The Royal Tombs of Ur, Mesopotamia

New Investigations, New Results from the Examination of Metal Artifacts and other Archaeological Finds

Workshop

Deutsches Bergbau-Museum Bochum, May 2015

Organized by Andreas Hauptmann and Sabine Klein

Contents

An Introduction

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The ancient city of Ur in the southern part of the lowlands of Mesopotamia (today Iraq, Figure 1) was excavated in the 1920s and 1930s by the British archaeologist Leonard C. Woolley. Among other architectural remains, a cemetery in the southeastern part of the central part of the city was excavated (Figure 2). This cemetery consisted of some 2000 graves. Of them, 660 dated to the Early Dynastic III period (ca. 2600–2500 BC). The 16 large shaft graves provided precious grave goods and thus represent enormous wealth. Woolley considered them to be the graves of the "kings" and "queens" of Ur and termed them "Royal Tombs" (Woolley, 1934)(Figure 3). After the end of the excavations in 1934, the finds were distributed among the National Museum in Baghdad, the British Museum, London, and the University of Pennsylvania Museum of Archaeology and Anthropology in Philadelphia.

Once the finds and findings of these Royal Tombs have been known, a scholarly discussion began about the physical objects, the composition, craftsmanship, technology and provenance of the materials, about their social meaning and importance, the dating and the interpretation of the burials, and about the enigma that numerous attendants apparently followed the deceased of the main burial into the grave. The discussion is still ongoing to date. Based on the latest knowledge, the cemetery dated between c. 2500 – 2000 BC, i.e., until the beginning of the III Dynasty of Ur (see Vogel, 2014, p.170).

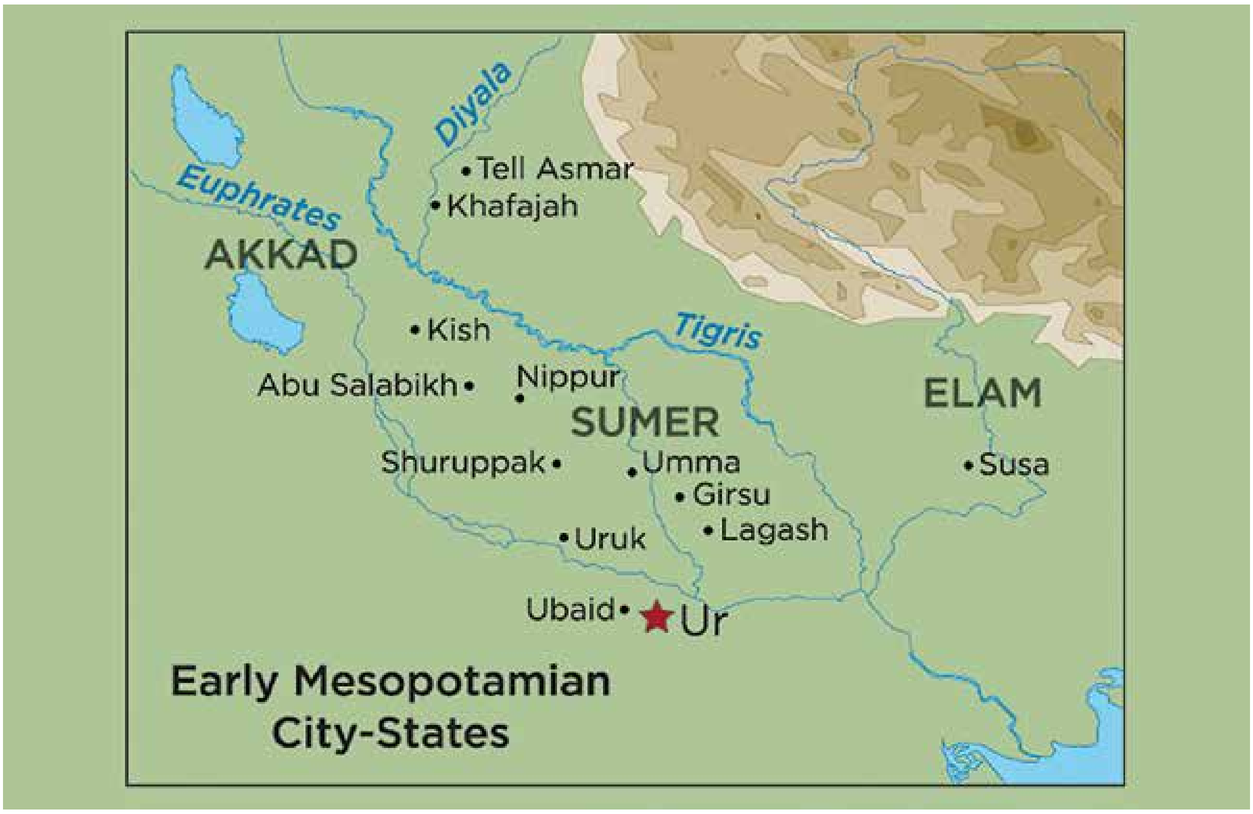

Figure 1. Topographic map of the southern part of Mesopotamia, the land of Sumer, between the rivers of Euphratus and Tigris, showing the location of the city of Ur and many of the other first cities of the 3rd / 2nd millennium BC. Note that in this map the ancient coastline of the Persian Gulf ("Lower Sea", Heimpel, 1987) is not far from the city of Ur. Image courtesy of the Penn Museum, Philadelphia.

Figure 2. Aerial photograph taken in March, 1930, showing the excavations of the Royal Cemetery at the southeastern corner of the Nanna temple complex (bottom of photograph). Photo: University of Pennsylvania Museums Archive. Image courtesy of the Penn Museum, Philadelphia, Image no. 191616.

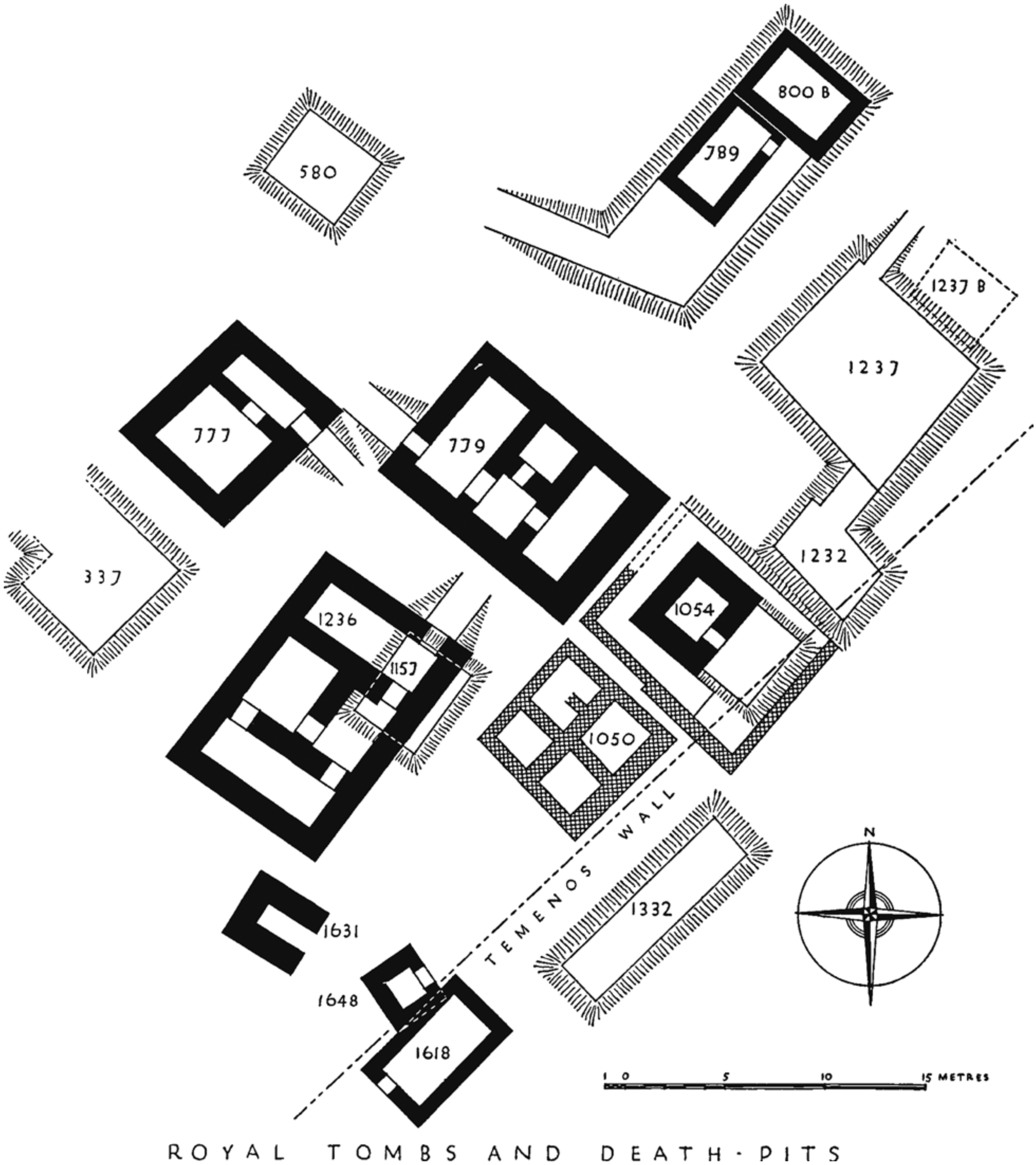

Figure 3. Detail of the Royal Cemetery at Ur showing the sixteen tombs deemed "Royal" by Woolley (1934, pl.273). Image courtesy of the Penn Museum, Philadelphia.

Analytical investigations on the metal artifacts and other materials from the Royal Tombs were performed shortly after the completion of the excavations by Leonard Woolley. H. Plenderleith (1934) who was a conservator at the British Museum at that time, was the first to publish a very small number of chemical analysis of the gold, silver, copper and bronze artifacts. These were predominantly performed by C. H. Desch. Desch performed the first systematic program of analytical and metallographic studies of metals from Mesopotamia after his appointment to the Sumerian Copper Committee by the British Association for the Advancement of Science in 1927 (Desch, 1929). Among all the finds he had investigated, there was a large number of metals that were shortly excavated at Ur. There were two objectives of these studies. 1) The natural resources should be identified from which these metals and alloys were manufactured because, especially in the southern part of Mesopotamia (Sumer, Akkad), no metal-bearing deposits occur. Consequently, all metal objects that were found in Ur must have been imported from elsewhere. 2) The level of metal craft should be studied. The development of urban centers in Mesopotamia since the 4th and 3rd millennium was obviously connected to economic and technological growth. It was a period in which supra-regional contacts to the west and to the east were intensified. Raw materials can be seen to have moved over long distances. Amiet (1986) coined the term "Age of Exchange" (see also Helwing, 2014, p.413), and this was the period in which metals were deliberately mixed to produce alloys, e.g., the copper-tin alloys. Desch who had analyzed a number of elements such as lead, arsenic, nickel, tin, iron, silver and sulfur, found especially that nickel was almost invariably present in copper and copper alloys from Ur. Nickel is an element that is, for example, present in the copper-bearing minerals and as well as the smelting slags of Oman. He thus suggested that the copper ore district of Oman in the southeast Arabian Peninsula had to be considered as one of the major sources for copper in Mesopotamia.

Plenderleith (1934) benefitted from Desch's results, knowledge and experience. In his article on the metal finds from Ur, he published dozens of metal analyses of Desch, also analyses of objects from Ubaid, Nineveh, Susa, Kish and Bahrain. The Ur finds were primarily those allocated to the British Museum after the excavation. Plenderleith, who was a chemist and archaeologist by training, discussed and interpreted the chemical composition and textures of gold, silver, bronze and copper artifacts with great expertise. On the basis of trace element results, he latched onto Desch's idea, which was that the origin of the Sumerian copper was Oman or *Magan*. This idea was confirmed at a much later date through modern analytical techniques, more precisely, by comparing the lead isotope signatures of Sumerian copper with Omani copper mineralization (Begemann, et al., 2012). The interpretation of the cuneiform texts strengthened this interpretation by supporting a maritime trade of copper from *Magan* to the small island settlement Umm an-Nar and the island of Bahrain (*Dilmun*) in the „Lower Sea“ (Persian-Arabian Gulf) (Heimpel, 1987).

Unlike for the copper, the tin, as the second alloying constituent in the bronzes, thwarted any attempt to locate its origin and its source could be nothing but speculation. The tin deposits of Afghanistan were indeed known as being a potential source, but without any analytical nor textual proof.

The ambiguity of origin is also a problem for the gold objects. Plenderleith consistently found objects containing silver concentrations up to 40 wt.%, termed electrum, a variety of gold that can occur in nature containing 20 % of silver or more. The gold was not refined to high-grade gold. The source locations for the gold from Ur still remain an mystery. But an important note in reference to the potential sources of the gold from Ur is the predonimant and close association of gold with lapis lazuli in various objects within the Royal Tombs. The source of the blue colored semi-precious stone is known because deposits of lapis lazuli are extremely rare in the world: It was mined in the famous mines of Sar-i Sang in northeastern Afghanistan and was already traded in the 3rd millennium BC in the many regions of the Middle East. The deposit of Sar-i Sang is therefore treated as a regional „anchor“, so it is possible that the gold may have its origin in Afghanistan as well. On a visual basis (for reasons of conservation and the limited analytical capabilities of the time, no more was possible) and also with regard to excavated tools of the ancient goldsmiths, Plenderleith suggested a variety of fabrication techniques: Different joining techniques such as soldering using mouth blowpipes, cloisonné, repoussé, chasing and engraving, manufacturing of gold leaf and gold foil, hammering and casting of gold and silver.

Long after Plenderleith's investigation on the material, in 1980, the Mesopotamian Metal Project (MMP) was initiated at the University of Pennsylvania Museum of Archaeology and Anthropology in Philadelphia in order to answer basic questions about the nature of the metals and alloys used during the different time periods and in different areas of Mesopotamia (Stech, 1999). The MMP was the joint work of Stuart Fleming, J. D. Muhly, V. C. Pigott and T. Stech-Wheeler. It was the inception of J.D. Muhly after Max Mallowan (1977) stated that it is still not known whether the Sumerian used copper or bronze (see discussion in Plenderleith, 1934, pp.285-286). The project included elemental analyses of main and minor constituents of 350 copper-based artifacts (copper artifacts and tin bronzes) from a number of Mesopotamian cities such as Ur, Kish, Fara, Nippur, Gawra, Billa, Nippur and Khafajeh. No gold artifacts were investigated. Metallographic analyses were made from about 150 samples, which in part were analyzed by scanning electron microscopy. Elemental analyses were obtained using the PIXE-technique by S. Fleming. One major focus was again the question of tin: Tin bronzes were identified in the Royal Tombs of Ur (Stech and Pigott, 1986). The authors argue that the tin derived from Afghanistan and was brought to Mesopotamia along with other prized goods such as gold and lapis lazuli.

The Heidelberg project „Early metals in Mesopotamia“ (FMM) was focussed on the recording and analysis of numerous metal finds. It was developed to provide a basis to link the development of metallurgy in Mesopotamia with the technological knowledge in the neighboring cultural regions of Eurasia (Hauptmann and Pernicka, 2004). Impetus for this project goes back to Dr. Michael Müller-Karpe, who had created an important basis with his work on the metal containers in Iraq. In their book „Die Metallindustrie Mesopotamiens von den Anfängen bis zum 2. Jahrtausend v. Chr." an enormous collection of more than 2500 chemical analyses of copper, bronze, silver and gold artifacts were presented. The analyses were mainly performed using a portable X-ray fluorescence spectrometer (pXRF), but also by neutron activation analysis (NAA). The authors mainly analyzed artifacts from the National Museum of Iraq in Baghdad. One of the major aims to be explored in this project was, once again, the question of the source or sources of tin for alloying copper to make tin bronze.

This study was followed up by Begemann and Schmitt-Strecker (2009). In a further investigation they analyzed the lead isotope ratios of 140 copper and bronze objects from the Heidelberg project. In this study, they also included more than 50 objects from the Museum in Philadelphia, which were analyzed for their elemental composition and metallographic texture. The lead isotope signature of the artifacts in comparison with their lead isotope database revealed new and interesting results and helped to confirm some of the existing theories and hypothesis. The authors found that the suite of metal sources supplying copper to Mesopotamian are in high probability to be located in Anatolia, Iran, Oman, Faynan in the Wadi Araba in Jordan and northwest India. Many tin bronzes, which appear in the middle of the 3rd millennium BC, deviate from the copper metal in their lead isotope ratios and suggest an import of tin bronze from yet unknown sources embedded in much older geological environments than the regions mentioned above.

In 2009, on recommendation of Prof. Dr. Richard Zettler, the authors received the permission from the University of Pennsylvania Museum for Archaeology and Anthropology to start a new project to investigate metal artifacts of gold, silver, copper and bronze and other materials from the collection of the Royal Tombs of Ur archived at the Museum in Philadelphia. This research project is a joint project of the Goethe-Universität Frankfurt am Main and the Deutsches Bergbau-Museum Bochum. The project is entitled "Die Königsgräber von Ur, 2600 v. Chr.: Analytische, archäologische und technologische Studien an Gold-, Silber-, Kupfer- und Bronzeartefakten aus der Sammlung des Penn Museums, University of Pennsylvania, Philadelphia".

A first screening of the material was performed by applying non-destructive analytical techniques to some dozens of gold objects from the collection in Philadelphia. In a second stage, we were permitted to sample 71 gold objects and 50 pigment powders which were typically stored in cockle shells. We were also allowed to borrow a collection of prepared mounted and polished samples (we named them "Nash-collection"), which included 89 samples of copper-based alloy fragments, 20 samples from silver objects and 2 gold fragments for investigations in Germany.

The scientific questions addressed in this ongoing project tie in with the problems adressed by Woolley and Plenderleith and by the authors previously mentioned. It continuously focusses on two aspects:

1.) The technological level of the craftsmanship of the metalworkers and the workers processing other materials: Are the technologies and innovations seen in the Ur metalwork a manifestation of the enormous political and cultural development of the urban settlements of Mesopotamia in the 3rd millenium BC? Were these techniques imported from elsewhere, i. e. form lands connected with Ur by its far-reaching trade contacts? This leads directly to the second major aspect:

2.) Provenance studies: Where did the metals and other materials come from? Much is known from archaeological sources, but there are many gaps of knowledge. Cultures and civilizations within distances of several thousands of kilometers in all directions from Mesopotamia have to be taken into consideration.

Today we are able to apply the most modern analytical methods with higher sensitivity than ever before, and the yield of the analysis of archaeological materials can be greatly intensified by micro-sampling methods that allow to take portions of the objects to the laboratories. We are able to analyze the isotope compositions of lead, copper and osmium. In addition, large databases are available today, for chemical compositions as well as for lead and copper isotopes of slags, metals and minerals all over Europe and beyond.

A workshop was organized to discuss the progress and preliminary results of the ongoing research project. The first results obtained in several sub-studies on the materials from Ur are promising. They were presented in a workshop at the Deutsches Bergbau-Museum Bochum, May 18th / 19th, 2015.

All people working scholarly in our project and some external colleagues working on the Ur collections and relevant themes were invited to attend this workshop.

The following colleagues attended the workshop and presented lectures:

- PD Dr. Barbara Armbruster, Université de Toulouse-Le Mirail, Toulouse, France: Technological Aspects of the Gold Objects from Ur – Preliminary Results and Perspectives.
- Dr. Kim Benzel, Department of Ancient Near Eastern Art, Metropolitan Museum of Art, New York City: Technologies of Jewelry at Ur: The Physics and Metaphysics of Skilled Crafting.
- Prof. Dr. Andreas Hauptmann, Research Laboratory for Archaeology and Materials Science, Deutsches Bergbau-Museum Bochum: Making and Provenancing of Cosmetic Pigments from Ur.
- Prof. Dr. Andreas Hauptmann, Research Laboratory for Archaeology and Materials Science, Deutsches Bergbau-Museum Bochum: Golden Artifacts from the Royal Tombs of Ur, Mesopotamia.
- Dr. Brad Hafford, University of Pennsylvania Museum of Archaeology and Anthropology: Ur-online and the Presentation of Scientific Data.
- MA Moritz Jansen, Research Laboratory for Archaeology and Materials Science, Deutsches Bergbau-Museum Bochum / University of Pennsyvania Museum for Archaeology and Anthropology: Where does the Gold from the Royal Tombs of Ur come from? Provenancing Gold Sources using Analytical Methods.
- Prof. Dr. Sabine Klein, J.W. Dept. of Geoscience, Mineralogy, Goethe University Frankfurt a.M.: Lead Vessels from the Jamdat Nasr-Period, Ur.
- Prof. Dr. Sabine Klein, J.W. Dept. of Geoscience, Mineralogy, Goethe University Frankfurt a.M.: New Analytical Results from the Ur-Collection of the British Museum.
- Dr. Stephen Merkel, Research Laboratory for Archaeology and Materials Science, Deutsches Bergbau-Museum Bochum: Silver Ores from the Panjhir Valley, Afghanistan.
- MA Eveline Salzmann, J.W. Dept. of Geoscience, Mineralogy, Goethe University Frankfurt a.M.: Analytical Investigations on Silver, Copper and the Earliest Tin Bronzes form Ur.
- Dr. Judith Thomalsky, Deutsches Archäologisches Institut: New Activities of the German Archaeological Institute in Afghanistan.
- MSc. Hendrick Wick, Dept. of Geoscience, Mineralogy, Goethe University Frankfurt a.M.: Petrological and Geochemical Investigations of "Alabaster"-Vessels from Ur.
- Prof. Dr. Richard Zettler, University of Pennsylvania Museum of Archaeology and Anthropology: A Horde of Copper-Alloy Vessels from PG 1422, a Late Akkadian Burial.

Extended abstracts of a eight of these lectures given at the workshop are presented in this supplement to METALLA 22(1). Due to the advanced stage of the results of the analysis on the pigments of Ur, they are presented as an independent and contribution earlier in this issue.

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- Metropolitan Museum of Art, New York

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Golden Artifacts from the Royal Tombs of Ur, Mesopotamia

Andreas Hauptmann and Sabine Klein

Introduction

At the confluence of Tigris and Euphrates, the Early Dynastic period was a time of great wealth and prosperity for the city of Ur and a time of secure long distance trade relations. Countless finds, which were recovered from the tombs of the Royal Cemetery of Ur are not only witnesses for an extraordinary degree of craftsmanship, they are number of precious artifacts crafted from (noble) metals and semi-precious stones. Only very few analytical investigations on these invaluable objects of enormous cultural importance were performed in the past, and those that were mostly were motivated by pressing preservation issues. Based upon the available analyses (Plenderleith, 1934, pp.294), it is apparent that there are different types of gold alloys present in the Royal Tombs and the availability of different types of gold is also supported by the textual evidence in cuneiform tablets (Reiter, 1997). Moorey (1994), however, stated that the interpretation of the textual evidence for the kinds of gold and silver and their origins is anything but simple.

Visual inspection of the gold artifacts shows that there are variations of color and this should be to be expected with gold alloys: The gold objects of Ur appear yellowish, whitish and reddish with changing tints. Details of color variations must have been certainly well-known already in early gold smithing, so that it is reasonable to assume that the different colors could have been produced deliberately.

As a first stage of the larger joint venture between the Penn Museum, the Deutsches Bergbau-Museum Bochum, the Goethe-Universität Frankfurt and the British Museum, a series of non-destructive elemental analyses on selected gold and silver objects were performed in 2009 at the Penn Museum.

Our question were the following:
1. Do the artifacts, which are conventionally termed as "gold" consist of pure gold or are they gold alloys?
2. If the artifacts were made of alloys rather than of pure gold, was the alloy produced deliberately by adding other components e.g. silver and / or copper to the gold, or do such alloys have a natural origin?

Materials and Methods

From the Penn Museum's collection, we have analyzed 30 objects: Three bowls, one tumbler, 19 jewelery objects and 7 tools and weapons. These artifacts were predominantly selected from two tombs, the tomb of Puabi (PG 800) and the Great Death Pit (PG 1237), from which most of the gold objects were excavated. Most of the gold artifacts from the Royal Tombs are made of sheet gold, which was presumably hammered out, e.g. from a bullion. These sheets were used to manufacture the many meters of ribbons for hair decoration or the large number of leaves used in pendants. Sheet gold was also used for making the famous bulls heads, which decorate the wooden lyres from the Great Death Pit, or for gilding parts of the Rams in a Thicket. Also, the tumblers and vessels were hammered out from bullions. Among all gold objects from the Royal Tombs, massive cast objects are rare. Only a few chisels, a dagger and a socketed adze could be identified as cast.

