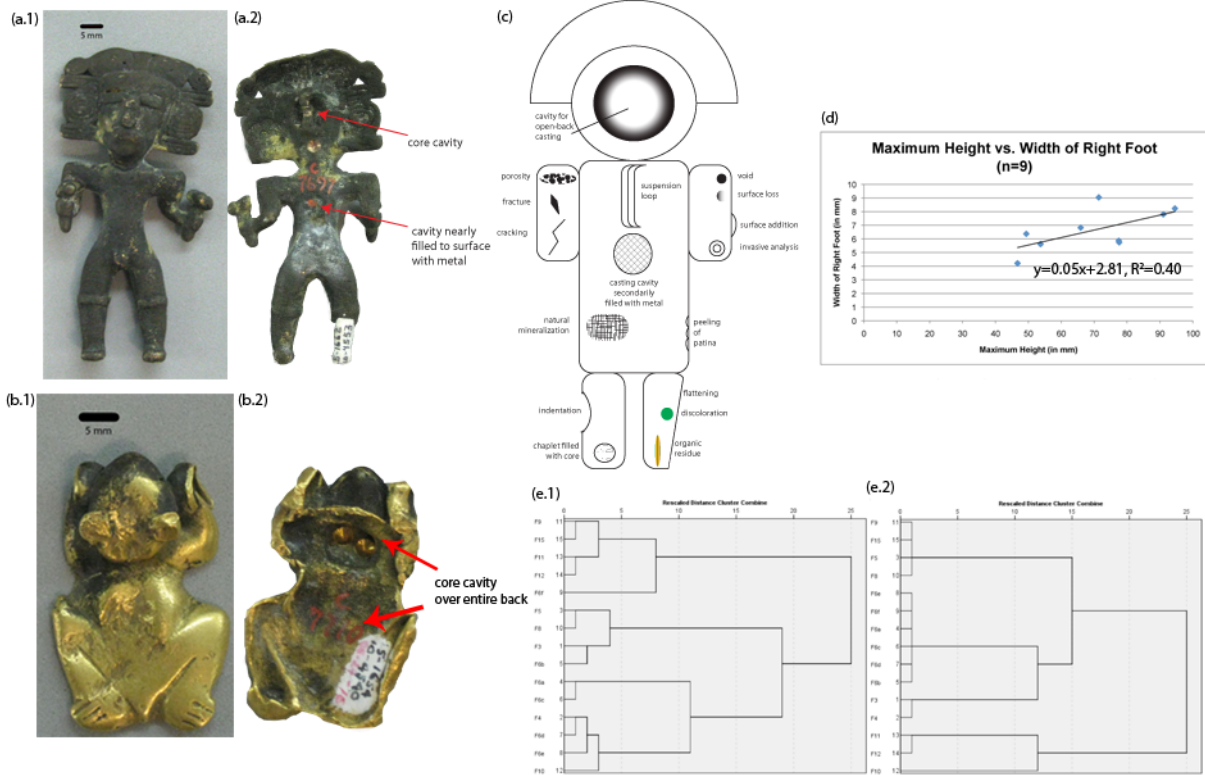
Figure 7. The front (1) and back (2) of an anthropomorphic figurine are shown in (a) and those of a zoomorphic figurine are shown in (b) with relevant details related to their castings indicated. An imagined 'Cenote figurine' with all of the superficial features mentioned in the paper is presented in (c). A direct correlation was detected (shown in (d)) between the maximum height and the width of the right foot of the anthropomorphic figurines, suggesting a relative interest in proportionality among the figurines' designers. Hierarchical cluster analysis with SPSS (squared Euclidean distance; average linkage) is displayed as dendrograms (for 15 figurines; F4's leg/foot was excluded), where variables are features of primary fabrication (e.1) and features of secondary fabrication (e.2).

(a)

Ag

Au

Cu

(b)

Figurine	Project	Cu	Ag	Au
F5	Root	77.8	2.8	19.4
	Current	13.8	7.8	78.4
F8	Root	46.6	4.6	48.8
	Current	22.7	5.0	72.3
F9	Root	5.7	1.3	93.0
	Current	13.4	2.0	84.6
F10	Root	37.8	10.2	52.0
	Current	22.0	5.2	72.8
F11	Root	1.3	1.3	97.1
	Current	0.4	4.3	95.3
F15	Root	ND	3.3	96.7
	Current	0.7	5.3	94.0