A handheld portable X-ray fluorescence spectrometer (pXRF) was used for the elemental analysis. The pXRF is an energy dispersive system and applicable for the determination of main and minor element composition of inorganic materials. The method lacks high percision and cannot be applied to obtain bulk elemental compositions; it only analyzes the small area of the surface. Corrosion, as a natural process of weathering, may affect gold artifacts buried in the soil. It is well-known that archaeological gold artifacts as well as natural gold nuggets occasionally may be "coated" with a layer of gold of higher fineness than in the bulk. In this case, the information gained with pXRF would not be represent-

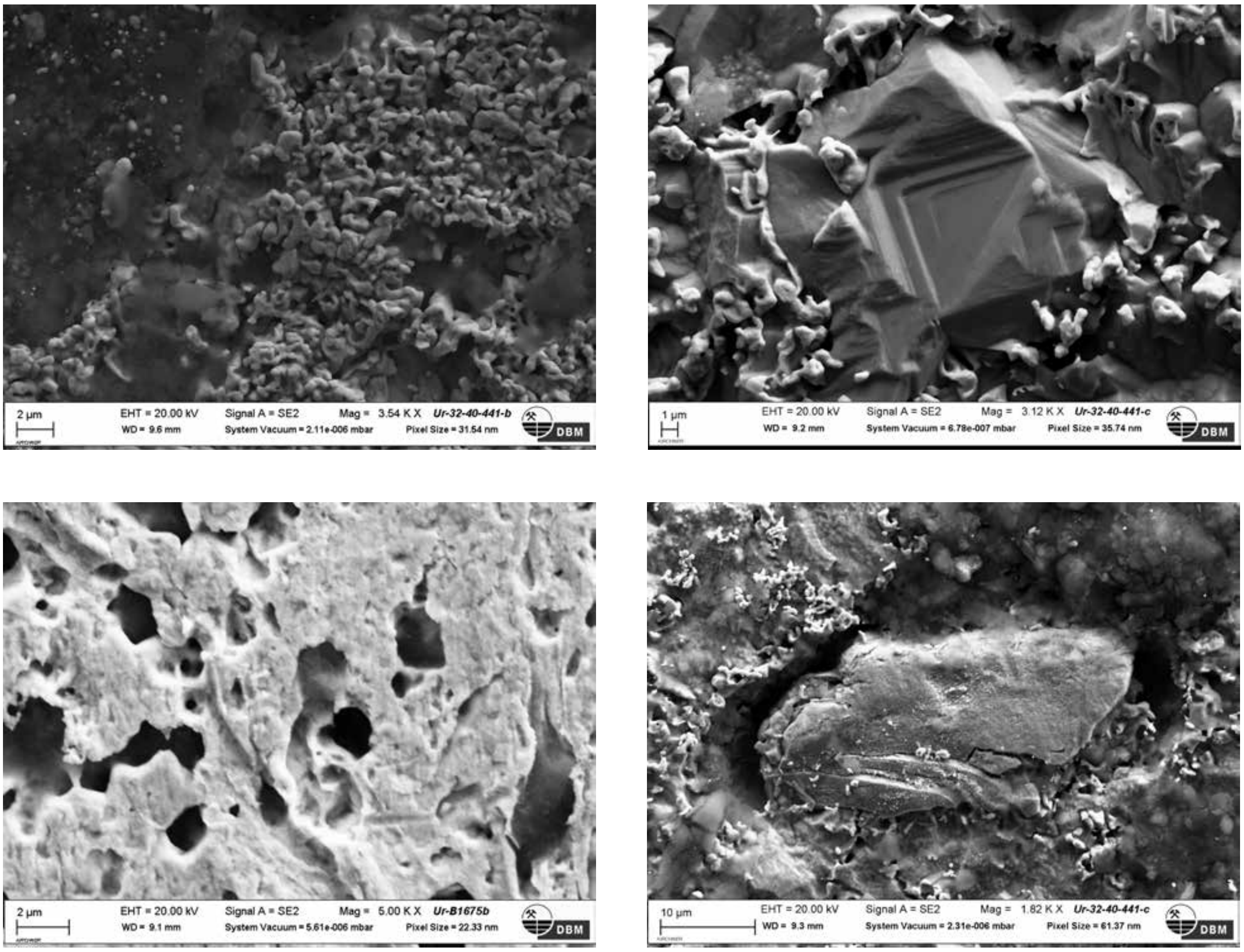

Figure 1.Scanning electron microscope secondary electron images illustrating the textural features of surfaces of some hair ribbons from Ur. a: Formation of a typical spongy texture caused by leaching of silver from gold by corrosion. b: Remains of spongy gold and formation of authigenic gold at the surface. Note network of anhedral gold buds sitting on etched crystals of the AuAg alloy. c: Nanoporous spongy texture caused by dissolution of silver from gold. d: One of the frequent inclusions of platinum-group elements (PGEs) in the gold alloy. Note the well crystallized habitus of the inclusion. Sample numbers under every image.

ative for the composition of the core metal. To explore this potential problem, selected pXRF analyses were cross-checked by electron microprobe measurements of core metal and only very slight differences were found (Jansen, in prep.). Therefore, pXRF was used as a first step, and the method was applied on object where destructive sampling was not permitted. However, only through the sampling of objects can the most high precision analytical methods be applied to gain the largest amount of information.

Besides elemental analyses, we investigated the surficial microtexture of a few samples by scanning electron microscopy (SEM). Microtexture analysis contributes to the understanding of technological information, e.g. crystallization state (cast or worked), dissolution or oxidation (corrosion / leaching processes) and tool marks (manufacturing techniques).

Results

The results are divided into four parts exploring different aspects of the analysis of the gold objects.

Tarnish and Corrosion

The golden color of the objects is frequently stained by red and black patches covering the surface. These splotches consist of thin layers of clay enriched with iron- and manganese hydroxides. They have to be treated as post-burial formations.

The surfaces of gold-silver-alloy objects are dull and show corrosion phenomena visible under the scanning electron microscope. This corrosion led to a spongy texture with irregular particles with gently sinuous outlines forming vermicular structures, which is called cellular honeycomb (Figure 1a). Below this surficial texture

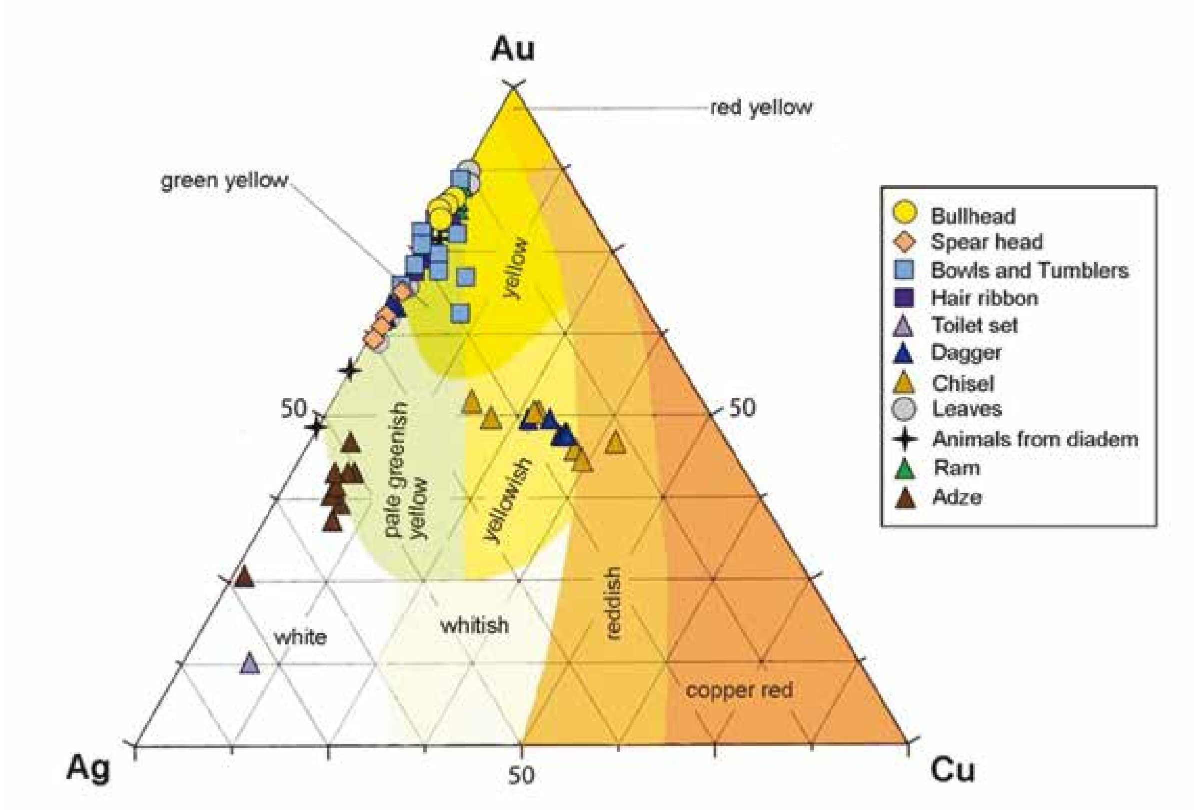

Figure 2. Multiple analyses of gold objects from the Royal Tomb of Ur plotted in the ternary system Au-Ag-Cu indicating the variation of colors achieved by specific mixtures of gold, silver and copper. Note that the variation of colors depends on the portion of single alloy components. This results in stability fields for the different colors of gold alloys. The analyses indicates that the majority of the objects plot within the field of yellow and greenish-yellow gold, while objects high in copper plot within the reddish-yellowish field.

etched crystals of AuAg are visible (Figure 1b). The material is interspersed by sets of minute pores (Figure 1c).

These spongy surfaces and pores result from silver dissolution from the gold-silver alloy as it is the case with widespread natural silver depletion of nuggets in sedimentary context (Falconer and Craw, 2009, p.89). As for the gold objects, silver was dissolved out of the alloy body and led to a precipitation of silver chloride. This effect was probably caused by the very typical soil conditions of the region during burial: Oxidation in salt-rich marshes and *sabkhas* with a surplus of chlorides (Möller, 1995). In the archaeological context, this phenomenon also occurs in artificially depleted gold observed at mid-1st millennium BC Sardis, where gold was refined. Comparable textures were described by Meeks (2000) and Geckinli, et al. (2000).

Chemical composition

Silver, and subordinately copper, are the predominant alloy components of the gold objects from the Royal Tombs. Additional traces of elements such as Sn, Zn, Pb, As, Fe and Ir are rare and in most cases below 1 wt. %. The variety of the gold alloy compositions as found in the objects from the Royal Tombs are well represented by the ternary phase diagram Au-Ag-Cu (Figure 2). The silver contents in the gold objects range between c. 10 and 35 wt. %. Many hair ribbons, leaves and other jewelery made of hammered foils belong to these alloys. There is no evidence for pure gold. This is in good correspondence with the co-existence of geological gold and silver occurences in natural alluvial placers. The silver-containing gold objects were thus most probably manufactured using natural alluvial gold-silver alloys (placers) without any further processing. Parting, i.e., a metallurgical separation process to remove silver from gold, as suggested by Levey (1959), is not known to have been practiced at Ur in the middle of the 3rd millennium BC.

Objects higher in silver (c. 50 wt.%) rarely occur and are connected with increased copper concentrations (5-8 wt.%) in the Royal Tombs. One of these silver-rich objects is a socketed adze, which is one of the few examples represented in the Royal Tombs that was cast instead of hammered. The adze has a distinctly whitish tint overall and differs from the color of other gold artifacts. The alloy composition would solidify in the range of c. 900 - 950 °C, much lower than the melting point of pure gold (1063 °C). We suggest objects of this alloy to be a deliberately produced alloys. Even if native gold may contain such high silver concentrations (Antweiler and Sutton, 1970), the copper is much too concentrated. Natural

Figure 3.Dagger # 30-12-550, PG 1054. The dagger is composed of several types of gold. For the decoration of the hilt, greenish-yellow gold was used to manufacture some 400 nails, the collar and the sheets (left). The blade consists of a gold-silver alloy high in copper, gilded by a depletion gilding process. The golden surface is only in parts preserved (right). Length of the dagger: 33 cm. A similar feature is to be observe on the blade of a dagger from the Baghdad-Museum (Internet: www.baghdad-museum.org).

gold bears only small quantities of copper (< 1 wt. %); slightly higher concentrations maybe caused by incomplete separation of gold from copper minerals during the washing of alluvial gold (Hauptmann, et al., 2010).

One of the most exciting results of our analyses is that, beside the variety of gold-silver alloys, also alloys with extraordinary high copper contents (23 – 40 wt.%) occur (Figure 2). This concerns several objects, which were all made of massive (cast) metal. The dagger blade of tomb 1054 (# 30-12-550) and two chisels (# B16724 and # B16725) from Pu-abi's grave (PG 800) belong to this group. The dagger is made of various components that consist of diffrent alloy compositions. The excellently burnished blade is fabricated in one piece of a copper-rich gold-silver alloy. However, it shows slightly varying pinkish to yellowish and shining tints of gold (Figure 3). Above the guard on the hilt and on the pommel c. 400 nails with spherical heads of pale greenish-yellow color were inserted on gold sheets. These are made of a gold-silver alloy low in copper. No sheeted metal objects were produced from this high-copper alloy. We presume that these gold-silver-copper alloys were mixed deliberately with (tin-containing) copper.

Depletion gilding

The surfaces of the dagger's blade and the chisel have much higher gold and silver contents than the cores, which consist of the above described gold-silver-copper alloys. The metallurgical technique to enrich gold on the surface of gold alloys containing copper is called depletion gilding. The technique is based upon the following metallurgical procedure: An object is cast from a homogeneous ternary gold-silver-copper alloy. The entire range of gold-silver-copper ratios is possible. The variable compositions of such alloys result in characteristic colors that vary from red-orange to red gold. The lowest solidification temperature of this alloy is around 900 °C, which is about 150 °C lower than the melting points of its individual metals. The lowered melting point of the gold-silver-copper alloys is of major advantage for the goldsmith's work, especially during further casting or other processing techniques.

After an object is brought to its final shape and design, it is heated in an open fire to selectively oxidize the copper. Since silver and gold have less affinity to oxygen than copper, they remain in metallic condition. In contrast, copper reacts with oxygen to copper oxides, which form a reddish or black crust. Finally, this crust is mechanically removed by hammering. Possible remains of copper oxide will be leached out in a boiling of plants high in tannic, oxalic-, apple-, citric acid or in urine. Finally, a spongy gold-rich surface results from this process, which can be compacted by hammering and polishing.

At the current state of research, it appears that these two examples from Ur are only depleted in copper and the gold to silver ratios remain constant. We found no evidence that chemical treatments, such as heating with iron compounds and chlorides, were applied to selectively leach out the silver from the surface of the alloy, and this technique may not have been known. Had the technology of separating gold and silver (cementation) existed at this time, then one would expect to find objects from Ur made of pure gold, but this is not the case. Depletion gilding from gold-silver-copper alloys, which are named *tumbaga*, with depletion of both copper and silver was described as a characteristic technique for the Pre-Columbian South Americas (Lechtman. 1973; 1979;

Ingo, De Caro and Bultrini, 2007; Scott, 2012). It was suggested that this technique was first invented there. In compliance with previously published data from Ur (La Niece, 1995; Hauptmann and Pernicka, 2004), and our own observations, it is confirmed that a variation of depletion gilding was already known at the time when the Ur objects were manufactured.

Inclusions of platinum group minerals

One of the most remarkable characteristics of the gold artifacts from the Royal Tombs are abundance of silvery shining inclusions, which are composed of platinum group elements (PGE), particularly consisting of alloys of osmium, iridium and ruthenium. They occur in unusual and unparalleled quantities in most of the gold artifacts from the Royal Tombs (Jansen, et al., 2016) (Figure 1d). Generally, PGEs are contaminants in placer gold neighboring (ultra-) basic rock, where such PGE-bearing minerals occur in primary mineralizations. Primary gold deposits are geologically very different from this type of deposit. Gold and PGEs are thus associated with each other only in geological environments with secondary mineral deposition such as placer deposits, in which the PGE minerals can combine mechanically with the placer gold. The presence of PGEs in gold artifacts confirm that the gold, which was used for the production of the objects originated from secondary placers rather than from a primary gold source in solid rock. The high frequency of the PGE inclusions might be an indication that the gold was not, or often, re-melted (Meeks and Tite, 1980), because then the PGE being solid inclusions would probably have been reduced step by step from the liquid gold. It may be possible to determine the provenance of the PGE-containing placer gold used for the Ur artifacts through isotope analysis as reported by Jansen, Hauptmann and Klein in this volume.

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Objects from the Ur collection of the British Museum Sampling and Analytical Investigations

Sabine Klein, Susan La Niece and Andreas Hauptmann

Introduction

Our core project on the study of the artifacts from the Royal Tombs of Ur was developed in collaboration with the University of Pennsylvania Museum for Archaeology and Anthropology (Penn Museum, curator R. Zettler) which, like the British Museum, holds approximately a quarter of the excavation material from Charles L. Woolley's campaigns at Ur. The major part of the finds is in the National Museum of Baghdad. Initially, the focus was mostly on the objects from the Ur collection of the Penn Museum, Philadelphia. In Philadelphia, the great chance arose to analyze, non-destructively, the most prominent of the precious artifacts, but also it was permitted to sample a great number of the artifacts by drilling or clipping in order to carry out high-resolution analysis in our laboratories. In total, approximately 170 metal objects, 50 pigments and 6 calcite-alabaster vessels were sampled personally by Sabine Klein and Andreas Hauptmann at the Penn Museum.

In addition to the material from the Penn Museum, which was already accessible in generous volume, access was requested to the British Museum to its portion of the Ur material from the Royal Cemetery. The aim was to supplement the material from Philadelphia, more precisely the different material groups such as the gold, the silver and the copper-based objects. The focus was on the metallic objects at the British Museum rather than on the stone material from Ur.

The first visit to London to inspect the Ur material in the British Museum's collection was in November 2013. The first contact was Susan La Niece, Senior Metallurgist at the Department of Scientific Research and afterwards there was an appointment with Sarah Collins, Curator of the Early Mesopotamia collections, Middle East Department. After the first orientation, an application was prepared to conduct scientific analysis of British Museum material, in this case the sampling of selected objects from the Royal Tombs, and finally permission was granted and the sampling was undertaken at the British Museum in December 2014. Usually, this permission can only be received if the project can offer analytical techniques that are not held at the British Museum.

Selection of samples

In particular, permission was granted by the British Museum to sample 7 gold, 10 silver and 16 copper-based objects from the Royal Tombs of Ur. The British Museum does not permit researchers to undertake the sampling themselves. Thus, the sampling was carried out by Susan La Niece, but with the other authors presence in order to discuss the optimal sampling strategy for each of the objects.

As for the sampling, this was performed either by drilling with drill bits (1 mm) or by clipping off small pieces from the objects. For the analyses, a sample of c. 10 mg of fresh material was required. The first step was remove of the surface corrosion layer to reach the fresh material. The total depth of the drilled hole was about 5 mm. The drilling can only be applied when the material is appropriate in thickness and stability, and has to be carried out on areas of the objects that are hidden to the viewer (e.g. bottom, rims and broken edges). The hole can be filled after sampling – if requested – with colored resin or bees wax (In this case it was not requested). Alternatively, a tiny bit of the metal was cut from an existing edge of the object whenever it appeared less destructive than drilling or if drilling was not possible as in the case of sheets or very flat metal objects.

The previously approved application required that the samples taken remain the property of the British Museum, and shall be returned to the British Museum afterwards.

Details of objects sampled

The following metal objects from the Ur collection (Early Dynastic III) were pre-selected by Sarah Collins and Susan La Niece as potentially suitable for sampling. Af-

Table 1. Complete sample list of objects from Ur. The sampling was done at the British Museum by Susan La Niece on December 11, 2014.

Inv. Nr.	Ur-#	Grave	Object	Sample Position
Gold Objects				
1928-10-10-294		PG 800	Gold Ribbon	Clipped from Edge
1928-10-10-293	U 9983	PG 800	Boat-Shape Earring Fragment	Clipped from Sheet Area
1928-10-10-292	U 9983	PG 800, Body 7	Boat-Shape Earring Fragment	Clipped from Sheet Area
1928-10-10-80		PG 800	Large Boat-Shape Earring	Clipped from Pin
1929-10-17-51		PG 1054	Gold Ribbon	Clipped
1935-01-13-437	U 10586A	PG 789	Gold Ribbon	Clipped from Edge
1928-10-10-166		PG 800	Leaf from Headdress	Clipped from Edge
Silver Objects				
1928-10-10-132(A)		PG 800	Tumbler, Crushed, Undecorated	Clipped from Rim & Drilled Sample
NN-B		PG 800	Tumbler Fragment, Decorated	Clipped from Edge (Not Rim)
NN-C		PG 800	Tumbler Fragment, Decorated	Clipped from Edge (Not Rim)
1928-10-10-124		PG 789	Pin with Lapislazuli Head	Drilled Sample
1929-10-10-562		PG 1234	Pin Shaft (Head Separate)	Drilled Sample
1929-10-17-63		PG 1133	Bowl with Electrum Handles	Clipped Sample from Body
1928-12-12-149		PG 1276	Hair Ring	Clipped Sample
1928-10-10-133		PG 800	Stopper for Skin Vessel	Clipped Sample from Twisted Wire
1935-1-16-17		PG 789 (Probably)	Silver Ox Harness	Clipped from Edge
1928-10-10-131		PG 800	Sieve	
Copper and Copper-Based Objects				
1928-10-10-331		PG 777	Tubular Lance Head	Drilled Sample from Rim
1928-10-09-316		PG 580	Barbed Spearhead	Drilled Sample from Tip
1928-10-10-338		PG 789	Narrow Spearhead	Drilled into Side
1928-10-10-400		PG 800	Table with Leg	Drilled into one of the Legs
1928-10-10-320		PG 789	Spearhead	Drilled into Side
1929-10-17-632(A)		PG 1054	Stack of Bowls and Strainers	Drilled Sample from Large Bowl
1929-10-17-632(B)		PG 1054	Stack of Bowls and Strainers	Drilled Sample from Handle of Small Vessel
1929-10-17-632(C)		PG 1054	Stack of Bowls and Strainers	Loose Piece from the Body of Small Bowl
1928-10-10-399		PG 800	Ladle Handle	Drilled Sample from Handle
1928-10-10-302		PG 800	Adze Head	Drilled Sample
1928-10-10-398		PG 800	Adze Head	Drilled Sample, into Previous Drill Hole
1928-10-09-242	U 9337	PG 580	Lance/Javelin Head	Drilled Sample
1928-10-09-245	U 9337	PG 580	Lance/Javelin Head	Drilled Sample
1928-10-09-247		PG 580	Lance/Javelin Head	Drilled Sample
1928-10-09-249		PG 580	Lance/Javelin Head	Drilled Sample
1928-10-09-299		PG 580	Chisel	Drilled Sample

ter examination, sampling positions were agreed upon for drilling at an unobtrusive spot with a 1 mm diameter drill or clipping at damaged edges as appropriate.

The following listing gives an overview of the items which were originally selected for sampling and what was finally sampled in the British Museum (see also Table 1):

GOLD – sheet metal items

1. Gold ribbon fragment 1928,1010. 294, PG 800, body 7,
2. Gold boat-shaped earring fragment, 1928, 1010. 293, PG 800 (U9983),
3. Gold boat-shaped earring 1928,1010. 292, PG 800 Body 7 of Puabi's attendants - thin gold foil, crushed and damaged,
4. Gold boat shaped earring 1928,1010. 80, PG 800, Queen's attendant (with a second earring filled with bitumen),
5. Gold ribbon 1929,1017. 51, PG 1054,
6. Gold ribbon 1935,0113. 437, PG 789,
7. Leaf from gold and lapis collar / headdress - 1928, 1010.166, PG 800 Puabi attendant body.

In the course of the sampling, it was decided that the sampling of a pre-selected small, single earring 1928, 1009.165, PG 337 (thin gold foil) would cause unacceptable damage to the object. It was therefore excluded from sampling. This also applies for several of the leaf-shaped gold pendants that were previously intended for sampling which were found to be heavily torn and damaged; they were not sampled.

SILVER OBJECTS

1. Silver tumbler fragment of Royal Tomb style 1928,1010.132 crushed and fragmentary PG 800
2. Tumbler fragment, decorated, unnumbered,
3. Tumbler fragment, decorated, unnumbered,
4. Silver pin with lapis head from Kings Grave 1928,1010. 124, PG 789. Broken shaft tip and poor condition,
5. Silver pin shaft 1929,1017. 562, PG1234 head broken off shaft,
6. Silver bowl with electrum handles 1929,1017. 63, PG 1133 (Tray 66)- bent in and broken on one side,
7. Silver hair ring 1928,1010. 149 (121465), PG 1276,
8. Silver stopper (for vessel in G56) with twisted wire 1928,1010. 133, PG 800,
9. silver ox harness fragment, 1928, 1016. 17,
10. Silver sieve on mount ex gallery 56 1928,1010. 131, PG 800

In the course of the sampling, it was decided that a silver ox harness encased in wax 1935,0116. 36, PG 789 Kings Grave (probably) - radiograph film 6735 in CSR - was too deeply corroded and fragile to be sampled.

COPPER AND COPPER-BASED OBJECTS

1. Tubular lance head 1928,1010. 331, PG 777 (NB also interesting technology of rivets),
2. Barbed spearhead 1928,1009. 316, PG 580,
3. Narrow spearhead 1928,1010. 338, PG 789,
4. Table with animal legs1928.1010. 400, PG 800,
5. Spearhead 1928, 1010. 320, PG 789 (strange chemical treatment),
6. Stack of bowls and strainer (very corroded but heavy)1929,1017. 632, PG 1054, three samples,
7. Ladle handle 1928.1010. 399, PG 800,
8. Copper-alloy adze head 1928,1010. 302 PG 800 - in G56,
9. (Small, green) copper-alloy adze head 1928,1010. 398 PG 800 - in G56,
10. Small lance / javelin heads (there are 4 we could select just 3?) 1928,1009. 242 - in G56,
11. Ditto – 1928, 1009.245,
12. Ditto – 1928,1009. 247,
13. Ditto – 1928,1009. 249,
14. Chisel 1928,1009. 299, PG 580 - in G56

Elemental composition

The British Museum generally favors proper sampling and subsequent high-resolution analysis rather than non-destructive analysis. Where non-destructive methods (e.g., portable or micro-XRF) only give the main and minor elemental composition, and this also only for the surface of the objects, the analysis by mass spectrometry on samples taken by drilling from the inner core of the objects can give exact information about the body, i.e., the true composition of the objects. Lead isotope analysis provides insight to the provenance of the metals used for the production of the objects. In consequence, it gives information such as about connection routes, trading of materials and interaction within the city of Ur. It also contributes to further enlarge the reference database of lead isotope ratios and build a new one for osmium isotope ratios, which is not available at present.

The results presented concentrate on the sampled copper-based objects. Silver and gold objects are still under study; further results will be presented separately. Elemental analysis was performed in Bochum on dissolved samples with a mass spectrometer (Table 2). They reflect relatively pure copper objects and objects made of a copper-tin alloy.

Table 2. Elemental analysis of the copper-based (copper and copper-tin) samples from Ur (BM) by Mass Spectrometry (solution). [Inv.Nb. = Inventory number, norm. = normalized to 100%, detected = total detected]

Sample	Inv. Nb.	Cu	Sn	Pb	Ni	As	Fe	Ag	Sb	Zn	Co	S	Te	Hg	Bi	P	Se	norm.	detected
		in weigth%					in ppm												
Copper objects																			
5004_14	1928-10-10-331	99.68	0.010	0.072	0.005	0.127	0.106	1400	200	470	2	860	5	6.3	35	20	25	100	94.62
5006_14	1928-10-10-338	98.27	0.041	0.386	0.260	0.761	0.284	730	310	20	120	860	70	4.3	110	20	110	100	99.85
5008_14	1928-10-10-320	98.57	0.006	0.082	0.077	0.973	0.288	670	380	15	15	400	40	1.5	45	6	25	100	100.77
5011_14	1929-10-17-632(C)	96.67	0.023	0.029	0.130	2.740	0.411	270	230	35	40	250	35	<1	15	5	80	100	100.00
5014_14	1928-10-10-398	97.96	0.028	0.061	0.176	1.302	0.471	490	500	30	340	520	10	<1	55	20	20	100	102.11
5015_14	1928-10-09-242	99.03	0.007	0.016	0.237	0.366	0.345	120	180	45	150	3000	35	<1	40	4	90	100	101.07
Leg of a table																			
5007_14	1928-10-10-400	96.57	0.010	1.751	0.169	0.894	0.607	610	1200	45	50	450	15	2.1	70	6	75	100	100.63
Copper-tin objects																			
5005_14	1928-10-09-316	91.66	5.648	0.519	0.294	1.041	0.840	1000	1200	80	35	1400	15	3.4	50	80	15	100	81.68
5009_14	1929-10-17-632(A)	89.68	9.376	0.049	0.399	0.357	0.136	35	85	30	35	1400	40	2.2	25	20	110	100	95.28
5010_14	1929-10-17-632(B)	92.50	6.545	0.154	0.236	0.272	0.289	70	170	80	20	630	35	4.1	45	45	25	100	84.60
5012_14	1928-10-10-399	86.94	12.909	0.012	0.089	0.02	0.033	95	85	10	15	1200	45	<1	10	65	20	100	68.71
5013_14	1928-10-10-302	88.87	10.695	0.006	0.021	0.181	0.222	620	150	40	7	560	4	<1	8	25	20	100	99.24
5016_14	1928-10-09-245	89.45	9.505	0.368	0.103	0.229	0.348	290	340	25	15	190	15	1.2	60	20	45	100	96.15
5017_14	1928-10-09-247	91.49	7.593	0.314	0.160	0.280	0.158	280	470	15	25	75	15	<1	65	3	10	100	99.82
5018_14	1928-10-09-299	90.92	7.450	0.351	0.237	0.553	0.493	380	590	35	80	730	30	1.9	70	3	50	100	101.22
5019_14	1928-10-09-250	89.78	9.766	0.029	0.026	0.189	0.207	460	200	120	15	350	6	1.1	20	15	15	100	100.54

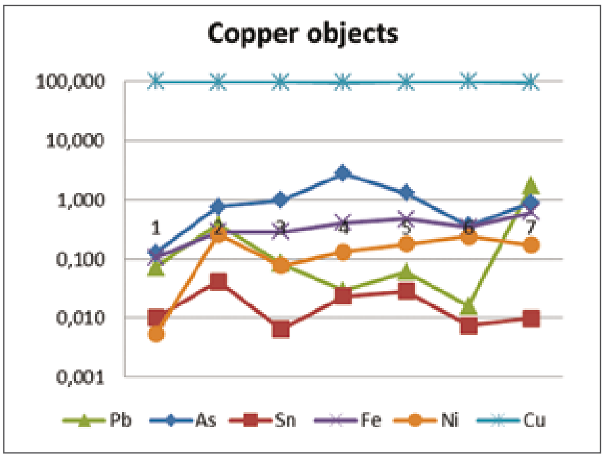

Figure 1. Elemental composition of objects made of copper. Objects are a lance head, spearheads, an adze head, a sample of a stack of bowls and strainers, a lance / javelin head and also a leg of a copper table. Values are in wt. %. Note that arsenic is variable and exceeds 1 wt. % in two samples (one adze head and one sample of the stack of bowls and strainers) and that one sample contains a high lead concentration (Leg of table, nb. 7 in diagram). Arsenic does not correlate with nickel.

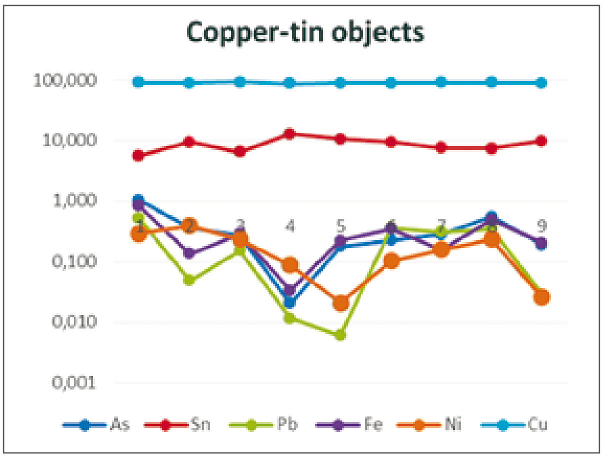

Figure 2. Elemental composition of objects made of copper-tin alloys. Objects are a spearhead, 2 samples from the stack of bowls and strainers, an adze head, a ladle handle, a chisel and lance / javelin heads. Values are in wt. %.

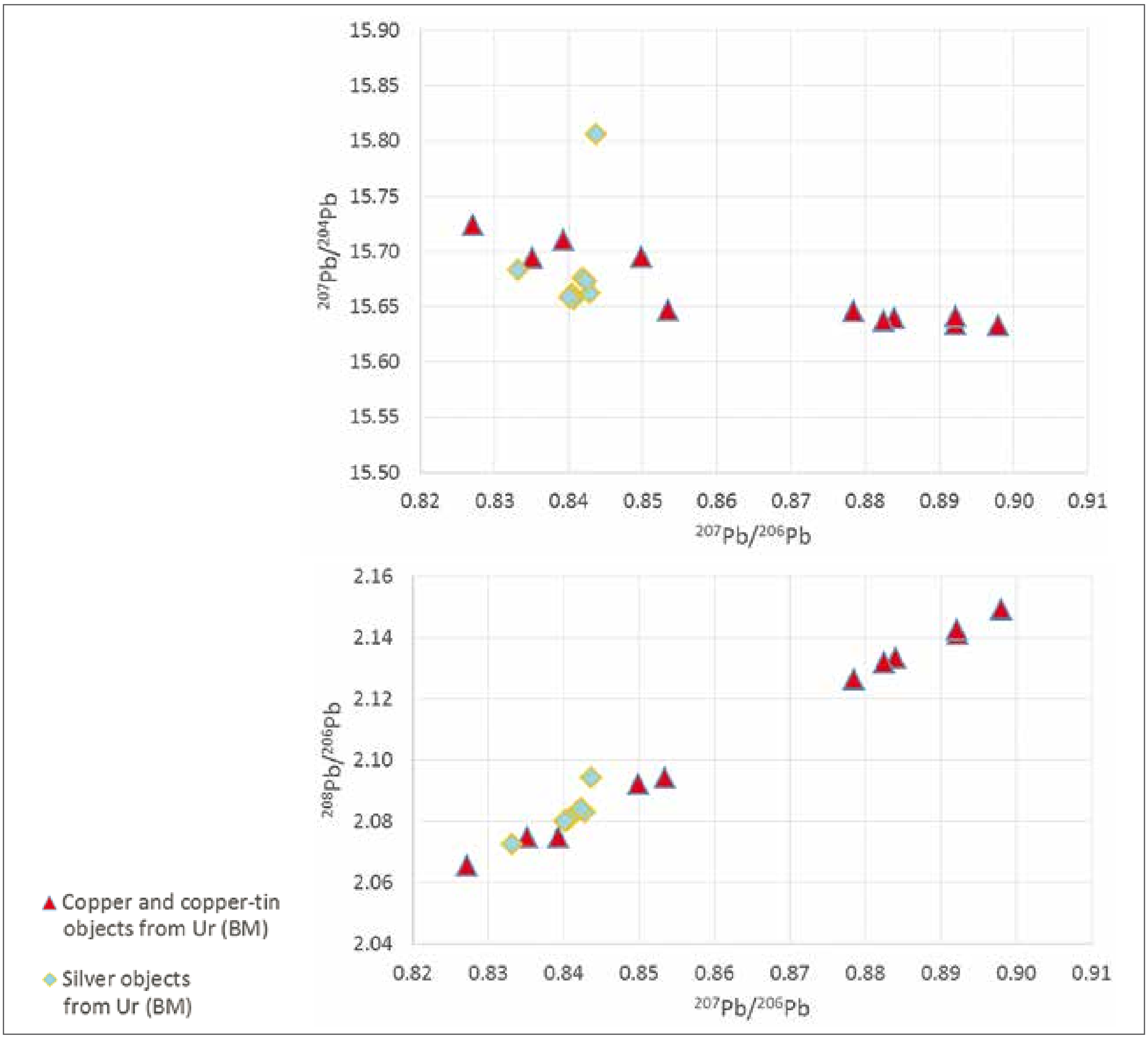

Figure 3. Binary diagram of lead isotope ratios of the copper-based objects and the silver objects sampled from the British Museum's collection (BM). The linear trend line defines the copper based objects.

Table 3. Lead isotope results for copper and copper-tin and silver objects from Ur (BM) by multicollector mass spectrometry (Frankfurt, from solution).

Sample	Inv. Nb.	$^{205}Tl/^{203}Tl$	2s	$^{206}Pb/^{204}Pb$	2s	$^{207}Pb/^{204}Pb$	2s	$^{208}Pb/^{204}Pb$	2s	$^{207}Pb/^{206}Pb$	2s	$^{208}Pb/^{206}Pb$	2s
Blank HNO_3		2.4148	0.0467	25.599	50.992	21.901	44.184	55.107	108.854	0.8464	0.1094	2.1511	0.1824
NIST 981 certified			**16.936**	**0.001**	**15.489**	**0.001**	**36.701**	**0.003**	**0.9146**	**0.0004**	**2.1670**	**0.0001**	
Std981-4		2.4139	0.0008	16.932	0.012	15.485	0.013	36.681	0.034	0.9146	0.0003	2.1664	0.0008
Std981-2		2.4093	0.0010	16.932	0.013	15.485	0.014	36.679	0.041	0.9146	0.0003	2.1664	0.0008
Std981-1		2.4091	0.0006	16.931	0.011	15.485	0.011	36.681	0.026	0.9146	0.0002	2.1664	0.0006
Silver samples													
4994-14	1928-10-10-132/A	2.4088	0.0008	18.623	0.013	15.657	0.011	38.749	0.034	0.8407	0.0003	2.0808	0.0011
4995-14	1928-10-10-132/B	2.4075	0.0011	18.619	0.012	15.676	0.012	38.788	0.033	0.8419	0.0003	2.0833	0.0008
4996-14	1928-10-10-132/C	2.4098	0.0010	18.582	0.022	15.662	0.017	38.703	0.050	0.8429	0.0003	2.0829	0.0010
4998-14	1929-10-10-562	2.4094	0.0006	18.823	0.016	15.683	0.014	39.012	0.036	0.8332	0.0002	2.0725	0.0006
4999-14	1929-10-17-63	2.4084	0.0010	18.637	0.015	15.658	0.013	38.765	0.038	0.8402	0.0003	2.0801	0.0010
5000-14	1928-10-10-149	2.4085	0.0012	18.605	0.016	15.673	0.016	38.776	0.046	0.8424	0.0002	2.0842	0.0009
5001-14	1928-10-10-133	2.3955	0.0783	18.732	0.595	15.806	0.749	39.239	2.460	0.8437	0.0134	2.0942	0.0661
5002-14	1935-1-16-17	2.4093	0.0008	18.634	0.021	15.662	0.019	38.765	0.047	0.8405	0.0002	2.0804	0.0008
Copper samples													
5006-14	1928-10-10-338	2.4119	0.0010	18.793	0.016	15.695	0.014	38.992	0.039	0.8351	0.0002	2.0749	0.0009
5008-14	1928-10-10-320	2.4104	0.0013	18.718	0.020	15.710	0.020	38.839	0.053	0.8393	0.0003	2.0748	0.0011
5014-14	1928-10-10-398	2.4086	0.0018	18.334	0.021	15.647	0.022	38.394	0.061	0.8534	0.0004	2.0942	0.0015
Leg of table													
5007-14	1928-10-10-400	2.4127	0.0007	18.468	0.018	15.695	0.014	38.640	0.038	0.8498	0.0002	2.0924	0.0006
Copper-tin samples													
5005-14	1928-10-09-316	2.4116	0.0011	17.523	0.015	15.634	0.015	37.521	0.039	0.8922	0.0004	2.1413	0.0010
5009-14	1929-10-17-632(A)	2.4092	0.0016	17.531	0.021	15.641	0.022	37.565	0.060	0.8922	0.0004	2.1427	0.0014
5010-14	1929-10-17-632(B)	2.4102	0.0010	17.410	0.017	15.633	0.017	37.421	0.052	0.8980	0.0003	2.1494	0.0012
5016-14	1928-10-09-245	2.4124	0.0007	17.693	0.019	15.640	0.018	37.742	0.047	0.8840	0.0002	2.1333	0.0006
5017-14	1928-10-09-247	2.4120	0.0009	17.720	0.017	15.638	0.017	37.775	0.048	0.8825	0.0003	2.1320	0.0010
5018-14	1928-10-09-299	2.4118	0.0008	17.810	0.015	15.646	0.013	37.870	0.032	0.8785	0.0003	2.1264	0.0008
5019-14	1928-10-09-250	2.4128	0.0012	19.011	0.015	15.724	0.016	39.269	0.047	0.8271	0.0003	2.0657	0.0010

1) Copper objects

Copper metal is represented by 6 of the samples from various types of objects: a lance head, spearheads, an adze head, a sample of a stack of bowls and strainers and a lance / javelin head (Figure 1). The objects are composed of: Cu = 96.8 - 99.7 wt. %, Sn low ≤ 0.03 wt. %, Pb low ≤ 0.3 wt. %, Arsenic (As) is variable with 0.13-2.74 wt.%, Ni ≤ 0.4 wt.%. One sample from the cast leg of a copper table had an elevated lead concentration with 1.75 wt.% Pb, Sn 0.01 wt.%, As 0.9 wt.% Fe low ≤0.06 wt.%. Despite the view that the copper adze head is supposedly a cast product, and thus must contain lead for the improvement of the casting conditions, the object contains an unexpectedly low lead concentration.

2) Copper-tin objects

This category is represented by 9 samples with a composition of Cu 92.7 - 87 wt. %, Sn variable 5.7 - 13 wt. %, As low ≤ 0.55 wt. % (one exception 1.04 wt. %), Pb low ≤ 0.5 wt. %, Fe low ≤ 0.84 wt. %, Ni 0.4-0.03 wt. % (Figure 2). Objects of this category are a spearhead, 2 samples from the stack of bowls and strainers, an adze head, a ladle handle, a chisel and lance / javelin heads.

Lead isotope composition

Lead isotope analysis was done on the copper-based samples and also the silver (Table 3). The copper-based samples plot more widely but string along a linear trend line (Figure 3) independently from the main element composition (pure copper, with arsenic, alloyed with tin). The silver samples form a homogeneous isotope group. One sample is anomalous: the twisted wire from a stopper for a skin vessel (1928-10-10-133, PG 800. The vessel is of silver, too, but imitating a skin bottle). Element analysis of the silver objects may help to clarify this difference.

Comparison with minerals from potential source regions

Most significant is the consistency of the lead isotope signature between copper and silver of the objects from Ur, and other similarities are observable for the lead isotope ratios of both the copper-based and the silver objects. Good matches are given with the a) the copper-based objects sampled from the British Museum's collection, b) copper objects from Ur published by Begemann, et al. (2010) and c) to the green copper-rich pigments from the Royal Tombs, which are presented in a parallel study (see pigments, Hauptmann, et al., this volume). Additionally, silver vessels and ingots from Troy (Romer and Born, 2009) are included in the comparison, but these are only similar in the ^{207}Pb / ^{206}Pb vs. ^{208}Pb / ^{206}Pb diagram, but do in fact show differences in the ^{204}Pb lead isotope (Figure 4).

Comparison was made with reference data of copper ores, predominantly from potential sources in Oman and Turkey. Figure 5 includes lead isotope reference data sets from a larger reference database than available in Frankfurt (own collection of reference data and incorporation of the database from F. Begemann & S. Schmitt-Strecker, Mainz). The copper ore deposits of Oman and Turkey overlap exactly in the region of the diagram where the major group of data points plot for copper objects and for silver objects from Ur. Begemann, et al. (2010) argue that many of the copper and bronze artifacts are consistent with the copper ore deposits of the Samail Ophiolite Complex of Oman. Oman was previously also suggested by our own interpretation for the green pigments (see pigments, Hauptmann, et al, in this volume). In combination with these previous observations, Oman gives strong evidence for being the raw material supplier here. However, Turkey cannot be completely excluded at present as an alternative candidate.

Conclusions

Copper was used at Ur in a wide spectrum of compositions. As has been proven previously on Ur material, the copper comprises either of pure copper metal or it is arsenic-containing or tin-containing (eg. Craddock, 1984). It is open to discussion in which cases deliberate alloying had taken place and what numerical limitation has to be drawn between naturally occurring "impurities" and deliberate addition of alloying material. The authors are convinced that compositional differences can also be caused by introduction of elements (such as arsenic, and possibly tin) through the natural mineral composition of polymetallic ores in many cases. The question arises, whether the typically postulated limit of 1 - 2 % of an element to indicate a natural impurity rather than a deliberate addition is still tenable.

Lead isotope analysis of the objects from Ur from the British Museum's collection testify to the similarity of copper-based objects with previous analysis (Begemann, et al., 2010) as excavated from various graves. Also, the lead isotope signature of the green copper-rich pigments found in the Royal Tombs appear to be identical. Surprisingly even the silver objects analyzed here appear to

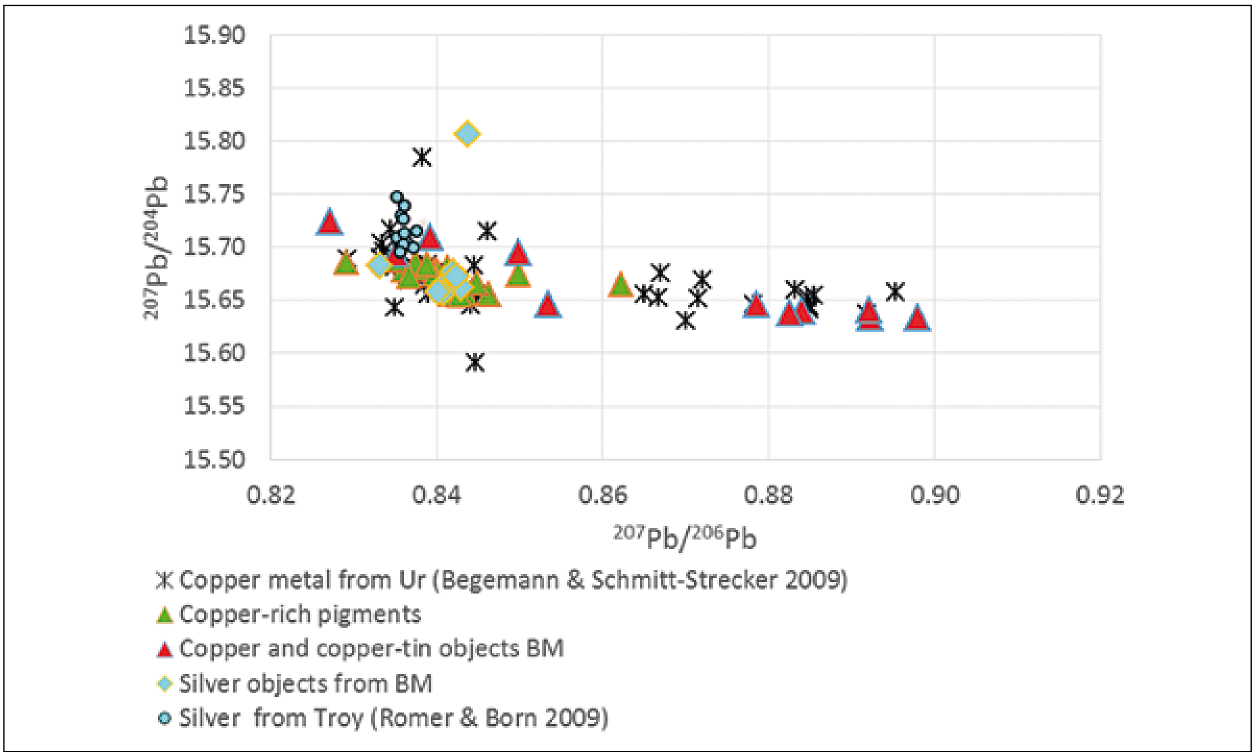

Figure 4. Binary diagram of lead isotope ratios of the copper-based and silver objects sampled from the British Museums collection (BM). The linear trend line defines the copper based objects. For comparison, copper metal from Ur (Begemann and Schmitt-Strecker, 2009) and silver vessels and ingots from Troy (Romer and Born, 2009) are plotted in the diagram.

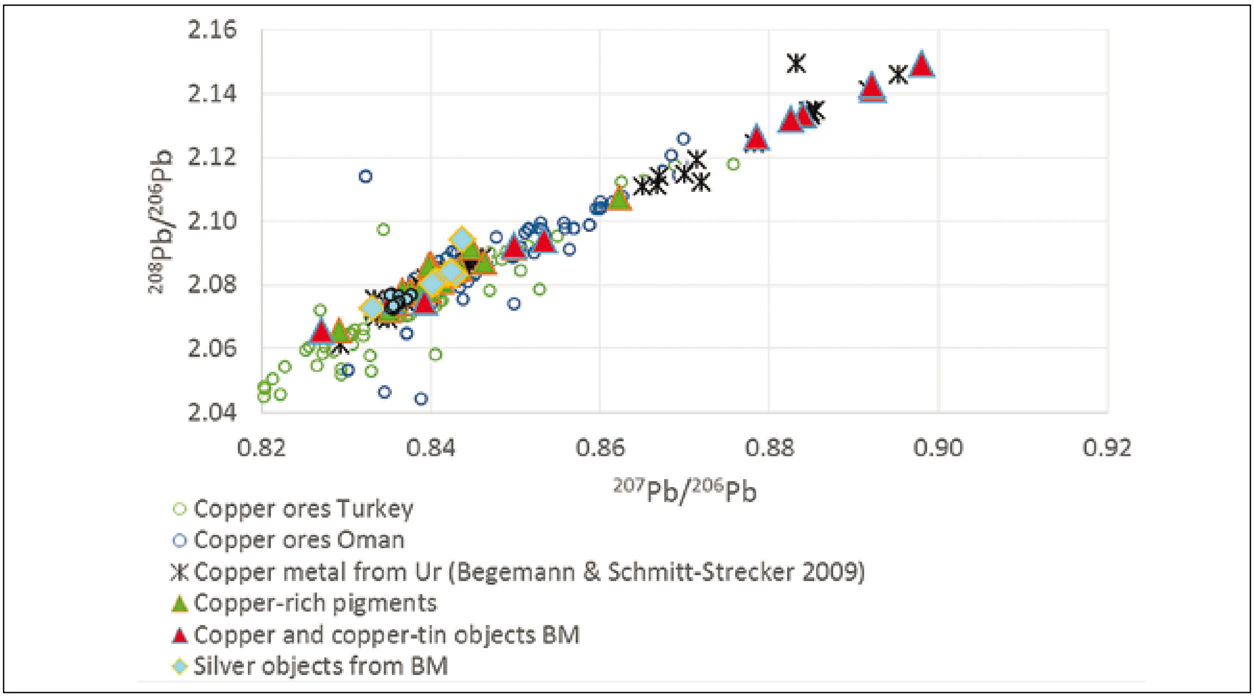

Figure 5. Binary lead isotope diagram. Comparison of objects from Ur (BM) with reference data of copper ores from Oman and Turkey.

be identical to the source or sources of a portion of the copper.

The matching lead isotope ratios point to a strong geochronological relationship between copper and silver sources, which means that silver might have originated from an identical source region to some of the copper metal, or at least from sources of similar geological age. Oman may be a potential candidate source region of the raw materials used for some of the copper objects, as there is a growing corpus of evidence suggesting this (Begemann, et al., 2010); however, Turkey may have been a source for the raw materials used for both copper and silver objects. A detailed examination of the trace elements in conjunction with the lead isotope data is still in progress and will be useful in sorting out the probable metal sources of individual objects.

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Where Does the Gold from the Cemetery of Ur Come From? – Provenancing Gold Sources Using Analytical Methods

Moritz Jansen, Andreas Hauptmann and Sabine Klein

Introduction

The following work is part of a PhD project on the archaeometallurgy of Bronze Age gold in the Middle East. In the current study, the origin of the raw materials for the gold artifacts from Ur will be discussed. The hundreds of golden artifacts from the Early Dynastic (ED) period are unique in the third millennium Mesopotamia. The fact that there are no natural sources of gold in Mesopotamia prompts questions about the origin of the raw material used to create these artifacts. Gold was likely imported from other regions such as Anatolia, Iran, Afghanistan, Egypt or India. The rich corpus of cuneiform tablets could help to identify possible trade relations, as they give an idea of possible origins due to named trading posts. However, these tablets date slightly later than the ED period in Ur and nothing is known about the provenance of the earliest gold artifacts at the site.

Therefore this project seeks to define the geochemical fingerprint of these objects in order to identify the origin of the gold through its chemical and isotopic composition. Ideally, this method could trace the gold back to the location of its natural deposit(s). For our analytical work, we used two different methods: first, the chemical compositions with main, minor and trace elements were determined by electron probe microanalysis (EPMA) and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS); second, the isotopic compositions of selected elements (Pb, Os, Cu) were measured by multicollector plasma mass spectrometry (MC-ICP-MS).

Golden alloys – natural or intentional?

The artifacts of Ur present different kinds of alloys (see Hauptmann and Klein, this volume). For the geochemical fingerprint of the gold itself, unalloyed gold artifacts need to be characterized. In alloyed artifacts the other components could obscure the distinct signature of the gold source. In this regard, it seems to be useful to analyze the artifacts of the headdresses with hair ribbons, flowers, diadems and necklaces instead of definitely alloyed artifacts like the chisel, adze and dagger.

The focus of our analysis is on the richly decorated Early Dynastic Royal Tombs. Forty-five samples were taken from artifacts of the Great Death Pit (PG 1237), the King's Grave (PG 789) and other tombs. Nine samples came from objects within the graves, which excavator Woolley attributed to the Second Dynasty and the Sargonid Period. These graves are mixed in date and grouped here as Akkadian to Ur III period. Twelve additional objects are without stratified contextual information and are discussed separately. The main components of the gold artifacts are gold, silver and copper. Between 15 and 45 percent of silver and between 1 and 6 percent of copper was typical for the samples. The jewelry of the Early Dynastic period has the same composition as the later Akkadian and Third Dynasty. Based on analysis of their main components, they could come from the same sources.

It needs to be clarified whether the gold composition is natural or is an intentional alloy. In ancient times silver was exploited by the use of silver-bearing lead minerals such as galena or cerussite. One would expect a positive correlation between silver and lead for the gold artifacts if the silver content of the gold was an intentional alloy (Hauptmann, et al., 2010). However, there is no correlation: the silver of the golden objects does not seem to originate from lead ores.