(c)

p-ED-XRF Analysis of Reference Materials (all values in weight percent)									
Reference		Fe	Ni	Cu	Zn	Ag	Sn	Au	Pb
Naval Brass 1107 (NIST)	*Theoretical*	0.037	0.098	61.2	37.3	--	1.04	--	0.18
	Empirical (n=5) (Bruker)	0.221± 0.003	0.148 ± 0.002	58.8 ± 0	37.2 ± 0		1.15 ± 0		0.17 ± 0.01
	Empirical (n=2) SANDRA	0.154 ± 0.020	0.103 ± 0.145	57.4 ± 2.9	42.3 ± 2.7		*		*
High-Silver L115 (Xcalibur)	*Theoretical*	--	--	48	--	52	--	--	--
	Empirical (n=5)			44 ± 0		52 ± 0			
14-kt Au (Xcalibur)	*Theoretical*	--	--	24.6	3.9	12.9	--	58.6	--
	Empirical (n=5)			22.4 ± 0.1	4.5 ± 0	13.3 ± 0		54.5 ± 0.2	
585-40	*Theoretical*			58.5		1.5		40	
	Empirical (n=2) SANDRA			59.1 ± 6.2		0.7 ± 0.3		40 ± 6	
Steel 2205 (Bruker)	*Theoretical*	66.134	5.396	0.172	--	--	--	--	--
	Empirical (n=5)	63.920 ± 0.295	4.868 ± 0.027	0.227 ± 0.005					

"--"indicates the element is not present in the reference.
1σ is provided for empirical values.
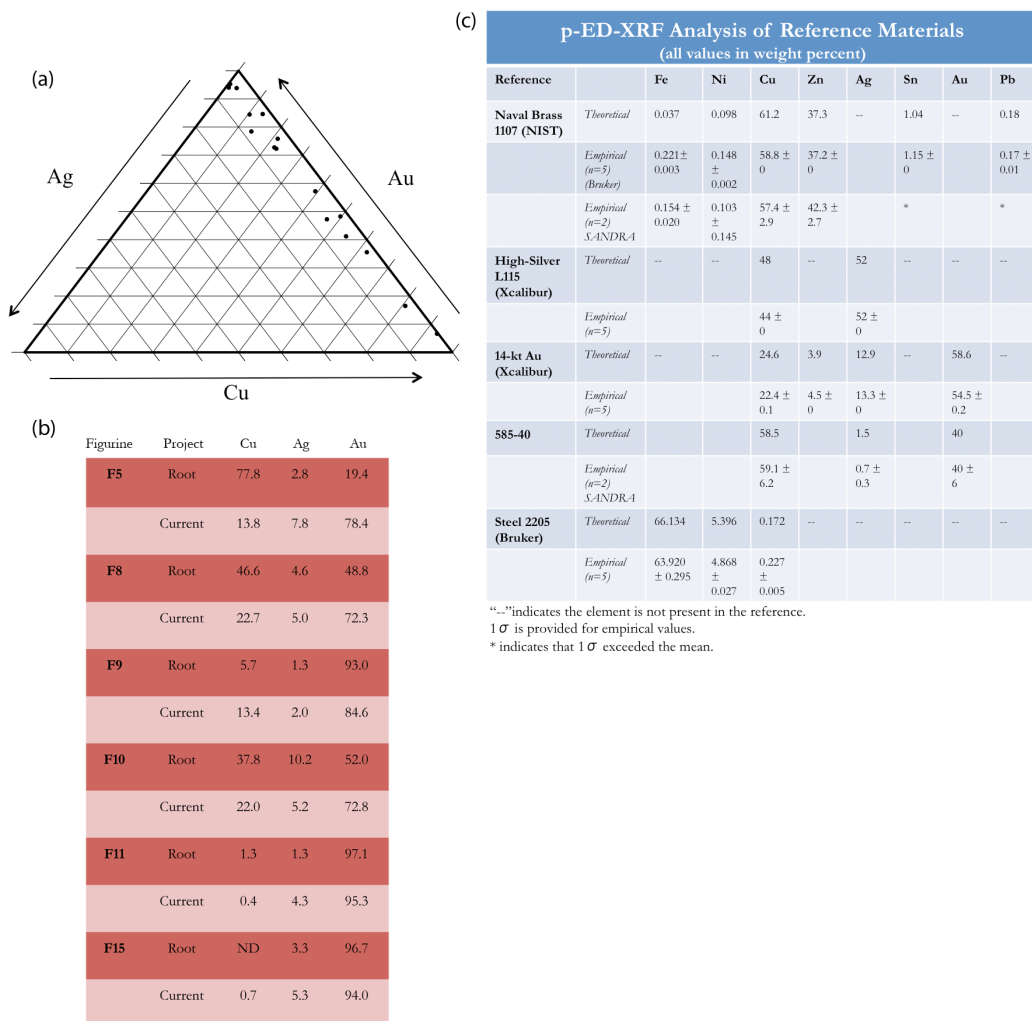* indicates that 1σ exceeded the mean.