For comparison, the composition of gold, both primary and secondary, of various occurrences in the Lesser Caucasus is shown in Figure 1. These deposits (unrelated to Ur) form a broad database because they were systematically investigated in recent years by the authors and a second group from Mannheim and Halle (Wolf, et al., 2011; Wolf, et al., 2013). There is an overlap between the silver contents of the artifacts with silver in natural gold from this region. The content of silver of the artifacts is within the range of natural composition. But it is also evident that natural gold does not contain copper in the range of the gold artifacts from Ur. So is this an intentional alloy? This question will be discussed again later.

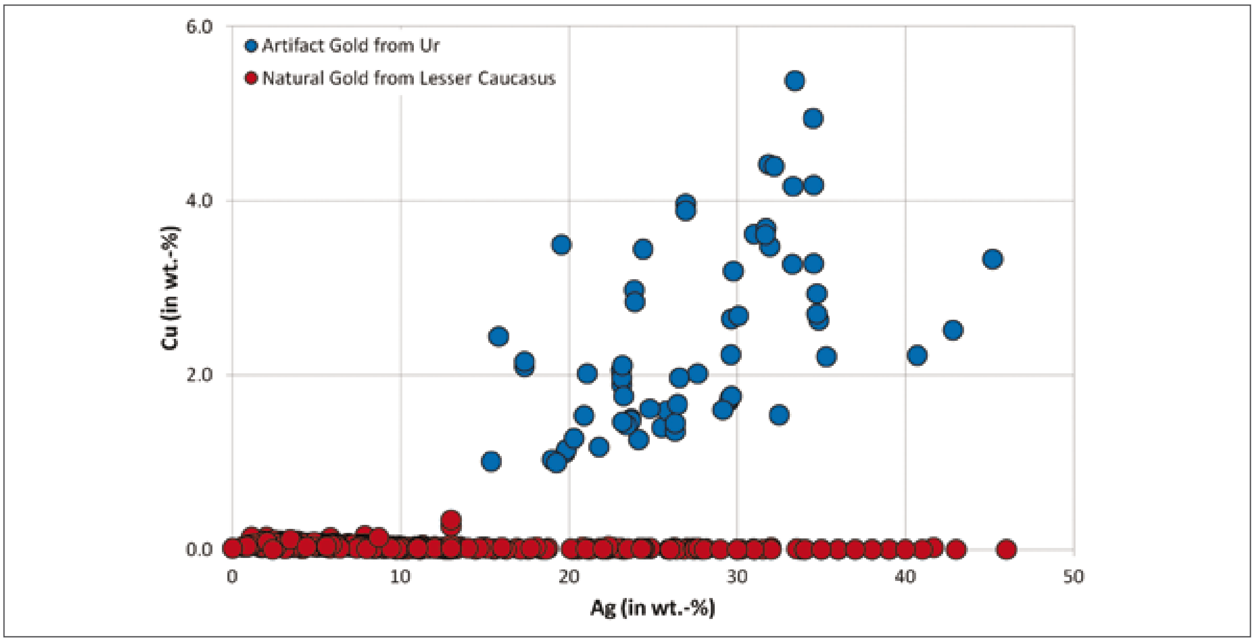

Figure 1. The alloy components of the gold artifacts from Ur are compared to natural gold of the Lesser Caucasus. The variability of the silver content is comparable, but the natural gold does not show significant contents of copper.

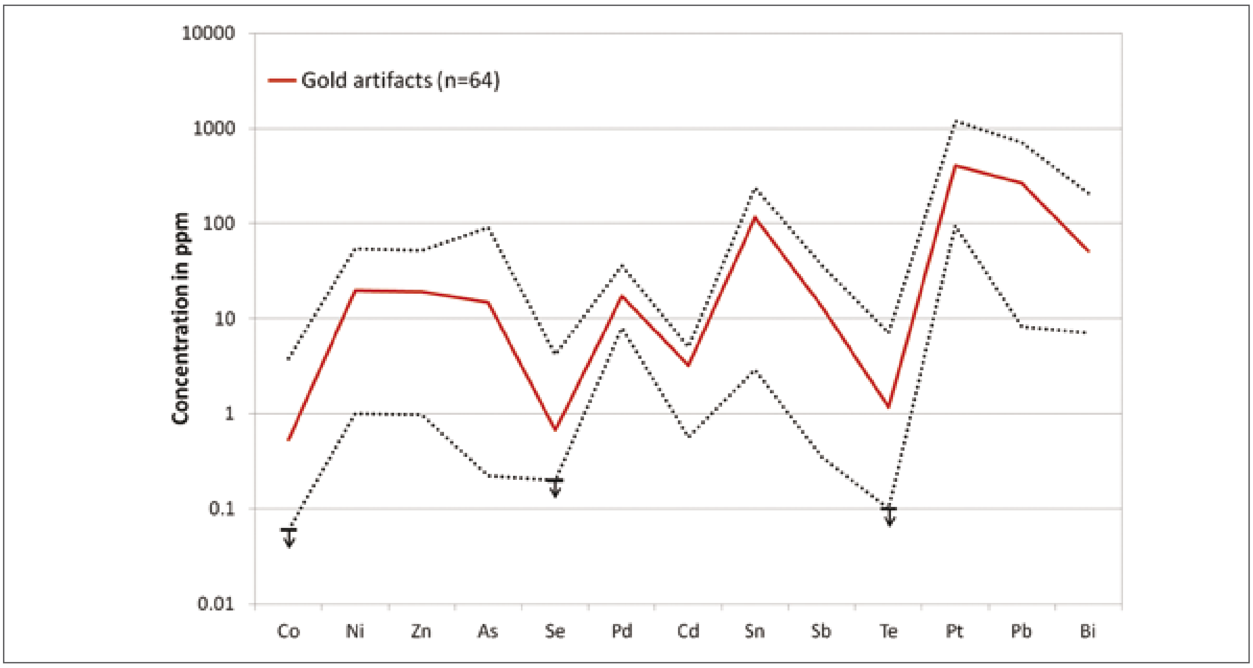

Figure 2. Trace element pattern of 64 objects from Ur. The red line shows the mean of all objects, the black lines show minimum and maximum. Arrow symbols showing detection limits.

Trace Elements as fingerprint

Trace element patterns of gold artifacts used for provenance studies have been discussed in recent years through the introduction of sensitive laser ablation plasma mass spectrometry (Ehser, et al., 2011; Hauptmann, et al., 2010; Kovacs, et al., 2009; Schlosser, et al., 2010). In the following section, the trace element patterns of the gold artifacts from Ur are presented. Following the definition in geochemistry, trace elements are elements with concentrations below 0.1 percent (given as ppm – parts per million) and which do not form their own phases. In Figure 2 the trace element pattern of the gold samples is plotted. There are significant occurrences of tin, platinum and lead above 100 ppm.

Because of the combination of tin and platinum, it is evident that the resources came from a placer deposit. Tin minerals like cassiterite are enriched in primary occurrences in granitic rocks. Platinum minerals are typically formed in basic rocks. After erosion they can

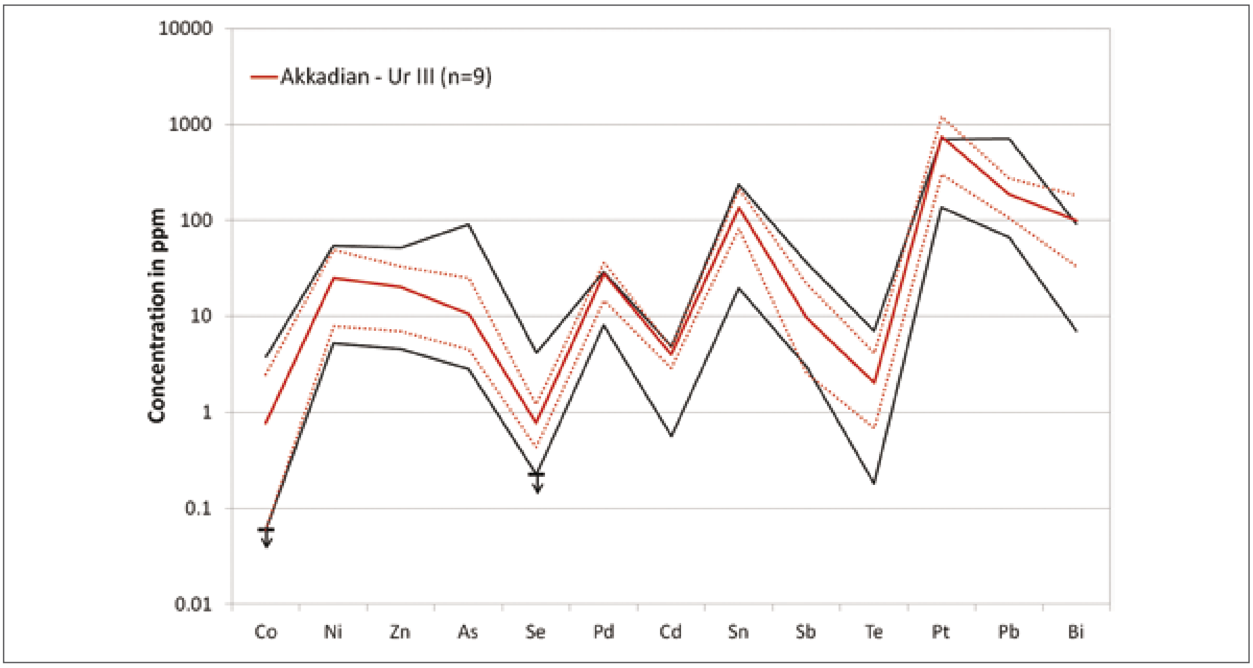

Figure 3. Comparison of the trace elements between the Early Dynastic (given minimum and maximum as black lines) gold artifacts and the later Akkadian / Ur III artifacts (red line: mean; dashed red lines: minimum and maximum). The patterns are the same. Arrow symbols showing detection limits.

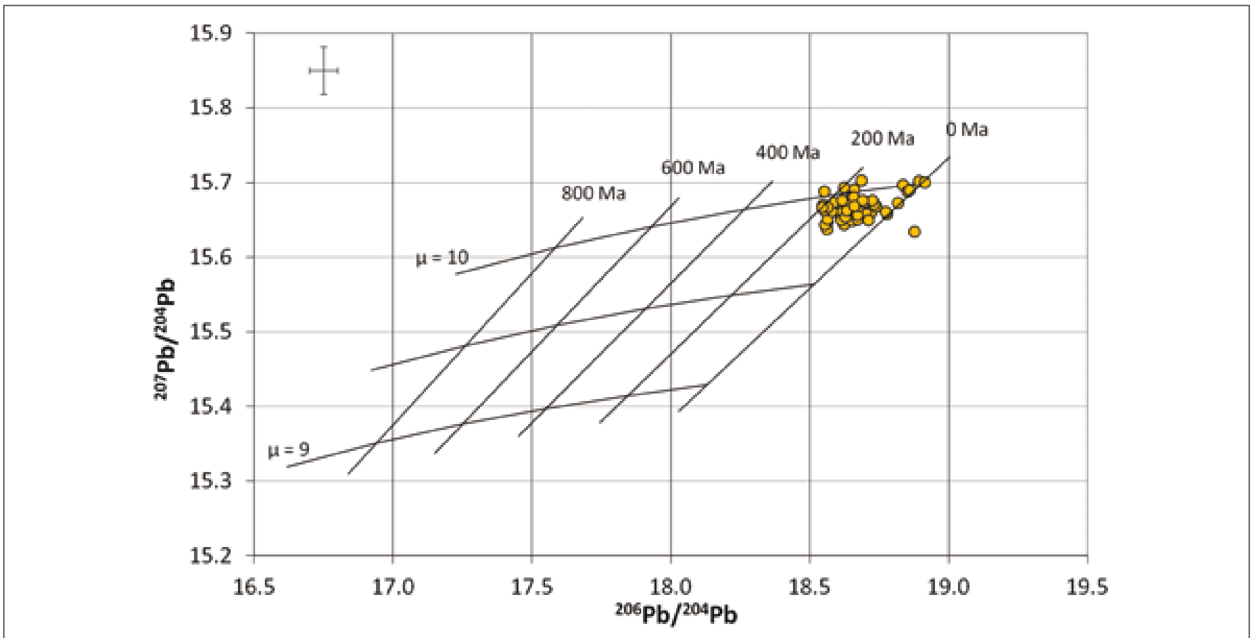

Figure 4. The lead isotope ratios of the gold artifacts from Ur plotted with the Stacey and Kramers lead evolution model (Stacey and Kramers, 1975). The sources of the lead traces in the gold artifacts were formed in the last 200 Ma.

be co-deposited in placers. Compared to the composition of analysis from reef and also alluvial gold, elements like nickel, arsenic and bismuth are also enriched. Only if there are inclusions of other minerals, the analysis of natural gold shows significant traces of other elements. The gold of the artifacts seems to have been contaminated during metallurgical processing. Washing gold never leads to pure gold concentrate. Different heavy minerals change the trace element pattern of the gold flakes / dust during the melting of the concentrate.

By focusing on the dated artifacts, a very small variation in the trace element patterns of all the Early Dynastic gold contents is visible. If we compare the later artifacts of the Akkadian period and Third Dynasty as red lines, these objects have the same pattern (Figure 3). The contents of palladium, platinum and bismuth are slightly higher. That does not mean that other resources were used. Maybe other parts of the same deposits were exploited. A stable use of the same occurrences over hundreds of years might be possible.

Ratios of Isotopes

Isotope ratios of different elements were determined in order to define a geochemical fingerprint. The lead isotope composition provides information about the geological age of the deposits used in ancient times for metal exploitation. For the golden artifacts of Ur a lead evolution model age of 0 to 200 million years can be determined (Figure 4). The source of the lead in the gold artifacts could not have been formed more than 200 Ma. If the groups of different dates are compared, no significant differences are visible. That means that the sources of the gold from Ur may be continuous from Early Dynastic and Akkadian to Ur III times. Both the chemical composition and lead isotope ratios support this conclusion.

A number of copper-based objects from Ur dating between Early Dynastic and the Akkadian period were analyzed for their lead isotopic composition by Begemann and Schmitt-Strecker (2009). The dataset forms two clusters. The gold artifacts have the same composition as one of these clusters (Figure 5). The question arises whether this is due to the alloying of gold with copper from the same source as where the copper-based artifacts originated. Meaning: could it be that the copper content of 1 to 6 percent is an expression of intentional alloying? The lead traces in the gold could originate from the copper due to the low lead content of natural gold.

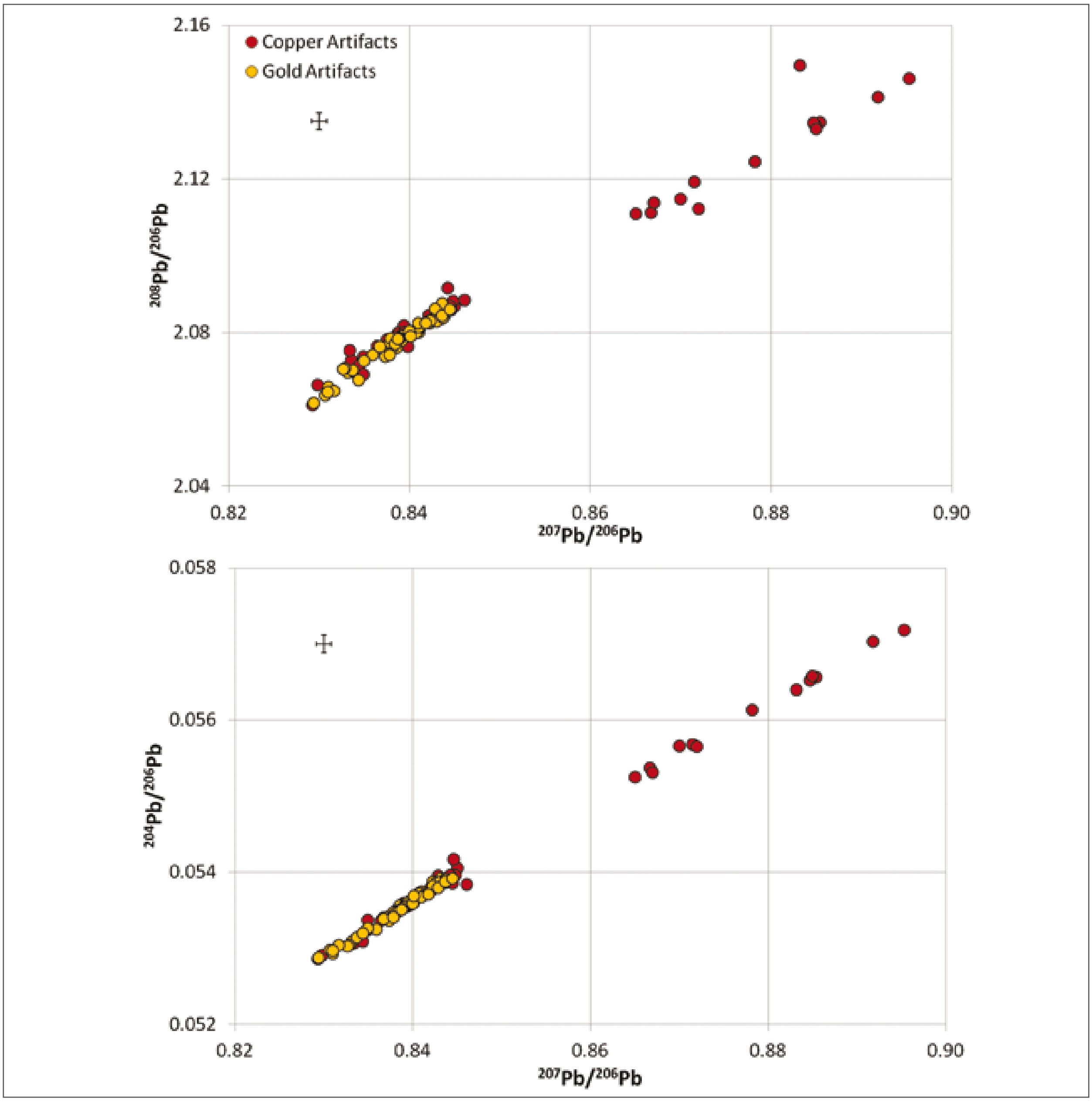

Figure 5. Lead isotope ratios of gold artifacts as well as copper-based artifacts from Ur analyzed by Begemann and Schmitt-Strecker (2009). The gold artifacts are compatible with one of the two clusters.

Most of the analyzed copper objects in addition were characterized for their chemical composition by Lutz and Pernicka (2004). We are able to calculate from these analyses an expected lead content due to alloying with this specific copper (Figure 6a). The expected lead content is much lower than the determined lead content in the objects and there is no positive correlation with increasing copper content. The lead does not originate from an alloyed copper. In addition, a high arsenic content is typical for the copper artifacts of Ur. Because of this we would also expect a much higher arsenic content in the gold artifacts and a positive correlation with copper (Figure 6b). Instead of an intentional alloy, a contamination by the other heavy minerals in the gold concentrate is more realistic.

As the artifact gold can be characterized as originating from alluvial gold, the lead isotopes reflect the sources of a region, eroded and deposited in placers, and not of a single ore occurrence. These sources have the same lead isotope signature as the group of copper artifacts. The gold occurrences could be in proximity to the copper sources. So what is the "metallurgical" origin of the copper content itself in the gold artifacts?

The identification of copper isotope composition allows a characterization of the types of minerals that were used to produce the ancient copper. The copper isotope

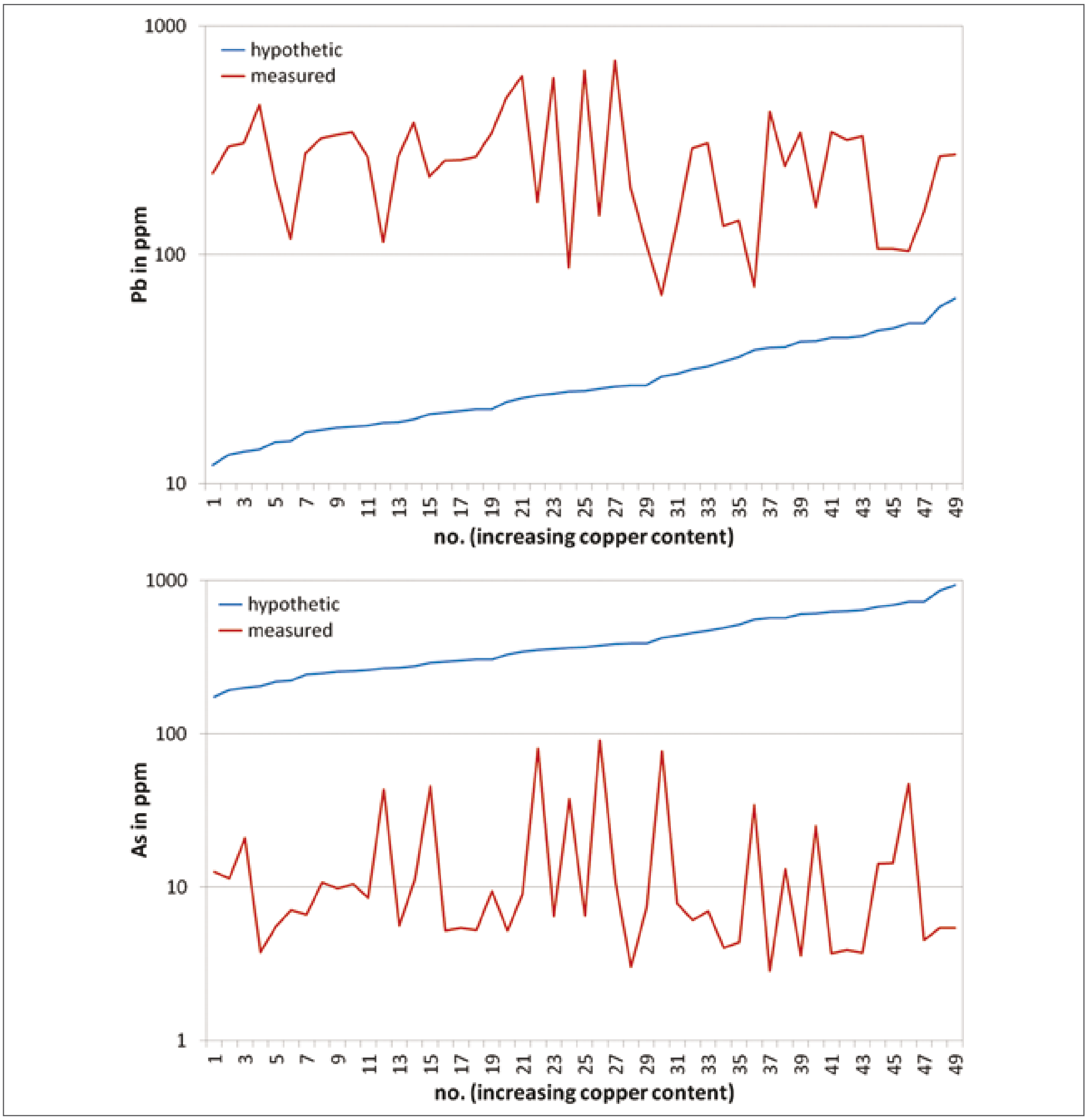

Figure 6. Hypothetic and measured lead and arsenic contents in the gold artifacts. Calculation based on the analyses by Lutz and Pernicka (2004).

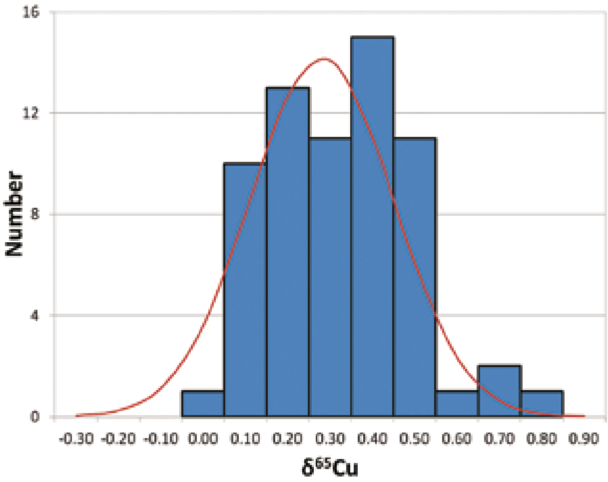

Figure 7. Copper isotopic composition of the gold artifacts from Ur. The positive δ^{65}Cu-values indicate oxidized copper minerals in the gold-bearing heavy mineral concentrates.

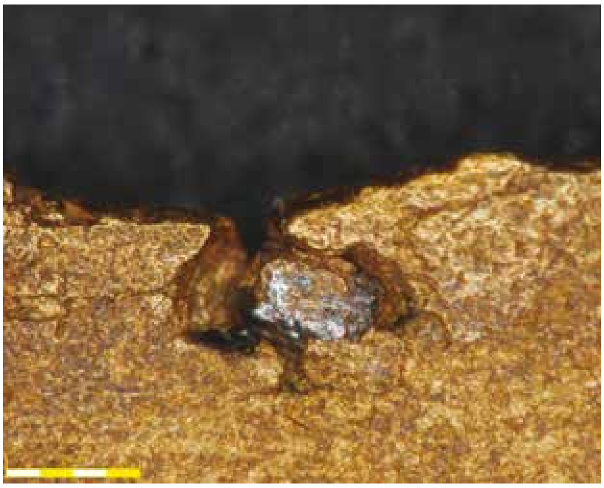

Figure 8. PGE-inclusion in a gold artifact from Ur. The scale is 200 µm.

signature of the gold from Ur shows a range of positive delta values (Figure 7) which is typical for a source of oxidized minerals (Klein, et al., 2010). Heavy mineral concentrates can also contain oxidized copper minerals like malachite (Hauptmann, et al., 2010). The copper in the gold seems to originate from the heavy mineral concentrate containing oxidized copper minerals. The copper source of the gold is also different from the copper-based objects in the copper isotopic composition (Salzmann, et al., this volume), indicating that the copper in the gold does not originate from intentional alloying with this copper.

Geochemistry of PGE inclusions

A significant characteristic is the numerous inclusions of natural alloys of elements of the so-called Platinum Group (PGE). In more than the half of all samples PGE inclusions were found (Figure 8). For comparison, we could identify such inclusions only in two samples of 120 artifacts from Georgia. The PGE inclusions are topic of another article (Jansen, et al., 2016). These Os-Ir-Ru alloys are not soluble in gold. The high contents of Pt and Pd in the trace element pattern originate from a second PGE source: Pt-Pd-minerals which are soluble in gold. The results of the investigation of PGE show that the chemistry of these inclusions is compatible to PGE alloys originating from ophiolite complexes where they formed in chromites of ultrabasic rocks. By calculating different models, a possible age of 290 – 610 Ma can be estimated for the crystallization of the alloys using their most frequent Os isotopic composition.

Discussion

After the geochemical characterization of the artifacts, possible candidates for the origin of the gold from Ur can be discussed. The calculated formation date of PGE inclusions in the gold from Ur is higher than the age of the Mesozoic ophiolites of the Tethyan Eurasian Metallogenetic Belt (TEMB) which hosts most of the ophiolites ranging from the Alps, Balkan, Anatolia, Iran, Afghanistan and further East to the Himalayas.

Older ophiolite complexes can be found in Egypt and Arabia. They were formed 700 to 900 Ma ago. There are many gold occurrences in the Eastern Desert next to these ophiolithe complexes. They were exploited since the third millennium BC (Klemm and Klemm, 2013). The gold-silver ratio of the gold deposits of the eastern desert is the similar to the objects of Ur. The occurrences in Nubia contain less silver. However, the deposits of Egypt and Saudi Arabia can be excluded as sources for the gold from Ur: if these deposits were used for the exploitation they should have the same lead isotopic composition as local ore resources (data published by Doe and Rohrbough, 1977; Stos-Gale and Gale, 1981). They are not compatible with the lead isotope ratios of the golden artifacts of Ur. In addition we can exclude the Egyptian deposits by comparison with Os isotopes. The Os isotope composition of the inclusions of Ur is different from that of the Os-Ir-minerals of the ophiolites from the Eastern Desert with lower ratios. The Eastern Desert ophiolites are older than the calculated model age.

The Omani ophiolite is one of the Mesozoic examples of the TEMB. It also shows a different Os isotopic

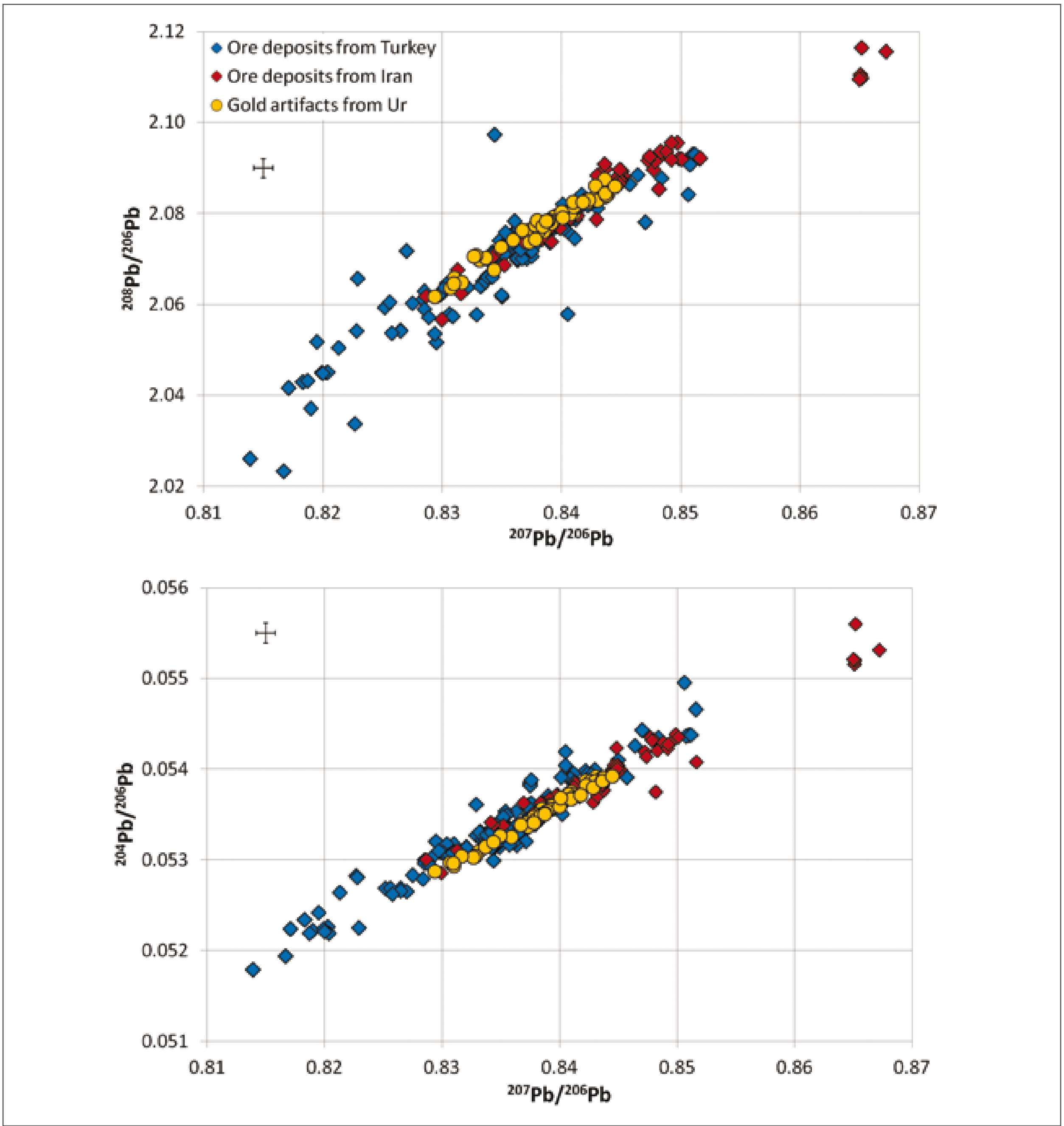

Figure 9. Lead isotopic composition of the gold artifacts compared to deposits from Turkey (Wagner, et al., 1986) and Iran (Mirnejad, et al., 2011; Pernicka, et al., 2011). The gold artifacts are compatible with this composition.

composition with higher ratios. We have to search ophiolites which are older than Mesozoic and younger than Proterozoic ones. In the Middle East there are some rare remnants of Paleozoic ophiolites. The model age of the PGE inclusions fits their age. We have to compare the lead isotope ratios of deposits within the TEMB, where remnants of these ophiolites occur.

The lead isotope composition of ore deposits from Anatolia and Iran fits with the golden artifacts from Ur (Figure 9). Little is known about the lead isotopic composition of deposits from Afghanistan. The rare datasets show some highly radiogenic lead isotope compositions like the deposits of Mes Aynak (Begemann and Schmitt-Strecker, 2009). There is an overlap with a few ore specimens, but additional samples are needed. The general conclusion is that the gold artifacts from Ur fit well to the ore deposits of the TEMB.

The gold occurrences should be next to Paleozoic ophiolites due to the Os isotopic composition of the PGE inclusions. For Anatolia and the Caucasus, there are no gold occurrences in proximity to the Palaeozoic ophiolites. In Iran the largest gold reserve is close to Paleozoic ophiolites next to Takab. There are very rich gold placers which were also worked in premodern times.

Another hint is given through the artifacts artistic style. The leaves of the headdresses of Ur were interpreted as the Indian Rosewood (Dalbergia sissoo Roxb.) which indicate an association to the east (Tengberg, Potts and Francfort, 2008). The present day distribution of this tree is in the Indus Valley, Baluchistan and the Asian coastal area of the Gulf of Oman. The later cuneiform tablets also described gold from *Meluḫḫa*.

Typical for the gold of Ur is the association with lapis lazuli and carnelian. There are some analogies between the inventories of gold from the Harappan culture of the Indus Valley and the gold from Ur, including an association with gemstones, the shape of diadems, and the discoid beads. Unfortunately, only a few analyses were done for the Harappan gold (Kenoyer and Miller, 1999). Five artifacts from Harappa itself contain less silver (6 – 9 wt. %) than the Ur artifacts, while analyses of two artifacts from Lothal (34 & 42 wt. %) have the same silver content. In the Indus Valley gold deposits are not present. The gold sources of the Harappan culture therefore are expected to be to the north or northwest of the Indus Valley, possibly in Afghanistan or Iran.

In Afghanistan some relics of Paleozoic ophiolites exist in Badakhshan. In proximity to the ophiolites, the richest alluvial gold deposits of Afghanistan can be found at the Amu Darya River near Samti in Northern Takhar. This area is also of interest because the Harappan trading post Shortugai was found here. It is hundreds of kilometers away from the Indus Valley. Shortugai has the typical inventory of a Harappan city with its architecture, ceramics, seals, copper-related metallurgy, beads of gemstones, but also some of gold (Francfort, 1989). The lapis lazuli deposit of Sar-e Sang is in its vicinity. Shortugai indicates a direct connection between the Indus Valley and a region of interest for gold.

Conclusions

The golden jewelry from Ur is a natural alloy of gold and silver originating from placer gold. In addition, it contains some copper, presumably from an oxidized mineral source. There are high contents of tin, platinum, lead and other trace elements. In contrast, there are low trace elements in natural gold. For artifact gold, there is a contamination during metallurgical processing due to the presence of other heavy minerals. There are no changes in the amount of alloy components as well as the trace element pattern between Early Dynastic III and Akkadian / Ur III period. The sources of the trace element lead are heavy minerals which are not older than 200 Ma old. There are no changes in the lead isotope composition between EDIIIA and Akkadian to Ur III period. This is explained by the use of the same sources of gold over hundreds of years.

The PGE inclusions are Os-Ir-Ru alloys which are not soluble in gold. In addition, Pt-Pd minerals were dissolved during metallurgical melt. The PGE minerals originate from ophiolites which were formed 290-610 Ma ago.

The provenance of the gold can thus be stated: the source of the gold from Ur is likely located within the Tethyan Euarasian Metallogenetic Belt. The PGE inclusions most probably trace back to older ophiolite complexes. Possible origins of these are rare remnants of Paleozoic ophiolites. There are two locations that are potential candidates for the origin of the gold found at Ur. These two sources are the placer deposits found at Takab in Iran and at Samti in Afghanistan. These sources should be investigated in the future to compare the lead isotopes of gold-bearing heavy minerals and Os isotope ratios of PGE minerals in local chromite occurrences.

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Technologies of Jewelry at Ur: the Physics & Metaphysics of Skilled Crafting

Kim Benzel

Introduction

My primary contribution to the scholarship of the Ur jewelry has focused on a detailed study of the materials and techniques used to create Pu-abi's jewelry (Figure 1), most particularly her gold ornaments (Figure 2), for which I relied on my training and skill as a practicing goldsmith. The many ornaments fashioned from gold appear on the surface to be of rather simple manufacture, made primarily of undecorated, hammered sheet; however, by examining these pieces closely, under a microscope when possible, it became apparent that the methods used to hammer and assemble the pieces were deceptively complicated and time-consuming and that they required exceptional skill. There seems to have been some sort of premium placed on fashioning the ornaments from a single piece of gold whenever possible, even at the cost of additional labor-intensity, presumably due to specifications that called for seamlessly produced objects. The making of this jewelry is also noteworthy for a prescriptive-like consistency and repetition of technique, seemingly intended to enhance properties of purity and shine already embedded or coded in the materials themselves. The process of production thus required not only substantial material resources but also a considerable and coordinated investment of human energy consisting of craftspeople both skilled in mechanical techniques and knowledgeable in the techniques of seemingly dictated specifications. A certain amount of advanced planning would therefore have been necessary to form Pu-abi's assemblage because the individual pieces were clearly made in a highly prescriptive way that suggests that they were conceived together.

Analysis

Although a complete analysis of the materials and methods used to create all of Pu-abi's jewelry, as was done for my doctoral dissertation (Benzel, 2013), is not feasible here for reasons of space, I will present two examples of the jewels in question and describe how they were fashioned. Beginning at the top of Pu-abi's body with the

Figure 1. Current reinterpretation and display of the majority of Pu-abi's attire at the University of Pennsylvania Museum of Archaeology and Anthropology (photo courtesy the Penn Museum, image no. 184431)

Figure 2. a) Pu-abi's head ornaments as reconstructed on mannequin and as separated into individual pieces (image courtesy of the Penn Museum, no. 152100). b) Pu-abi's comb, c-e) three of Pu-abi's wreaths, f) beaded ornament (Cat. no. 61a-e, photos by Anna Marie Kellen, courtesy of Richard L. Zettler, Associate Curator-in-Charge, Near East Section, University of Pennsylvania Museum of Archaeology and Anthropology)

large hair comb (Figure 2b), a close inspection shows that a tremendous effort was made to create this large and heavy ornament out of as few pieces of gold as possible, and without evident use of any joining medium other than the purely mechanical. The body of the comb was made out of very large and thick sheet gold that most likely began as a solid mass, probably in an elongated shape. In order to plan for and achieve from a single piece of gold the wire pin at the one end and the wide splay into seven prongs at the other, the goldsmith must have possessed an intimate knowledge of the mechanics and movements of gold as it was hammered repeatedly.

While the comb appears simply made in the sense that its body has no decoration or ornamentation, the process of hammering such a large piece of gold requires tremendous feel for the metal as well as time and patience. All metals harden and become brittle as they are worked, especially by hammering. They require constant heating and reheating (called annealing in modern technical terminology) to regain their malleability for further hammering or for other kinds of manipulation. If they are not annealed properly and often enough, metals simply stop responding or become so brittle that they show cracks and fissures.

In the case of the comb, I imagine that the goldsmith would have begun hammering at one of the short ends of the elongated solid gold mass – first to secure enough length for the wire pin at the one end, then to continue with the large flat surface that makes up the body. He or she would have needed to anneal the metal scores of times, for this much gold to remain malleable enough to be hammered successfully into the sizeable body of its completed form. The process of annealing each time is not a particularly speedy one, in addition to being highly repetitive. The metal must be heated evenly and carefully so as to achieve maximum compliance but not to melt or blister it. The constant annealing required in order to proceed with hammering is deceivingly labor intensive and takes great skill and sensitivity. Unlike intricate decorative techniques such as granulation or filigree, which immediately present themselves to the viewer as difficult and time consuming, the hammering of metals does not "advertise" the labor and expertise involved. The technique and the process are largely hidden and silent within the final product.

What is also hidden within a final product made in this manner is the fact that if, at the end of the hammering process, the mass of gold had not been sufficient for the desired design, then the goldsmith would have had to begin from scratch or resort to soldering or brazing additional sections to the main body. This is an important technical point when evaluating the procedural decision not to use any means of solder or baser alloy and the consequent implied skill of the goldsmith. Thus, while one's first impression of the comb is that, although quite large and lovely, it is rather simply made from undecorated sheet gold, it becomes clear from even this abbreviated analysis that its manufacture was anything but simple.

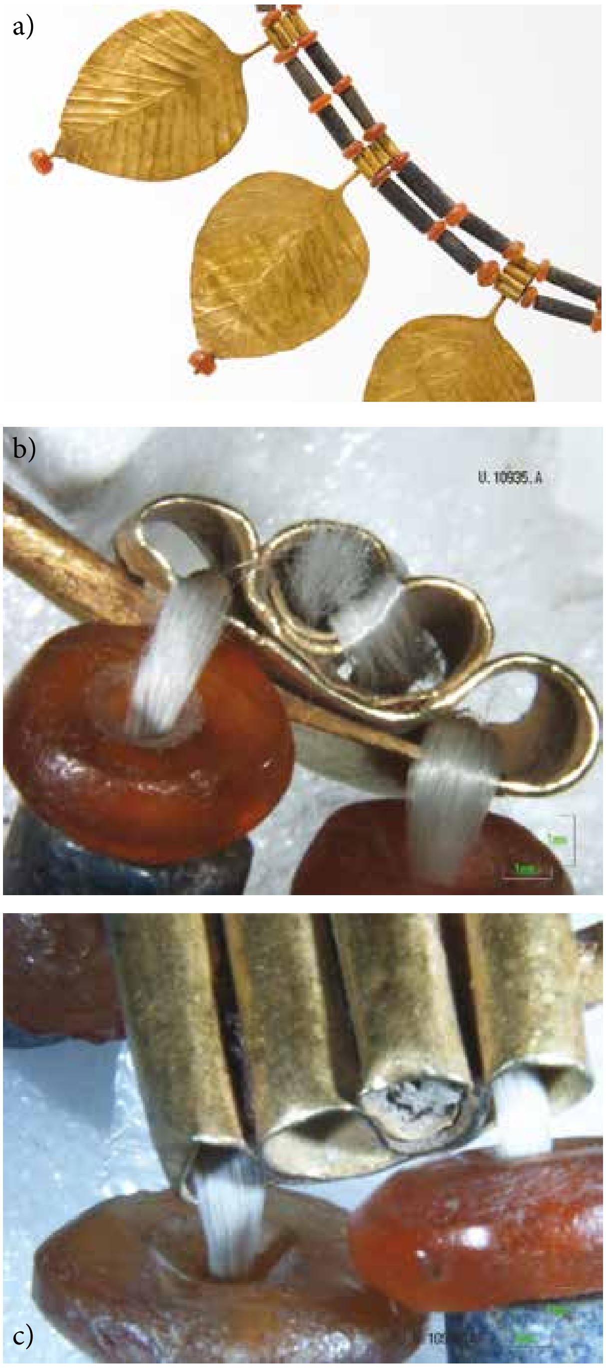

Figure 3. a) detail one of Pu-abi’spoplar wreaths (photos by Anna Marie Kellen, courtesy of Richard L. Zettler, Associate Curator-in-Charge, Near East Section, University of Pennsylvania Museum of Archaeology and Anthropology); b-c) microphotography details of one of the suspension loops (photos by Kim Benzel)

Figure 4. Selection of ornaments from various tombs, Ur, Mesopotamia, ca. 2500 B.C.E., British Museum, London (Aruz and Wallenfels, 2003, Cat. no. 74a,b,c,d; Cat. no. 72a,b,d,e; Cat. no. 73a,b,d © The Trustees of The British Museum)

Looking at the botanical wreaths that adorned Puabi's head (Figure 2c-2e), the predominant technique employed to make the gold elements of the wreaths is once again hammering. The goldsmith fashioned the majority of the many leaves from a single unit of gold, hammering in one direction to make the leaf shape and in the other direction to form the suspension loop for stringing – much like the comb was hammered in one direction to form the pin end and in the other to make the body with splayed prongs. In the case of the wreath pendants the shaping of each leaf was a fairly simple procedure since individually they did not involve the large amount of gold and surface area that the body of the comb did. Nonetheless, frequent annealing was required both for the hammering of the shape and for the chasing that was done to delineate the veins.

By examining the suspension loops that belong to each leaf element and that were formed from the same piece of gold as the leaf, the procedural aspect becomes more significant. As with the allotting of gold for the comb, the hammering of the gold leaves entailed planning not just for the leaf design but also for the narrow strip of gold that continued beyond the fine stems and served as the suspension loop for each leaf once it had been folded into the desired shape. While the three separate wreaths have three separate design variations of this loop, they share a fundamental aspect of technique: the use of a single, continuous – and seamless – piece of metal whenever possible.

In the case of the two poplar-leaf wreaths, and I show only details one of them here (Figure 2d and Figure 3), one can see that the strip of gold extending from the leaf stem was folded and rolled, almost ribbon like, into tubes intended for strands of beads. The amount of annealing, and therefore time, needed to hammer and fold each of the many loops was again considerable. Likewise, a significant amount of feel and skill were once more required to calculate and execute the movement of a single unit of gold into both the leaf shape and the suspension loop. An easier and more practical way would have been to produce multiple tubes that could be laid side-by-side, soldered together and subsequently attached to the leaf to form the loop. In this system if something went wrong in the making of the ornament, one could replace one part rather than starting from scratch to create an entire new leaf and loop out of a single piece of gold. The sum of making the parts separately would have required less work than the making of each leaf and loop as a coherent whole. It seems that this alternate approach would have been especially relevant since there were so many of these leaves made for Pu-abi and for others in the cemetery (Figure 4). One could quite efficiently have made each type of part in an almost production-line manner and then assembled them into complete ornaments. Yet, the goldsmith chose the more difficult and time-consuming method. Was this to avoid breaking the gold into various bits and thus needing to join parts, thereby compromising the seamlessness of the pieces, both physically and conceptually? Was the goldsmith circumventing the use of solder, which would have added impurities to the gold and compromised the physical and conceptual purity? Was there a particular method prescribed for ritual reasons? These are all questions that immediately come to mind once the technology has been closely examined.

Discussion and Conclusion

From this brief examination of Pu-abi's jewelry, several technical aspects must be reiterated and stressed because they have as much conceptual as technological significance. First, the goldsmith must have been an expert at his or her craft. As we have seen, the amount of hammering into a shape such as the comb, although not a complicated technique, required considerable knowledge of the mechanics of the metal and a feel for knowing where to begin and how to hammer the gold so that the overall design of this rather large ornament could be achieved in a seamless manner. Hammering also entailed a substantial amount of time because of the need to constantly and carefully anneal the metal. The primary components of hammering are thus feel and time – technical elements that are not evident in the final result but requiring as much, if not more, expertise as fanciful decorative techniques. In other words, the expertise involved in hammering is largely hidden but far from insignificant.

Furthermore, it is crucial to note that the hammering of flat sheet is the primary metalworking technique among the ornaments produced for Pu-abi. Of particular interest to me is the design decision to favor flat sheet over ornamental details, which produced surfaces that actively enhanced the sheen of the gold being used and exploited the resulting reflection of light, or shine. On a more theoretical level, this approach created in technique the semantic equivalent to the Sumerian word for "shine" that formed part of the Sumerian term for "gold" because "shine" was deemed inherent to the metal. Furthermore, the Sumerian sign indicating "shine" could also signify "holy" or "sacred," so the two concepts were often equated. Thus, I would argue that in the case of Pu-abi's jewelry, the technology itself exhibits agency and that shine – and conceivably some aspect of the sacred – were being deliberately produced or "performed" in its very making. If indeed purposeful, and I believe strongly that the technique of hammering so much flat metal sheet was very consciously chosen or prescribed, this reinforcing of material and semantic properties in the associated technical processes represents a subtle yet sophisticated use of repetition or doubling, a conceptual operation that is well known in the visual and literary imagery of Mesopotamia, and seen here in technological form.

Seamlessness was mentioned earlier and comprises another crucial aspect of the jewelry technology at Ur for several reasons, again both physical and conceptual. For one it entailed the use of a single piece of gold whenever possible rather than multiple ones joined together. This technique preserved the integrity and relative purity of the gold as well as the visual unity of the piece. The use of separate elements would have interrupted both the material and the form, and the use of solder quite literally would have added impurities to the metal by way of the baser elements contained in solder. For instance, by hammering the prongs out of the same piece of metal as the body of the comb and the suspension loops directly out the same metal as comprised the leaves – rather than soldering, or joining by any other means – the goldsmith opted for the more difficult but purer and more holistic method. Easier means were available during this period so one must assume the choice was not by default but deliberate.

This approach has implications concerning not only the compositional or economic value of the gold but also the potential ritual value or symbolism of the finished object. Once again, the procedure chosen achieved in technical terms the semantic equivalent to the Sumerian word for “pure” that formed part of the Sumerian term for “gold” because, like “shine,” it was deemed inherent to the metal. In fact, and perhaps not surprisingly, the Sumerian sign indicating “pure” is the same one used for “shine,” which you may recall is also the one used to signify “holy” or “sacred,” suggesting that all three concepts could be conflated in certain contexts. Thus, one might again argue that the technique itself had agency, that “purity” – as well as “shine” and “sacredness” – were being “performed” in the very process of making.

Finally, seamlessness quite literally hides the hand of the mortal maker, thereby leaving open the question of who made the object, and how, and giving the impression that the object simply “exists” rather than being made at all. A similar operation is well known from ancient Near Eastern texts that describe the making of cult statues, where the process entailed rituals that purposefully obscured the role of the sculptor, allowing a statue to miraculously emerge in its fully finished and animated state, as if made by the gods. I believe that a related conceptual maneuver was likely being carried out in the technical processes chosen for the making of Pu-abi’s jewelry.

Acknowledgements

It was with great pleasure that I was able to present some of my research on the Ur jewelry to this distinguished group of scholars, and for that I owe tremendous thanks to Prof. Dr. Andreas Hauptmann, to Prof. Richard Zettler, and to the Metropolitan Museum.

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Technological Aspects of Selected Gold Objects from Ur - Preliminary Results and Perspectives

Barbara Armbruster

Introduction

Gold is a rare metal, whose magical power derives from its shining, sun-like color and its resistance to corrosion. The noble metal played an important role in all cultures of the ancient Near East in art, religion, trade, and society (Boese and Rüß, 1971). Works concerned with Mesopotamian jewelry or Ancient Near Eastern gold often focus on style and iconography whereas technological matters are rarely considered. However, technical knowledge, and the goods produced with it, form the material conventions of a culture and, consequently, manufactured objects are especially able to transmit a visible and archaeologically comprehensible expression of that specific culture (Armbruster, 2011a, p.419). The craft of goldworking was anchored religiously, socially and economically in Bronze Age society. The objects produced testify to a specialized craft knowledge with a high technical and aesthetic standard. The goldsmith, who knew how to work with valuable materials and whose task was to make important prestige goods and ritual objects, can therefore be seen as a prominent figure in Bronze Age society.

Excavations at Ur in the 20th century brought to light extraordinarily rich funerary evidence of mid-third millennium BC goldwork from Mesopotamia (Maxwell-Hyslop, 1960; Maxwell-Hyslop, 1974; Reade, 2003; Woolley, 1934). The treasures from Ur are suggestive of the lavishness of Sumerian art and craft. These masterpieces in precious materials mirror the sophisticated design and technological knowledge of craftspeople from Bronze Age Mesopotamia. As it is common for the Near East in general, the main functional categories of Bronze Age gold at Ur are: jewelry, decorative elements, and ritual objects, which include tableware, sculptures and weapons. This panoply, with exception of sculpture, is also relevant for Bronze Age Europe (Armbruster, 2013).

Parts of the artifacts from the royal Ur cemetery are housed in the collections of the Penn Museum in Philadelphia comprising a remarkably large amount of goldwork. They are presented in detail in the significant publication accompanying the permanent exhibition at Penn Museum (Zettler and Horne, 1998). Moreover, Puabi's personal ornaments were recently also featured in a remarkable PhD thesis, which, among other topics, explores some aspects of manufacturing (Benzel, 2013).