Figure 8. A ternary (Au-Cu-Ag) diagram is presented for the figurines (a). Each point represents the p-ED-XRF analysis of one representative location on each figurine (n=16). Comparisons are possible between the compositions (analysis by p-ED-XRF) of six figurines studied in this project (F5, F8, F9, F10, F11, F15) and the data obtained by Root (in Lothrop 1952 and the PMAE archives) for those objects (b) (current project data presented in wt%; it is uncertain whether Root used atomic or weight percents). Analyses of certified reference materials used for p-ED-XRF standardization of both the Bruker and SANDRA systems are shown in (d) and compared to their expected compositions.
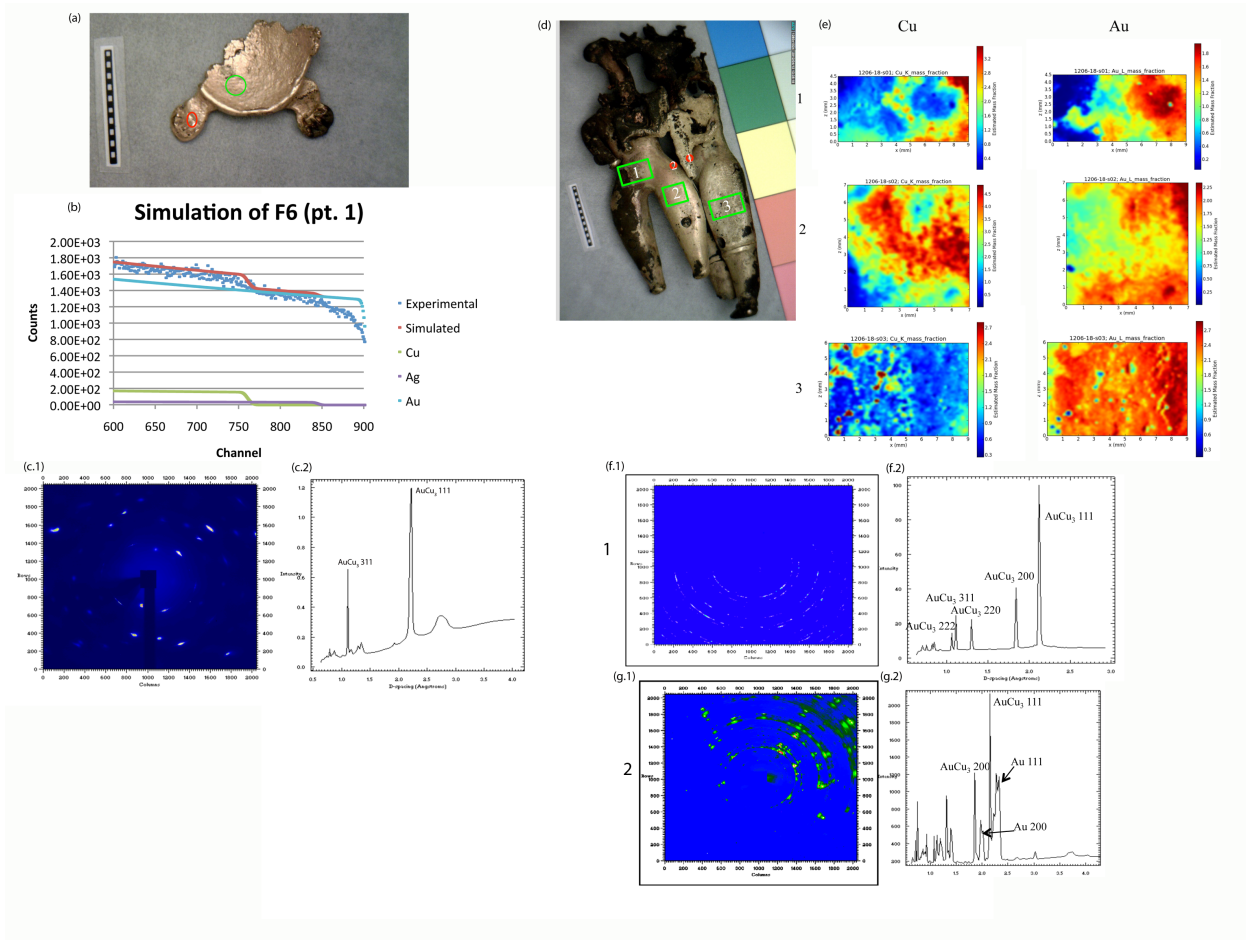
65

Figure 9. Figurine F6f (shown in (a) was analyzed with RBS (He++, 3 MeV) (area studied indicated with green circle in (a)), which revealed, instead of superficial enrichment, one homogeneous layer whose composition was modeled as Cu: 44.8 at%, Ag: 3.7 at%, Au: 51.5 at% (shown in (b)). SR-XRD analysis of the area shown in the red circle in (a) showed a pattern (c.1) consistent with a metal left in its as-cast state with phases tentatively indexed as AuCu3 (c.2). Figurine F5 (shown in (d)) was evaluated with SR-XRF, yielding distribution maps for Cu and Au (covering areas consistent with the green rectangles 1, 2, and 3 in (d)). SR-XRD yielded patterns consistent with cast polycrystalline materials that were subsequently hammered (f.1 and g.1) and phases indexed as either AuCu3 or pure Au (f.2 and g.2).