The focus of this paper is to present preliminary results of a study of selected goldwork from the Royal Cemetery of Ur focusing on the technological aspects. It is based on the optical study of a number of artifacts: one vessel, two statues, one weapon, one tool, and a dozen of personal ornaments examined during a stay of four days at the University of Pennsylvania Museum of Archaeology and Anthropology (Penn Museum). This work offers a first glance on the large variety of fine metalworking techniques used by Mesopotamian goldsmiths of the 3rd millennium BC. Non-invasive methods were used to determine the nature of form, decoration and constituent elements of the objects, and the *chaîne opératoire* of their manufacturing techniques. The aim is to illustrate the high standard and level of specialization of Sumerian fine metalworking techniques and to discuss the types of materials and tools used in goldsmith's workshops. The objective of this research is also to address perspectives for future examinations to be undertaken with an interdisciplinary approach including material science studies, which have the potential to increase our knowledge of the technical skills of the ancient artisans.

The technological study of the goldwork from Ur is complementary to the analytical investigations completed by Hauptmann and Klein and Jansen, Hauptmann and Klein (both studies in this volume).

Investigation methods in ancient gold studies

The study of prestigious objects in precious materials covers a large variety of aspects including condition, form, decoration, function together with the social, economic and spiritual values of the objects as symbols of power and religious beliefs. Besides typology and style, ancient gold studies also comprise the interpretation of trade and exchange, social status of the artisans, and last but not least the specialized know-how of the manufacturing techniques.

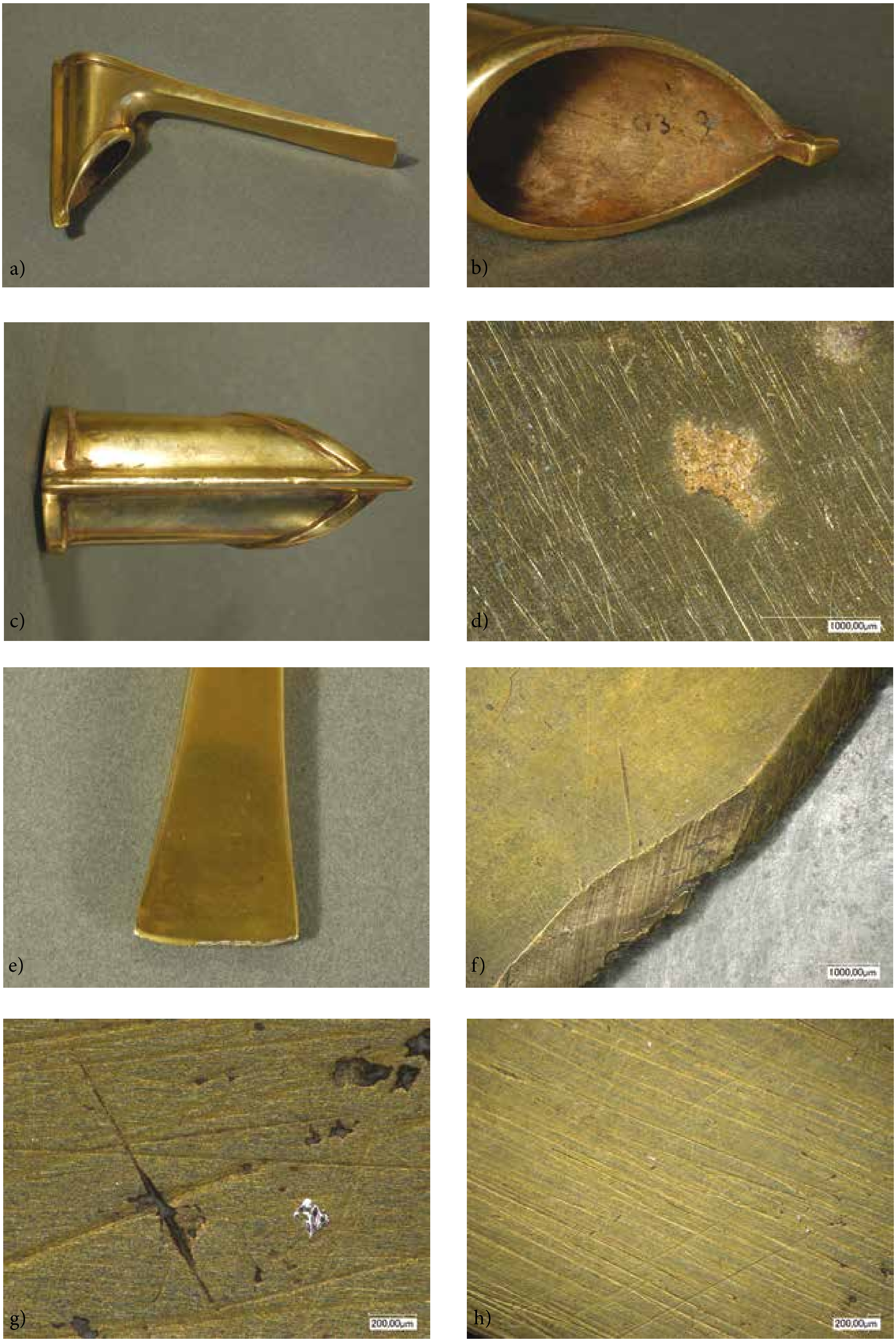

Figure 1. a-h Adze, B16691. All photographs in this paper were made by Barbara Armbruster, Moritz Jansen and Sabine Klein.

Ancient written sources mention gold as a means by which conflict between elites could be resolved, it being used in the exchange of political gifts or as a sign of hospitality (Boese and Rüß, 1971; Scheid-Tissinier, 1994). Golden tableware were also used in sacrifices or in feasts for those of high rank. However, textual evidence and pictorial representations giving detailed information about fine metal working in the Bronze Age in the Near East are rare. Consequently, our knowledge relies mainly on the examination of the archaeological artifacts themselves, the circumstances surrounding their burial and their socio-cultural context. Furthermore, direct proof of goldworking workshops is also exceedingly rare for the Bronze Age. Therefore, the interpretations of the goldworking craft are also based on functional analogies and modern material science analysis. So, the interdisciplinary methods available to the archaeologist today for studying the history of goldworking are diverse (Armbruster, 2011a).

The study of style – typology of form, decoration, and function – remains fundamental, together with visual examination of tool marks and thus of the implements and, perhaps, workshops involved. Analogies drawn from ethnography, experimental archaeology, iconographic and ancient written sources facilitate the development of explanatory models. Lastly, a range of analytical approaches which can yield information about the components and properties of the materials and various techniques for determining the alloys elemental composition have greatly contributed to research on gold artifacts. Radiography and computer tomography makes it possible to see inside the object and can show the thickness of material, tool marks, and repairs. Scanning electron microscopy, besides allowing non-destructive semi-quantitative elemental analyses, also enables detailed observation of the surface topography of an object. Analytical studies might find answers to the questions surrounding gold and its alloying components, to the origin of the raw material used in Bronze Age goldworking, however, it can be assumed that the metal could have been rapidly recycled.

Bronze Age goldworking technology

Because of its exceptional material properties, gold is highly suitable for the manufacture of jewelry, ornamentation, and vessels by means of casting or plastic deformation techniques (for material properties and manufacturing techniques see: Brepohl and McCreight, 2001; Plate, 1988; Untracht, 1982; Wolters, 1984). The melting point depending on the purity of gold alloys is around 1000 ± 50° C. To reach this temperature the charcoal would need a forced air supply and therefore must be equipped with bellows and tuyères. Also mouth blowpipes could have been used. Gold is very malleable and can be burnished to a high luster. It hardens through cold-working such as by forging, chiseling, punching, bending, or twisting. To avoid cracking or breaking, precious metals are annealed at approximately 750° C. Annealing promotes the recrystallization of the metal after hardening which became brittle by plastic deformation. Except for the melting, casting, soldering, and annealing, goldworking is done in a cold state. As gold is chemically resistant in most situations, its shining color stays unchanged even after millennia.

Before a piece of goldwork is started, an idea of the morphology, decoration, and technical processes of the desired object must be developed from a knowledge based in a stylistic and technological tradition. The quantity of metal is then measured using weights and scales, and, if the composition is not known, the gold content is checked. Touchstones for this colorimetric test of the gold quality are chosen of dark color and fine grain, and were already in use in the Bronze Age (Armbruster, 2010, pp.16-17).

Pyrotechnology - melting, alloying, casting and soldering

Gold objects were produced from a cast primary product. Castings were made in moulds of stone, metal, or clay. Ingots could also just be cast in a wooden mould. For this the gold had to be melted in a clay crucible heated by charcoal, possibly alloyed with silver or copper, and then poured into the mould. Three different casting techniques are relevant to prehistoric goldworking: bar (or ingot) casting in an open mould, piece mould casting, and the lost-wax technique (Armbruster, 2001). Piece moulds can be used for solid casts and in combination with a clay core for casting hollow objects. Usually a gold bar would be shaped by hammering into rods, sheets, or wire. The casting in permanent piece moulds is rare in ancient goldwork, but appears at Ur through a ceremonial weapon cast in a three piece mould consisting of two halves and a core (Figure 1).

By contrast, in the lost-wax method a model of the desired object is made of wax (Hunt, 1980). The wax model is coated in tempered clay which is applied in several layers and then the wax is melt out after drying. The remaining hollow space is then filled with molten gold. The clay mould is destroyed to release the cast piece. The unfinished cast must be worked and clean with chisels

Figure 2. a-h Spouted vessel, B17692

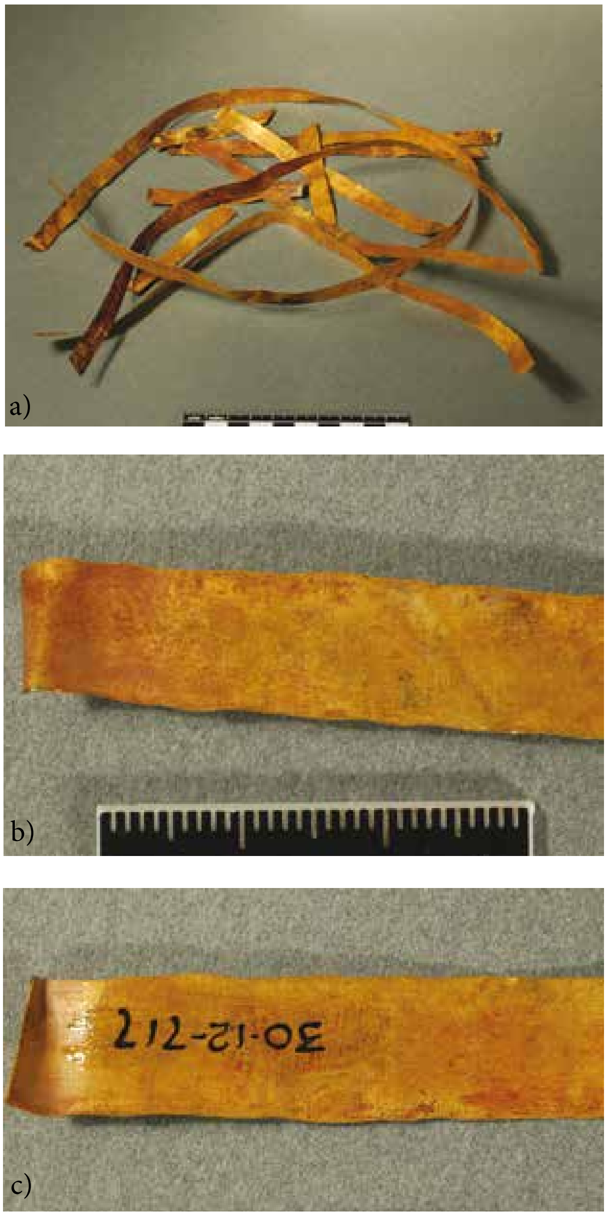

Figure 3. a-c Ribbons, 30-12-717

and the surface smoothed by grinding with abrasives. Solid beads (Figures 12b; 13c and e) and the spouted vessel (Figure 2) are presumably cast with the lost wax process. A rough cast surface is clearly visible on the interior of biconical beads (Figure 13f). The cast items have a high weight compared to sheet objects of similar shape.

Two different soldering techniques were carried out in Bronze Age goldworking and may be contemporary. A metallic hard solder was in use, the melting point lower than that of the base metal (Perea, 1990). Metallic solder is an intentionally made or selected alloy of gold with silver and copper. Tiny particles of solder are placed in position at the joining area, melt during heating, and join the separate parts together. Often this technique can be identified by gold solder bits that have melt on smooth surfaces or flooded with an excess of solder material, for instance at the pendant with four filigree cones (Figures 14b and h-i). The second possible technique is reaction soldering based on the application of a copper salt powder and organic glue forming a hard solder during heating (Pacini, 2006). Through heating, the organic glue transforms into carbon that reduces the copper salt to metallic copper. At the joining point the copper forms a tiny solder area by diffusion. Reaction solder leaves very little solder remnants. Analyses through material science are necessary to distinguish the two techniques with certainty.

Plastic deformation - hammering, tracing and chasing

The technique of forging sheets, rods, and wire from a gold bar was perfectly mastered. Sheet and wire were made exclusively by deformation of a cast pre-product using hammer and anvil. Wire as fine as about a millimeter in diameter and even less was achieved by hammering. Clear tool marks from hammering are apparent on the wire from the loop-in-loop chains and on pendants as small facets (Figure 12f-j). Several items from Ur show a combination of hammering sheet, strip or wire parts in one single piece of gold as it is the case for the ear ornaments, like certain other objects and pendants (Figures 5 and 9).

Sheet ornaments are present without decoration through a large quantity of flat hair ribbons (Figure 3) (Zettler and Horne, 1998, p.102). Those with punched and chased decoration appear as decorative sheets or filets (Figure 4), and leaf-shaped pendants from wreaths (Figure 9) (Zettler and Horne, 1998, p.103). Three-dimensional hollow shapes are present through large hammered and chased earrings (Figure 6) (Zettler and Horne, 1998, p.107). Sheet metal was also used for the production of beads (Figure 9a-c), shaped by rolling of sections of broad hammered ribbons. Sheet was furthermore used for corrugated composite beads made from two roundels shaped in dies (or chased) and soldered together (Figure 13b and d) (Zettler and Horne, 1998, p.116, Figure 80).

Wire appears through thick spiral hair rings (Figure 10) as well as through loop-in-loop chains and tiny filigree work. Filigree ornaments occur in the form of pendants shaped as rosettes, double spirals or quadripartite with filigree cones (Zettler and Horne, 1998, pp.110-111).

Among the plastic shaping techniques used for decorative purposes, twisting of square-section bars or wires can be seen as well as the bending of wires, for instance, to make spiral wire cones. Sheet products were shaped and decorated by tracing and chasing or by the use of dies.

Filigree is an ornamental technique based on the use of small decorative elements of fine wires (Ogden, 1982, pp.46-56). Very fine threads, used for filigree work, were rolled from small flat strips or fine square sectioned wires (Figures 13h-k) (Formigli, 1993). They can be applied to a gold sheet or wire structure, or single wires could be soldered together, as it is the case for the conical filigree pendants (Figures 14c-d) (Zettler and Horne, 1998, pp.121-122 Figures 92, 93 and 95). Both techniques reach a high technical standard in the Near East and the Mediterranean region during the Bronze Age.

Observations on Ur goldwork from the Penn Museum collection

The early use of gold is amply attested at Ur for manufacture of personal ornaments, decorative elements, vessels, weapons and statues. The design of these objects is multifold, including two-dimensional objects (like sheet jewelry, decorative items and strips), three dimensional solid bodies (like weapons) and three-dimensional hollow bodies (like sheet ear pendants and cast vessels). The gold artifacts can be classified into functional groups such as persnonal ornaments and ceremonial objects, including vessels, statues and weapons. Beside geometric forms and decorative patterns, the early representation of zoomorphic and floral forms in gold appears. Gold was also used for sheet "gilding" or plating of other materials such as wood. The combination of gold with different materials often results in polychrome work for aesthetic, social and religious functions.

The following observations details a selection of gold artifacts arranged in technical groups, from simple to complex. In cases where the items are composed of elements belonging to different technical groups, they will all be discussed together. Penn Museum inventory numbers are helpful to identify the individual artifacts.

Observation methods

The techniques of examination at our disposal for this study were optical macro and microscopy and the documentation by macro and micro-photography.[1] Tool mark and surface structure analyses were the main goals of this study. They allow to distinguish and to determine techniques of casting, plastic deformation, decoration, joining, finishing and repair. The optical study also allows the identification of the number of elements constituting an object, combination of several materials as well as provide information about the technical solutions and choices made. Finally, the visual study also reveals traces of use and damage.

Cast objects

Two large and heavy cast items were studies in order to determine their manufacturing techniques. Both are of three-dimensional character and have a considerable weight due to the casting processes. Other cast ornamental elements within the studied selection are solid beads whose technical features are described further below with the beaded strings[2] (30-12-618; 30-12-561).

The solid golden adze (B16691) with a shaft hole appears to be a ceremonial tool or weapon (Zettler and Horne, 1998, p.170). The blade and the shaft were made in a single cast. The adze is undecorated except for the ridges lining the exterior of both the top and bottom shaft openings and on the shaft's back (Figure 1a-c). The cutting edge is partially damaged (Figure 1e-f).

This heavy prestige object has been cast in a three piece mould consisting of two halves and a core element. The three mould components might have been constructed of stone or tempered clay. The outer surface has been carefully ground and polished leaving nearly no visible traces of the ancient casting surface, except for some small areas (Figure 1d). Traces of abrasion and platinum group element (PGE) inclusions (see contribution of Jansen, Hauptmann and Klein, this volume) are apparent at the surface (Figure 1g-h). The former casting seams were also erased by grinding and polishing with abrasives. In contrast the inner surface of the cylindrical shaft hole still bears remnants from the casting process, in particular a rough surface structure (Figure 1b). The cutting edge has probably been hammered for strengthening. As the surface is smoothened by grinding and polishing no tool marks of hammering are visible.

The vessel (B17692) has a conical form with a flat base and it is supplied with a long handle-like spout (Figure 2a-b; Zettler and Horne, 1998, p.127). The only decorative elements are a circumferential groove under the rim (Figure 2c) and the bent extremity of the spout. Both ornamental features have also practical functions such as the strengthening the container's body and rim, and to facilitate pouring of a liquid.

This spouted bowl was hammered out of a blank, a preliminary cast product and the raising was finished by plastic shaping to accomplish the final three-dimensional form. The object clearly shows tool marks from the hammering process. The round base starts in a short hammered cylindrical form before widening to the conical shape (Figure 2d). Tool marks of intensive hammering are evident at the inside's surface while the

Figure 4. a-f Decorative sheet, B16921

outside is burnished. The groove under rim was created by plastic deformation using a tracer for chasing. The groove's surface also shows evidence of grinding. The spout was already present in the pre-cast form of the vessel, but has been strengthened by hammering. Finally, the spout's terminal has been beaten in the shape of a thin sheet strip and then bent over forming a small loop (Figure 2g-h).

Sheet and wire work - Personal ornaments

A large number of long sheet ribbons were part of complex headdresses (Figure 3a) Zettler and Horne, 1998, p.102). These decorative ribbons (30-12-717) have parallel lateral edges and a regular width. They were hammered from a preliminary product. The front side surface was carefully polished (Figure 3b), whereas the rough surface on the back was left raw and probably results from hammering with stone percussion tools (Figure 3c). The lateral edges have a slightly undulating shape. So, they were not cut with a chisel but left raw after plastic shaping. It can be assumed that the sheet ribbons were hammered from a long thick wire.

The thin decorative sheet ornament (B16921) has tapering ends of rounded shape (Figure 4). It is decorated with a series of small bosses along the rim and around one perforation at each end (Figure 4b-f). Along the line

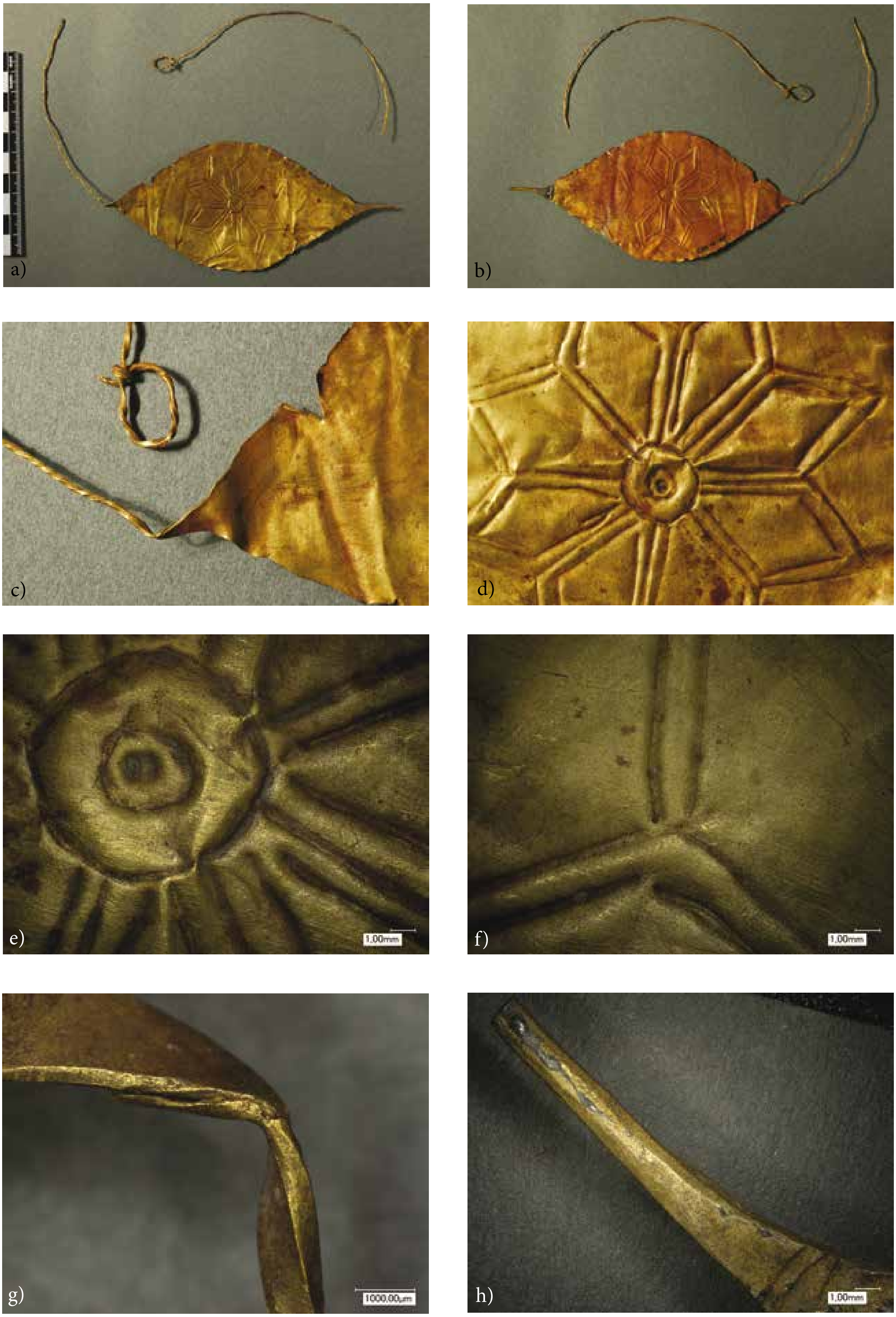

Figure 5. a-h Decorative sheet with wire endings, B16706

Figure 6. a-h Ear ornaments, 30-12-766 and 30-12-729

Figure 7. a-h String with sheet beads, B16801

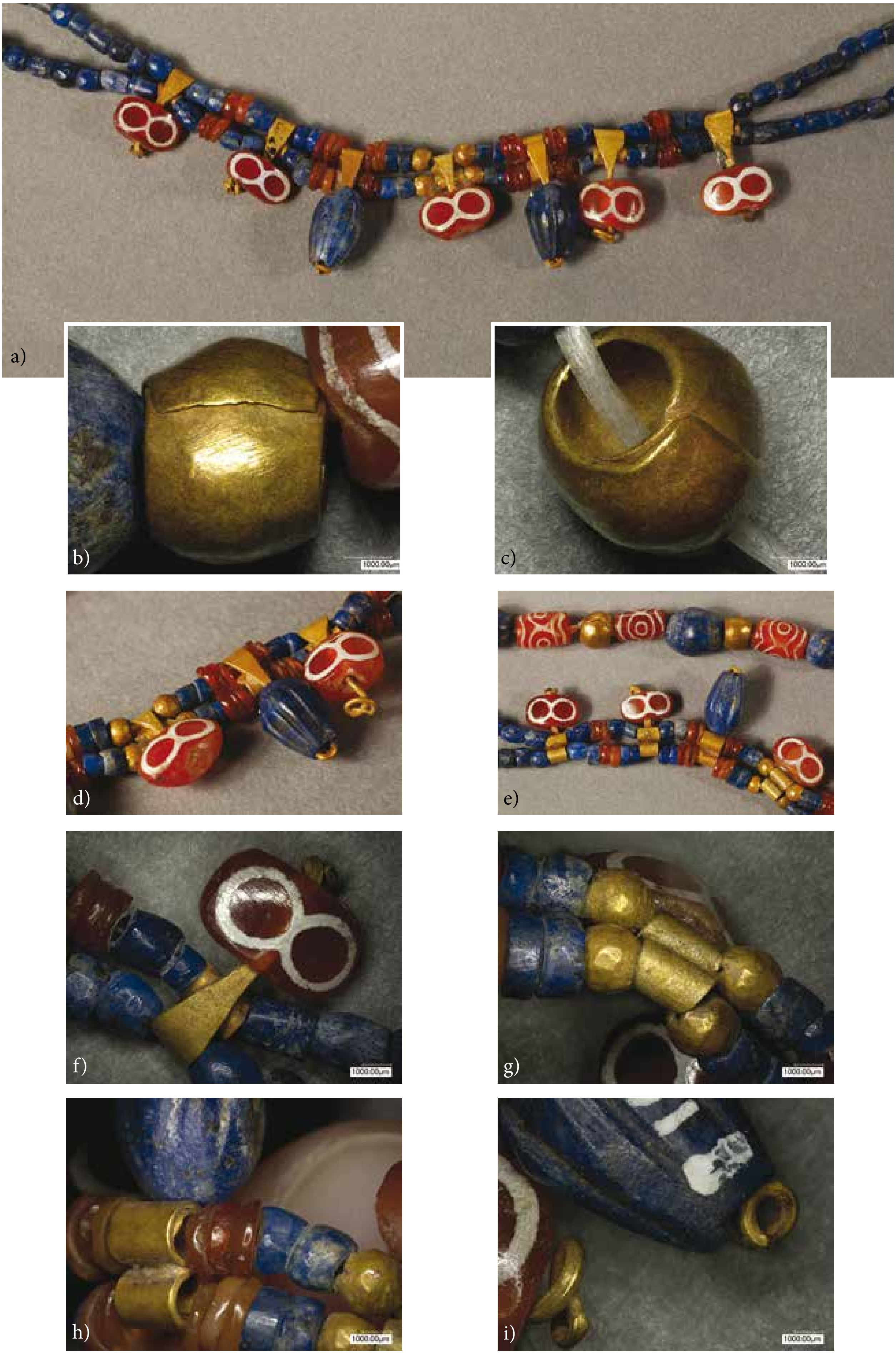

Figure 8. a-i Strings, B16799 and 30-12-573

of bosses 16 smaller perforations appear. They were presumably used for fixing the sheet on a support material. The perforations were pushed through using a conical point (Figure 4f). The sheet's surface is burnished and the contour outline cut with a sharp chisel.

The flat sheet ornament with wire endings is decorated with a rosette motif (B16706; Figure 5a-b). This composite ornament is made from one sheet element and two wires. One wire terminal is lacking and the other wire is broken but still has its bended loop ending. Cast ingots were hammered to obtain a sheet and a rod. The rod was transformed into two long square-sectioned wires with a broadened and flattened end. Tool marks are left on this part (Figure 5h). This was twisted, cut in two and the terminals bend into the shape of a closed loop (Figure 5c). The wires were probably soldered with the broadened end to the central sheet (Figure 5g). One modern repair with a gray soft solder is obvious at the junction on the broken side (Figure 5b).

A rosette with eight petals was traced with double lines on the thin sheet using a tracer (Figure 5d-f). This decorative linear pattern is poorly executed compared to the skillful quality of other items.

Large crescent-shaped ear rings appear in pairs (Zettler and Horne 1998, 107). These ear ornaments (30-12-766, 30-12-729, B16989 a-b) have a three-dimensional hollow shape of large volume compared to their low weight due to the use of thin chased sheet (Figure 6). They are composite ornaments put together from two individual hammered and chased sheet parts in the shape of hollow vessels. One piece has a wire ending starting from one tapered end of the sheet part (Figure 6c) whereas the other part has a tubular bent terminal for holding the wire's end like a fastener. The wire's function is the suspension of the earring. Wire and sheet are made from one piece by plastic shaping techniques starting as a cast ingot. The sheet components were most likely chased and also possibly worked using a wooden die. The two very similar parts are joined by soldering. The solder was applied punctually (Figure 6g). As no chemical analyses of the solder's alloy composition were performed, no inferences can be made on the soldering process.

This small beaded string (B16801) is composed of 14 flat gold and 15 circular flat lapis lazuli beads (Figure 7). The gold beads bear traces of long wear (Figure 7e). Some have a foliated appearance (Figure 7c and e-f) suggesting a fabrication by soldering two sheets together. But the threading tunnel does not confirm this hypothesis. Presumably they were executed by the lost wax technique. In this case wax sheet elements were used to make the wax model. The threading tunnel can be produced by inserting a carbonized wooden stick in the wax model, and finally in the clay mould. The charcoal is removed after casting. This technique of lost wax casting of tiny beads with a cylindrical threading tunnel is well known from ethnographic sources in particular from Ghana (Garrard, 2011).

The strings (simple 30-12-573and double B16799) are composed of sheet beads, as well as lapis lazuli and etched carnelian beads (Figure 8). The gold beads of the smaller string (30-12-573) are worked from a rolled strip shaped into a cylinder (Figure 8b-c). The ends are overlapping. To achieve the slightly conical shape, the goldsmith uses a sort of a hollow conical die or doming block in which he or she pushes the sheet cylinder with a percussion tool. This tool can be as simple a wooden bar.

The double string (B16799) has four small sheet beads made in a similar way as for the previous example. In addition, it provides 5 gold pendants each with an engraved carnelian bead of flat oval shape. Furthermore, two gold pendants with drop-shaped corrugated lapis lazuli beads complete this ensemble. These pendant beads are fixed on wire-shaped appendages. The gold pendant is composed of a double loop suspension made of a bent sheet strip continuing into the wire appendage (Figure 8d-h). The whole is hammered from one piece of gold. The wires still show obvious tool marks from the hammering process (Figure 8i).

The double-looped suspension system also appears on leaf shaped pendants. Two strings with leaf shaped pendants were examined (30-12-445 and 30-12-679; Figure 9). Such a kind of flexible threaded adornment was apparently used as a wreath in a complex headdress (Zettler and Horne, 1998, p.98 and 103-104). They are composed of a dozen (or more) golden leaves with spacer beads made of carnelian and lapis lazuli. The iterated concept of three colors creates an attractive polychrome effect.

The very thin sheet leafs were hammered (0.1 mm thickness) in one piece with a long appendage. This ribbon-like extension was also shaped by hammering and then folded in two directions, forming kind of a double suspension loop (Figure 9b and f-h). The lines, a central rib and oblique lines representing the natural leaf structure are traced with a tracer in more or less symmetrical shape (Figure 9c-d). The outer edges of the gold leaf forms were cut out using a sharp-edged chisel. The gold leaves are integrated into an ensemble of long and short cylindrical or lentoid-shaped beads of carnelian and lapis lazuli. Some of the gold leaves are damaged. No fastening system for the wreath survived.

The second string (30-12-679) is comparable to 30-12-445 with a minute difference as one of the leaves

Figure 9. a-j Strings with leaf shaped pendants, 30-12-445 and 30-12-679

has a double rib (Figure 9i-j). This detail shows that the goldsmith corrected an error in the direction of the chased line.

Two hair rings (B16841 A and B) made of wire spirals constitute the simplest wire ornaments of the selection (Figure 10a-b). The round-sectioned wire was achieved by hammering a rod, starting from a square shape changing to a polygonal shape until finally attaining the round section (Untracht, 1982, p.248). The wires are carefully polished. They were bent around a hard cylindrical rod circling two and a half times.

The three-colored string (30-12-759) is composed of 20 ring-shaped gold pendants threaded on a triple band of cylindrical lapis lazuli and lentoid carnelian beads (Figure 11). Each ring pendant consists of a ring made from hammered round-sectioned wire and closed by soldering to which a corrugated sheet ribbon-shaped suspension loop is attached. This loop is made from a sheet strip, first folded to double the sheet and then bent in a way to achieve a spacer for three threads and a doubled ending to be attached on the ring by soldering (Figure 11b-e).

This detached ornament (30-12-618) is composed of two loop-in-loop chains, one faceted biconical gold bead, two lentoid carnelian beads and two biconical lapis lazuli beads (Figure 12). The faceted biconical gold bead was made by lost wax (Figure 12e). The wax model was shaped around a burnt wooden stick to produce the threading tunnel; the tunnel is slightly recessed around the edges. The surface was finished with abrasives (Figure 12b-c). It bears PGE inclusions (Figure 12d).

The loop-in-loop chains (Figure 12f-k) were created from a round-sectioned wire (Ogden, 1982, pp.57-58). The wire loops still bear tool marks from hammering (Figure 12h-j). To achieve a large quantity of equal sized loops the goldsmith bends a long wire around a core stick forming a cylindrical spiral. Each loop is cut with a sharp chisel from this spiral and is then closed by soldering. The solder points are easily recognizable (Figure 12j). The loops were then formed to a oval shape and the loop extremities bent. They were linked one in another to form a flexible chain with links of standardized shape.

This polychrome string (30-12-561) is composed of 29 gold elements (14 long cylindrical filigree beads, 14 biconical gold beads and one corrugated spherical bead), 28 lapis lazuli elements (2 corrugated, spherical lapis beads) and 6 carnelian beads (4 lentoid and 2 biconical) (Figure 13). The aesthetic attraction relies in the three colors and the elements of the same shape executed in different materials. The corrugated gold bead is made of thin sheet, presumably made of two parts pressed in a die and decorated by chasing (Figure 13b and d). The gold sphere is so well polished that the joining seam is invisible.

The biconical gold beads seem to have been made also from sheet at first glance, as the seam on the outside shows, but this could be made by lost wax casting using a wax sheet model (Figure 13e-g). They bear significant PGE inclusions.

The long, hollow and cylindrical gold beads are composed of several pairs of twisted wires (Figure 13h-k), that are oriented in opposite directions to provide them an aspect of interlaced shape. The wires are clearly made by rolling a strip as shown by the helicoidal marks on the wire surface (Figure 13k) (Formigli, 1993). Both terminals of each bead are strengthened by a slightly smaller wire bent three times around the composite cylinder. All the filigree elements are joined by soldering. The gold beads bear traces of long wear in particular at the contact point between the stone and gold beads and is visible by the rounded surfaces caused by abrasion (Figure 13f and i).

The bichrome string (B16794) is a delicate composition of beads and pendants (Figure 14). Its constituents are three golden filigree pendants, four drop-shaped hollow gold beads combined with lapis lazuli elements and a large number of lapis lazuli beads (Zettler and Horne, 1998, p.111). Two pendants function as spacers. The two small conical filigree pendants are made from one piece of wire each, forming the decorative wire and a ribbon for the suspension loops. The filigree cones mark the three-dimensional character of this remarkable bichrome ornament. The shape of the small cones is reiterated in carved lapis lazuli at both the terminals (Figure 14c).

The central pendant is the most complex part of the ensemble, with four filigree cones made of two wires. The ends of two long wires were rolled in shape of a coiled cone with the central part of the wires left open. The two wire elements with coils were then twisted along this central part in order to link the two wires producing the four cone motif (Figure 14c and e-g). This composite filigree element is then fixed within an annular frame of thicker wire with small loops soldered circumferentially (Figure 14g). Between these loops small lapis lazuli beads are fixed with a string or wire forming a crown of alternating gold and blue elements. An ancient repair appears in the center where one of the small filigree cones was renewed. The goldsmith replaced a lacking or broken cone by another one coiled in the inverse direction (Figure 14g-h).

This filigree work is undoubtedly constructed of gold wire soldered with metallic solder (Figure 14b and g-k).

Figure 10. a-b Wire spiral rings, B16841 A and B

Figure 11. a-e String with annular wire pendants, 30-12-759

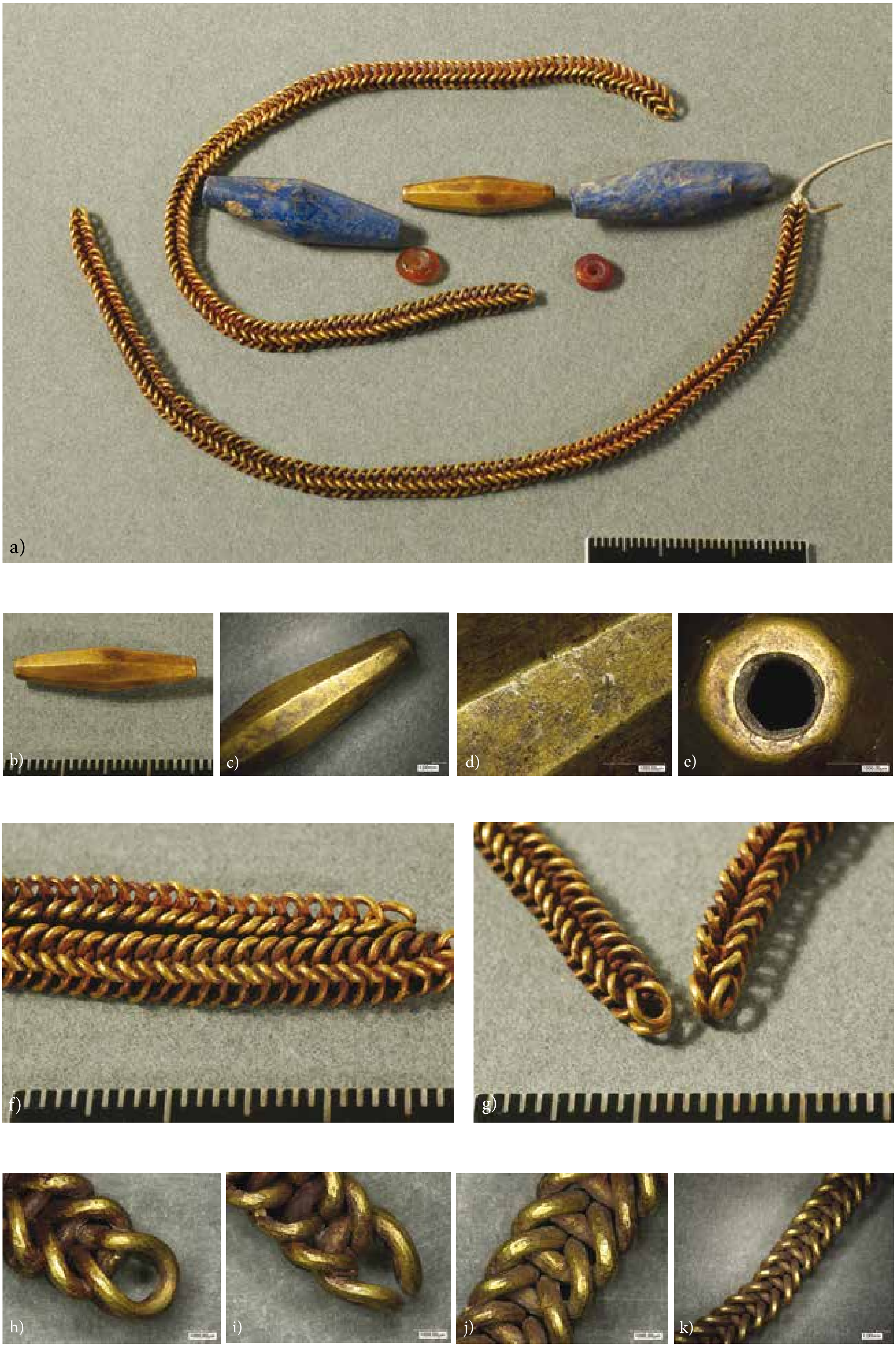

Figure 12. a-k Loop-in-loop chain with conical beads, 30-12-618

Figure 13. a-k String, 30-12-561

Figure 14. a-k String with pendants and beads, central pendant with filigree work, B16794

Figure 15. a-h Bull's head, B17694

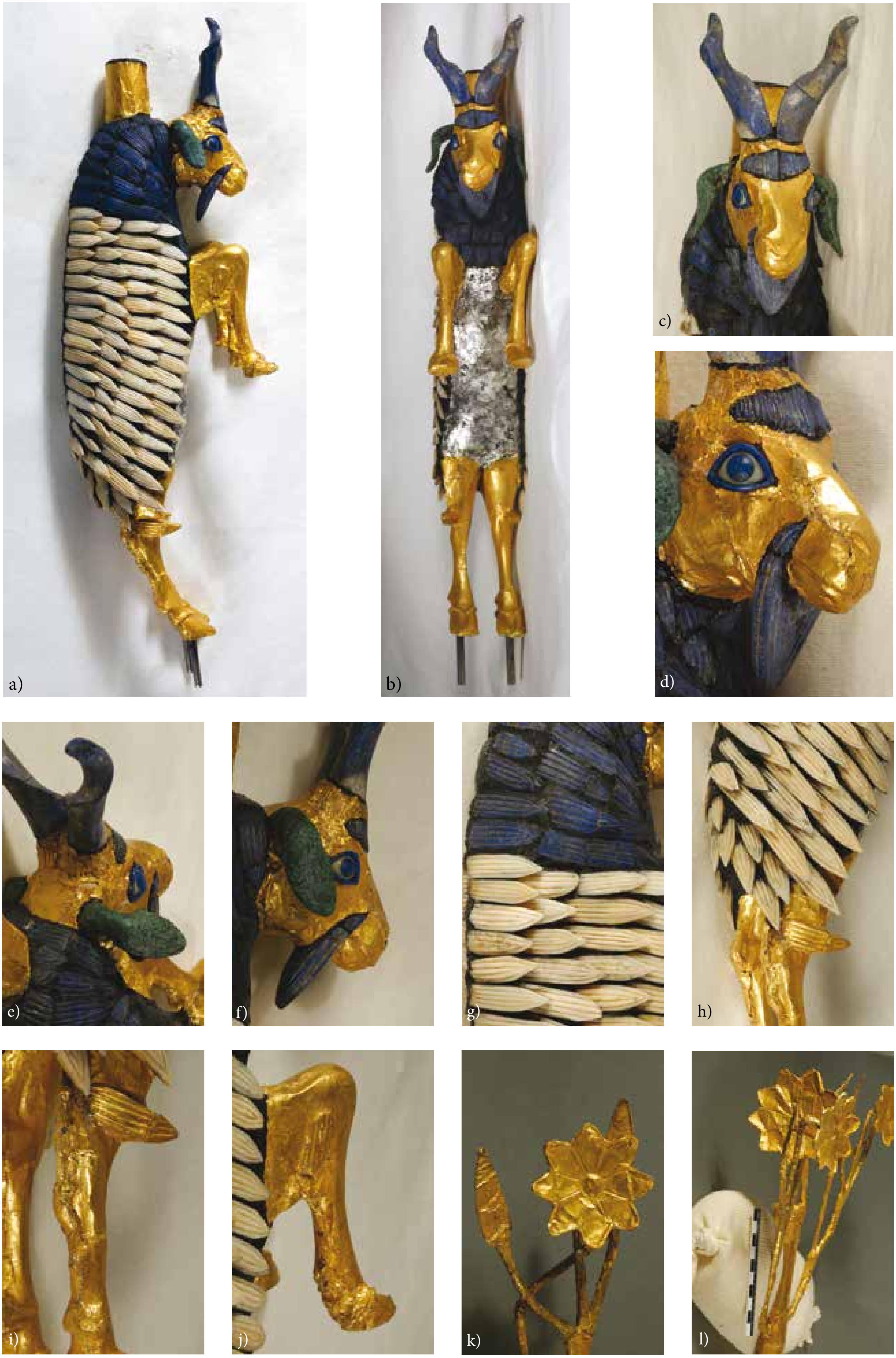

Figure 16. a-l Ram caught in a thicket, 30-12-702

The metallic solder material can be clearly seen on the filigree elements as well as on the solder joints between the filigree, the frame and the suspension loops. Some solder bits melted on the smooth surface of the thick wire frame (Figure 14g and i). The quadruple suspension loop is composed of several sheet elements joined by soldering and attached to the round-sectioned wire by solder. There is a modern soft solder repair visible as a gray lump of lead or tin solder at the suspension loop (Figure 14e and g). Parts of the surface of the filigree pendants show damage by overheating the work pieces during soldering (Figure 14h-k).

Sculptures

Two prominent sculptures were examined within the technological study, a bull's head that served as a decorative element of the great lyre from the king's grave, and the free-standing composite sculpture of a goat or a ram caught in a thicket. Both figurative works are constructed and decorated of several different materials set on a carved wooden structure. These sculptures are suggestive of the aptitude of the craftspeople to produce figurative art of extraordinary aesthetic and technical standard.

The bull's head (B17694, Figure 15) is a three-dimensional figurative, polychrome masterpiece made of gold sheet, lapis lazuli, and shell applied on a perishable material (Zettler and Horne, 1998, p.XVI and 53-57). The thin gold sheet elements have been hammered and chased delicately to conform to the hollow parts of the form. Several sheet elements were assembled to form the main head body, ears and horns. Ears and horns were wrapped and a mechanical seam (not soldered) is visible (Figure 15c-f), while the head seems to be made of one single sheet, prepared by chasing and hammering, and then pressed over the carved surface of the core material (Figure 15a-c). The joining of the golden sheets was executed by folding and riveting or nailing (Figure 15g-h). There was no possibility to measure the gold sheet's thickness. The bull's eyes are composed of shell and lapis lazuli and most probably fixed by glue or bitumen (Figure 15d). Sculptured lapis lazuli highlights the horn tips as well as the large beard and tufts of hair on the forehead with a fine carved relief (Figure 15a).

The "Ram Caught in a Thicket" (30-12-702; Figure 16) is a composite sculpture, like the bull's head, made of gold sheet, copper alloy, silver, lapis lazuli, shell on an wooden support (Zettler and Horne, 1998, p.42 and 61-63). The goat is standing on a base composed of shell, lapis lazuli, red limestone and silver elements on wood (not at disposal for the present study). The different non-metallic parts were most probably fixed with glue or bitumen. The sculpture has been restored and the copper ears, gold sheet, lapis lazuli and shell are today fixed on a modern frame. To shape the gold sheet to the three dimensional form of the sculpture it has been partially hammered and chased to fit it into the desired relief. Like the head, four legs and the cylindrical part above the animal's neck and the floral elements of this statue are carefully wrapped in thin gold sheet and fixed mechanically by folding and bending (Figure 16c-d and i-l). In some areas it forms wrinkles and pleats. Traced lines enhance the details of the ram's head and legs as well as on the floral motives of the thicket elements (Figure 16b-c and k-l). As with the bull, the ram's eyes are composed of shell and lapis lazuli (Figure 16d). Sculptured lapis lazuli adorns the horns as well as the beard and hair on the forehead with a fine carved relief (Figure 16c-d). In addition, individually carved elements of lapis lazuli and shell were fixed on the body, the blue embellishes the ram's fleece on the shoulders and chest, while the back is white (Figure 16g-h). The copper alloy ears are solid casts (Figure 16e-f). It seems that the goat's belly was covered with silver sheet that hardly survived (Figure 16b).

Notes on the goldsmith's "*savoir faire*", techniques and workshop equipment

The investigated gold items from Ur belong to different functional groups: Jewelry (stings, ear pendants) and decorative sheet elements (hair ribbons), tableware (spouted vessel), ceremonial item / weapon (adze), and finally sculpture elements (ram and bull's head). They can be classified in several technological groups: 1) Cast in piece mould with cylindrical core (adze), 2) Cast in lost wax (cylindrical beads), 3) casting of a pre-product in lost wax and partially hammered (vessel), 4) sheet work (ribbons, decorative sheets, leaf shaped pendants, hollow ear ornaments), 5) Combined plastic shaping of sheet and wire, 6) wire work (hair rings) or filigree (elements of strings, ring-shaped pendants, filigree beads, loop-in-loop chains), and finally, 7) sheet plating of figurative sculptures (bull's head and ram).

The technical knowledge of the goldsmith – as confirmed by the technological study – can be described as a combination of pyrotechnical processes and plastic shaping. In the logical sequence of the *chaîne opératoire*, first to mention are measuring techniques such as weighing and assaying to determine and test the quantity and quality of precious metal alloys. That is followed by melting of the metal, possible alloying (See contributions of Hauptmann and Klein and Jansen, Hauptmann and Klein, both in this volume) and casting of ingots or artifacts by lost wax casting and two piece moulds with core. Plastic shaping of rods, wires and sheet from a cast ingot constitute the next step, and thereafter the three dimensional chasing, punching and tracing for decoration. Joining is executed by metallic soldering, probably also by reaction solder, and by mechanical joints like folding, riveting or nailing for the gold plated objects.

The small group of objects studied within the scope of the Ur-Project already shows the remarkable variety in function and typology of goldwork production as well as in technology applied in the manufacturing of the fine metal work. Some are created exclusively in gold, whereas others combine other materials such as lapis lazuli and carnelian. The examined object groups include flat items of two-dimensional conception and three-dimensional ones, comprising hollow and solid examples. There are objects made with only one constituent element, while others are composed of a large number of elements, individually manufactured and then joined. They also differ in their handling and motion. Chains and strings are articulated, while other items are rigid. Some are very light and fragile, while others are heavy and solid. Finally we distinguish objects that do not need any support, threaded elements and those consisting of a core material covered with thin gold sheet giving the optical illusion of a massive object.

Conclusion and perspectives

The gold artifacts from Ur are of remarkable quality in technical as in artistic terms attesting that the art of the goldsmith achieved a high level in Bronze Age Mesopotamia. The small heterogeneous group of gold objects studied illustrates how ancient craftspeople mastered technological challenges. These ornaments were worked for the living and for the dead, some obviously exclusively for the burial ceremony. The production of ornaments, decorative elements, sculptures and vessels must have been well organized. The skilled craftspeople worked in specialized workshops and they or their purchaser or patron had extended cultural contacts. The artifacts are of local Near Eastern design and created with a large variety techniques and combinations. They were obviously aware of the interdependence between aesthetics, decorative style and form and the mechanical constraints linked to functional aspects of use, and all of this relates back to the technical choices made by the craftsperson (Armbruster, 2011b).

The Ur material offers an extraordinary large range of object types of varying form, decoration, dimension, function, raw material and respective manufacturing techniques. Therefore, this extraordinarily rich material would be worthy to be studied in a comprehensive manner and with an interdisciplinary approach. Consequently, the intention of these preliminary investigations is to encourage further and more extensive studies with this very aim. Further studies of a larger corpus of objects and an exhaustive catalogue of the Ur goldwork (Penn Museum and British Museum) would provide more precise information on the technical / workshop traditions and perhaps several independent workshops or ateliers can be identified with specialization of object types and techniques.

Future studies could be aimed at exploring the origin of the highly developed gold technology, the emergence of local traditions, inventions as well as external influences. They also should investigate comparable artifacts and parallels from other Near Eastern sites.

Further investigations should incorporate scanning electron microscopy and X-Ray radiography in the detailed study of the manufacturing technology. The characterization of different alloy composition of a large number of gold items from Ur in particular and of Mesopotamia in general could help to form groupings in compositional as well as in technological terms (compare to Hauptmann and Klein in this volume). Spot analyses of junction zones could provide insights into the joining techniques. The alloy composition applied in soldering procedures and the distinction of natural and intentional alloying are of particular interest for technological studies.

Furthermore, the documentation of tool marks and surface structures of a large group of fine metal work could provide information as a basis for experimental replication or reconstruct of certain manufacturing techniques. An explanatory model of the equipment and organization of Early Bronze Age fine metal worker's workshops could then be established and possible forms, functions and materials used for the goldsmith's tools, such as technical ceramics, stone, copper alloys, antler and bone, be reconstructed. Analogies from experimental archaeology, ethnoarchaeology, and from ancient depictions of fine metal workers, could also assist to reconstruct the Ur's goldworking craft.

It would be a challenge to find out about the nature and the localization of the workshops that created the outstanding fine metal work from the Royal Cemetery of Ur. Such investigations could make a major contribution to the history of metal technology.

Acknowledgements

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Notes

1 Macro-photography was performed with a Nikon D100 digital camera with a micro Nikkor 60mm f/2.8 of the CNRS laboratory TRACES, Toulouse, while micro-photography was performed using the Keyence Digital Microscope of the Deutsches Bergbau-Museum. This microscope enabled images of the object to be taken with high topographic relief because of its substantial depth of focus.

2 The word 'string' was chosen as a function neutral term to denote a threaded bead assemblage like bracelets and necklaces or other types beaded jewelry.

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Ur, Mesopotamia: The Lead Metal from Pit X

Sabine Klein and Andreas Hauptmann

Introduction

The very last effort of Sir Leonard Woolley in Ur was the excavation of additional graves from the transition period between Late Uruk and the Early Dynastic Period, the Jamdat Nasr period (c. 3100 – 2900 BC). Pit X was the excavation site of his last season, and it brought out a total of 84 metal objects: 4 silver objects, 42 copper objects, and 38 lead objects (Woolley, 1956, pp.104 ff.). Regardless of the archaeological fact that most of the objects from Ur turned out to be later, dating mostly to the Early Dynastic rather than to the Jamdat Nasr period, [1] the present study focuses specifically on the lead objects from Pit X dated to the Jamdat Nasr period.

In the University of Pennsylvania Museum of Archaeology and Anthropology (Penn Museum), the lead metal from the Jamdat Nasr period of Ur is represented through a small variety of object types such as a flat bowl, a table or tray, or a number of lead metal sheet covering small ceramic cups (Figure 1).

Context of lead metal in Early Bronze Age

The use of lead metal is known for cast objects from other sites earlier than Ur, for instance in filigree seals from Central Asia.[2] The earliest lead metal finds are scarce, but individual finds have been identified in western Asia, e.g. in the Levante (Ashalim Cave, late 5th Millenium, Yahalom-Mack, et al., 2015), in Anatolia (Demircihöyük, EBA Ib / 1a, 2700 / 2900 BC) with lead bottles and decorated lead strips, the "Syrian bottles" from Sarıket & Kücükhöyük (EBA II), and the tall lead vessels / bottles with narrow openings from Tepe Hissar in North Iran (Efe and Fidan, 2006).

In regard to the copper / bronze metallurgy from the Royal Tombs of Ur in the Early Dynastic III, lead was not used as an intentionally alloyed component. It appears as vessels (bowls, tumblers, trays) to a significant extent only in the later phases of the prehistoric period at Ur. It is important to keep in mind for future interpretation that there may be correlations among metals with a possible common source, for example the lead bottles from Demircihöyük were not associated with copper objects (except one), but always with silver objects (Durgun, 2012). Yahalom-Mack, et al. (2015) discuss a correlation in the rise of silver and lead objects during the 4th millennium B.C. The typology of the "Syrian bottles" from Sarıket & Kücükhöyük indicate trade relations between inland Anatolia and southeastern Anatolia or the north of Syria (Efe and Fidan, 2006). This might be a hint towards the source regions for the lead of the Pit X lead objects, as well.

Function of the wrapped cups from Pit X

The function and use of the small ceramic cups wrapped with lead sheets appeared unclear to the authors at first, but after seeing the full spectrum of lead objects from the Penn Museum's Ur collection it began to be clear. Further comparison with the inventory of Ur material of other museums shed more light on the riddle: The small ceramic cups were used as lids for large ceramic bottles. The lead sheet that was wrapped around the inverted cups tightly and functioned as a seal. It is safe to assume that these seals were used for the safe transport of bottled liquids. Three complete bottle-wrapped seal combinations were found in the various Ur collections: Two in the Penn Museum's collection[1], and a third one in the Birmingham Museum's collection from Ur (Figure 2).

Analysis of the Elemental and Lead Isotope Composition of the Lead Metal Wrappings

The two museums permitted the sampling of lead metal sheets in order to perform geochemical analysis. Because the metal is very soft and easy to cut, a small piece of a few milligrams was chipped from each object. The metal samples were then used for elemental analysis by wet

Figure 1. Lead metal sheets used to cover small ceramic cups. The first one is flattened. (Penn Museum collection, Pictures taken by A. Hauptmann and S. Klein).

chemical ICP-MS in Bochum (DBM) and lead isotope analysis in Frankfurt am Main (Geochemistry laboratory of the Goethe University).

Elemental Compositions

Two assay analyses were obtained for their silver content prior to this study by E.C. Padgham. The results were presented by H. Plenderleith (Woolley, 1934, p.295): Two lead tumblers each had a quantity of 0.07 % (700 ppm) silver in the lead metal.

The present analyses of chemical composition were performed on the nine samples from Penn Museum. They comprise of 14 elements that were detectable in the sample solutions (Table 1). The Birmingham sample is not included.

The result of the chemical analyses can be summarized as following: The two lead tumblers (analysis by E.C. Padgham) have silver contents of 700 ppm each. One of the present cups has a comparable high level of silver with 500 ppm, a second one is with 110 ppm and all others (8 cups) contain 80 ppm Ag or less. Elements such as antimony, bismuth, copper, iron, sulfur, arsenic

Table 1. Trace element analysis of the lead samples from Ur, Pit X, by ICP-MS from solution. Analyses are normalized to 100% lead and are given in ppm (parts per million). [PM = Penn Museum]

Lab.-Nb.	Inv. Nb. PM	Ag	Sn	Sb	Te	Bi	Co	Ni	Cu	Fe	P	S	Zn	As	Se
4823_13	35-1-224	110	5	440	30	10	0.01	0.6	250	30	45	200	75	40	<4
4824_13	35-1-225	15	2	370	15	10	0.02	2	640	2	20	3100	15	15	<4
4825_13	35-1-226	500	220	210	10	170	<0.01	0.3	660	8	300	1300	7	4	<4
4826_13	35-1-227	40	6	360	6	20	0.05	7	830	50	120	320	6	60	<4
4827_13	35-1-228	75	<1	410	55	50	0.2	8	520	260	2600	1300	6	140	6
4828_13	35-1-229	30	2	280	20	60	0.03	4	390	20	370	450	15	110	<4
4829_13	35-1-230	80	2	260	10	120	0.02	3	380	2	1000	5700	5	35	<4
4830_13	33-35-97	15	<1	2100	10	110	0.08	8	910	60	230	4700	7	15	5
4831_13	31-17-12	15	15	860	40	35	0.02	4	340	15	60	4600	7	240	<4

Figure 2. Lead wrapped-seal on a jar from Ur, Birmingham Museum (Picture taken by A. Hauptmann and S. Klein).

and phosphorus are present, but statistically variable (heterogeneous) in concentration. As for the other elements, tin is individually high in the silver-rich cup (500 ppm Ag) with 220 ppm Sn, all others contain tin in the low ppm-level only. Concentrations of nickel and zinc are detected in low ppm-level.

Lead Isotope Compositions

Lead isotope analysis of the lead samples was performed using a inductively coupled plasma multicollector mass spectrometer (ICP-MCMS). The analyses were performed at the geochemical laboratory of Goethe-University, Frankfurt am Main.

In general, the lead isotope ratios are very widespread with ^{207}Pb / ^{206}Pb ratios between 0.828 and 0.883, and also with ^{208}Pb / ^{206}Pb spreading between 2.062 and 2.126. The same variability is true for the lead isotope ratios in respect to ^{204}Pb. However, the majority of the lead samples form a more homogeneous isotope cluster with smaller ranges. Three samples are outliers: Two lead sheets plot at higher ratios, and the lead sheet with the highest silver content (500 ppm) differs significantly having highest lead isotope ratios. The lead sample with the second highest silver content (110 ppm) plots within the major group. Although the individual sample with the highest silver content has the highest lead isotope ratios, with all the other lead samples there is no correlation between silver content and lead isotope ratio.

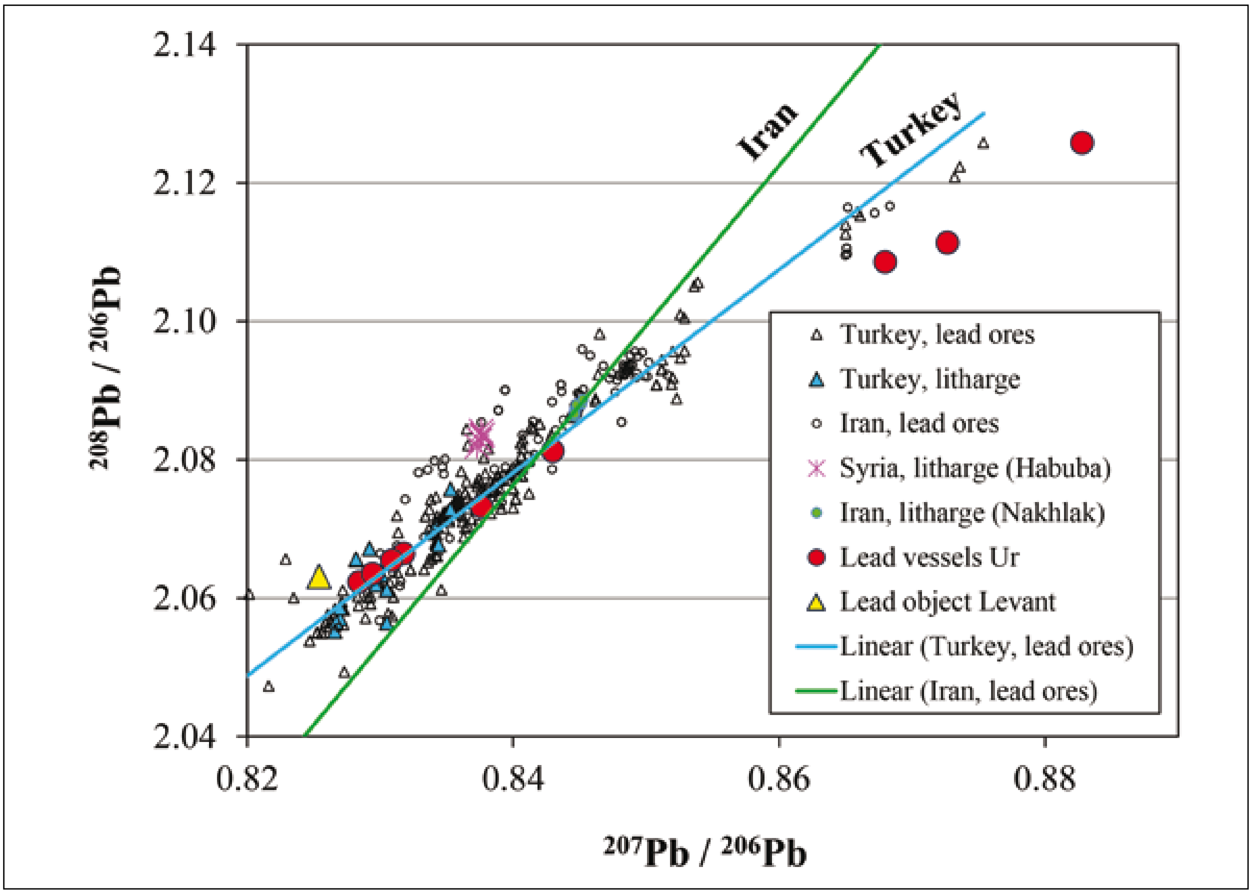

Figure 3. Lead isotope results of lead sheets compared with ore minerals and litharge from literature. Included are Turkish, Iranian and Syrian lead minerals and litharge from Turkey, Habuba Kabirah (Syria), and Nakhlak (Iran). Yellow triangle: Lead object from the Levant (Yahalom-Mack, et al., 2015). Linear trend lines based on the total of data points for each region. [Turkey, litharge: Arslantepe, Bolgardag. Turkey, ores: Hauptmann, et al., 2002; Lehner, Yener and Burton, 2009; Sayre, et al., 1992 ; Wagner, et al., 1986 ; Wagner, et al., 2003; Yener, et al., 1991].

Comparison with Minerals and Litharge from Potential Source Regions

When comparing the lead isotope signatures of the lead samples with minerals from potential geological units and with litharge as by-products remaining from lead-silver extraction processes of known locations, the following conclusions can be drawn: Litharge (PbO) match in all cases (Syria, Iran, Turkey) with the minerals from the same region. The major group of the lead samples plot with both Turkish and Iranian lead minerals (and consequently with their litharge), because the two overlap partially with their lead isotope fields. The sources in the two regions are difficult to distinguish as potential candidates for the Pit X lead sheet cup covers (Figure 3). If based on a linear trend line that is calculated for each region, a differentiation can be cautiously attempted: The lead sheets follow the trend line for Turkish lead ores (Anatolia, Taurus Mountains) rather than the Iranian trend line.

For comparison, also the early lead object from Ashalim Cave is plotted. Its lead isotope signature (Yahalom-Mack, et al., 2015) lies close to the present lead objects from Ur. It is interpreted by the authors as having its mineral source in the Taurus range in Anatolia. This collection of evidence strengthens Turkey as potential source region for the lead metal from Ur.

Conclusions

The lead sheets from Pit X in Ur were used as wrapping / sealing material for bottles. They are unique and appear only for a very short period of time.

The interrelationships between the silver contents and other trace elements and the copper isotope ratios will be sought in the future to discuss the mineralogical origin of the ore and explore the possible connection between silver and lead metallurgy. Concerning the lead isotope ratios, the objects show a variability of silver contents and there is an absence of a silver content to lead isotope correlation in most objects.

So far, the lead isotope signatures indicate that Turkey, more precisely Anatolia and the Taurus ore deposits, is the most likely mineral supplier for the lead metal from Ur. However, Iranian deposits have still to be taken into account in future discussions on the origin of these objects.

Notes

1 R. Zettler, Penn Museum, personal communication

2 N. Boroffka, personal communication 2015

3 http://www.penn.museum/collections/

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Analytical Investigations on Silver, Copper and the Earliest Tin Bronzes from Ur

Eveline Salzmann, Sabine Klein and Andreas Hauptmann

A key to understand economic and cultural relationships between Mesopotamia and other Early Bronze Age cultures lies in the analytical investigation of the related archaeological objects having the potential to answer specific archaeological questions. One is the question of the Bronze Age raw material supply of the region in question which may be traceable through the archaeological material. This may lead to conclusions about trading, organization, logistics and economic relationships. The present study is focused on the investigation of metal objects: particularly copper, arsenical copper, copper-tin alloys and silver objects excavated at the cemetery of Earl Bronze Age Ur in Mesopotamia. One fifth of our samples were excavated from the so-called "Royal Tombs of Ur", which provided a large number of finds and an amazing suite of precious metal objects (Woolley, 1934).

The University of Pennsylvania Museum of Archaeology and Anthropology in Philadelphia provided 89 mounted and 20 drilled samples for analytical investigations. The samples comprise 89 copper-based and 20 silver samples. This large amount is statistically relevant and gives a representative picture of the use of these metals in Ur.

Geochemical signatures such as elemental or isotope composition function as fingerprints of the metals which were produced in past times. This fingerprint is used here for the comparison of their geochemical signatures with various metal-rich mineral deposits.

The samples are currently under investigation at the laboratories of the Goethe-University Frankfurt am Main and Deutsches Bergbau-Museum Bochum. Preliminary to the analytical work, a portion of each drilled sample was mounted and polished in our laboratories for microscopy. The already mounted samples were re-polished to remove recent superficial oxidation. The analytical question requires spatial resolving techniques. To ensure representative bulk chemical compositions by point analysis, a statistically relevant number of measurement points was set randomly across the metal surface of the specimens. Characterizing the geochemical fingerprint involved the determination of the main and trace element composition with wavelength dispersive electron microprobe analysis (EPMA) and single-collector laser ablation mass spectrometry (LA-ICP-MS). Regarding the analysis of copper and lead isotopes, multi-collector laser ablation mass spectrometry (LA-MC-ICP-MS) was used. For quality control of our spatial resolving methods a portion of each of the drilled samples was dissolved in aqua regia or nitric acid to perform homogenized chemical and isotope analysis by solution-based mass spectrometry.

Archaeological metal is not as pure as modern metal. It is therefore crucial to evaluate not only the main elements, but also all accessory (trace) elements of the metal composition. More than the main elements, the trace elements provide important information about the mineral sources exploited for the production of the metals or alloys.

Different potential types of copper and silver mineral deposits have to be taken into account for the discussion of raw material sources:

(1) Native copper and silver, which occur only rarely in nature (Muhly, 1989). (2) Copper sulfide minerals from deposits, which occur along ancient marine margins through volcanic activity. In these hydrothermal deposits, hot fluids containing different metal ions and sulfur permeate marine rocks underground and precipitate in contact with cold sea water (Mahfoud and Beck, 1997). Commonly occurring copper-rich sulfide minerals are chalcopyrite $CuFeS_2$ and chalcocite Cu_2S (3) Copper-rich oxide, carbonate and siliceous minerals such as malachite $Cu_2[(OH)_2CO_3]$, azurite $Cu_3(CO_3)_2(OH)_2$ or cuprite Cu_2O are formed by weathering processes and occur in the alteration zones of sulfide deposits. (4) Silver occurs as argentite (Ag_2S) or cerargyrite (AgCl) in nature, but it was also extracted in Early Bronze Age from lead minerals such as galena (PbS) or cerussite ($PbCO_3$) by cupellation (Helwing 2014, Moorey 1994). Galena forms in various geological settings through

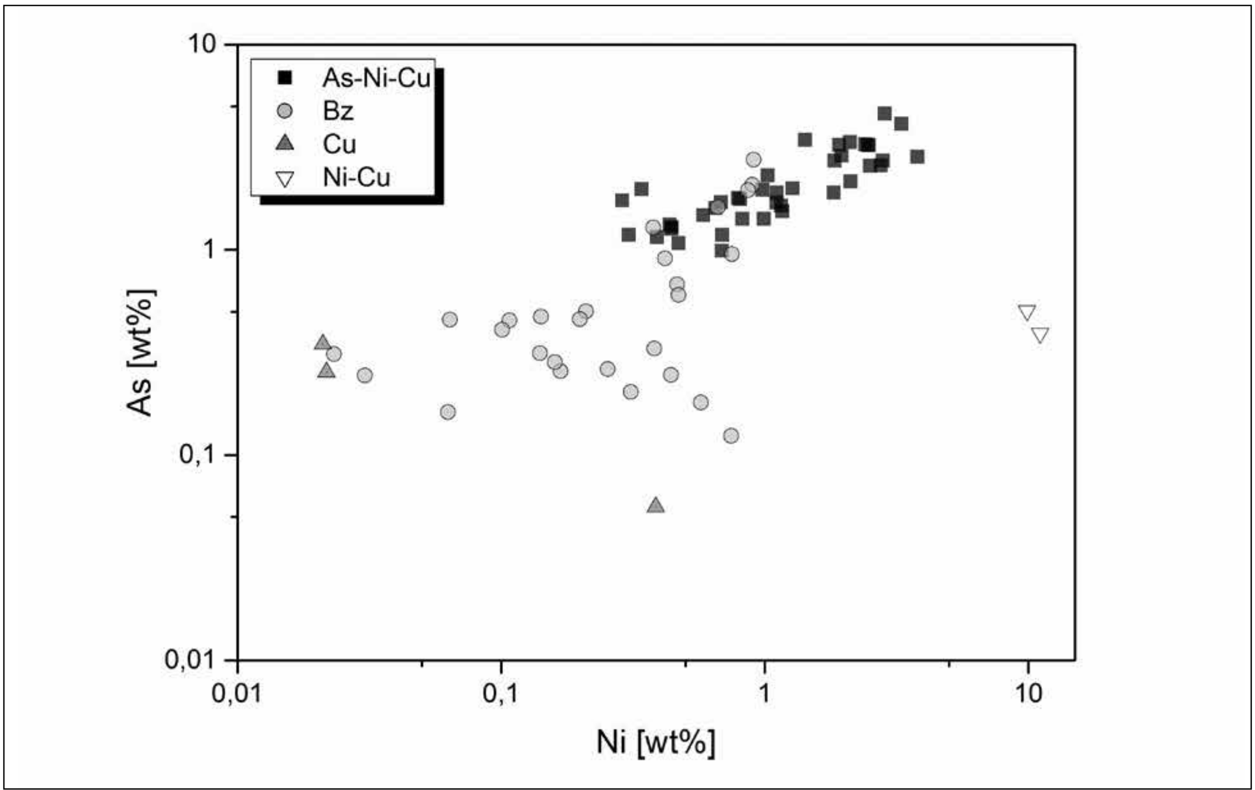

Figure 1. Scatter plot of arsenic and nickel content in the copper-based metals of Ur. We distinguished between copper rich in arsenic and nickel (As-Ni-Cu), tin bronzes (Bz), "pure" copper, and copper rich in nickel (Ni-Cu). Note the positive correlation of copper rich in arsenic and nickel, while tin bronzes are widely dispersed.

magmatic, sedimentary or metamorphic processes and is therefore commonly found. (5) Tin occurs mostly as cassiterite (SnO_2) in placer deposits or primarily near igneous intrusions, mostly granite. Other tin minerals occur in mixed copper-tin hydrothermal deposits where stannite (Cu_2FeSnS_4) and corresponding secondary minerals occur.

The analysis of the main elements in the metal samples allows the classification of the copper-based metals by their arsenic, nickel and tin contents. Samples containing more than 2 wt. % tin are commonly defined as tin bronzes (Stech, 1999). The tin bronzes from Ur contain 7 - 12 wt. % tin, which is considered an ideal alloy composition range for cold and hot working and casting due to their physical properties.

A large number of samples contain significant amounts of arsenic (1 - 4 wt. %) (instead of tin) and nickel (0.4 - 4 wt. %) (Figure 1). Both elements show strong correlation to each other, predominantly for the arsenic and nickel-rich copper alloys as well as for few tin bronzes. All samples including the arsenic and nickel-rich copper contain small amounts of tin. Two samples of a dagger (PG 737) contain very high amounts with bulk concentrations of nickel around 10 wt. %. Small amounts of antimony, cobalt, lead, iron and sulfur are associated with the arsenic-nickel copper. Whereas the tin bronzes low in arsenic and nickel are relatively poor in trace elements. High arsenic combined with high nickel occurs in ultramafic rocks as it is found in ophiolite belts. Ophiolites are uplifted oceanic crust (ultramafic rocks) that has been emplaced onto continental crust (Moghadam, et al., 2012).

Our silver samples are characterized by high copper contents from 0.1 to 7 wt. % followed by lead contents of 0.1 to 1.5 wt. %. The gold levels are below 1000 ppm except one silver bracelet containing 5000 ppm gold. . The concentration of other elements (Sb, As, Cr, Pt, Sn, Pd, Ni, Co, Fe, Mn < 100-500 ppm) is low. Copper shows correlations with lead, arsenic and nickel. The silver was most probably produced from a cupellation process of argentiferous lead minerals mixed with fahlore (Pernicka and Bachmann,1983).

The sulfur content of 0.01 to 1 wt. % as well as the non-ferrous metals in the copper-based artifacts already indicated a hydrothermal sulfide deposit as a potential source for the collection of copper-based metals from Ur. This fact is strengthened by the identified copper isotope signature given as $\delta^{65}Cu$. Copper isotope ratios have the potential to differentiate between various types of mineral deposits from which the artifacts derive. $\delta^{65}Cu$

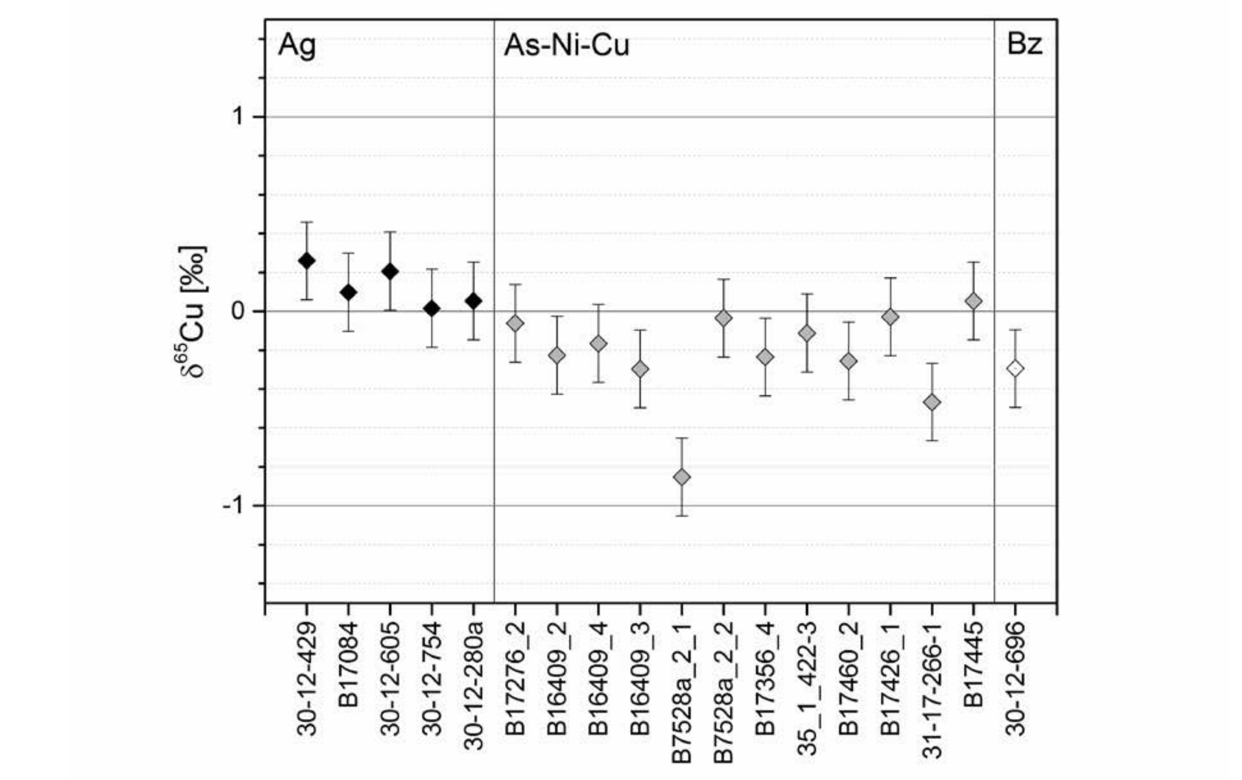

Figure 2. Results of copper isotope measurements with femtosecond-laserablation mass spectrometry. Data are mass bias corrected with Ni spike. All artifacts (silver – Ag, arsenic nickel copper – As-Ni-Cu, tin bronze – Bz) show typical copper isotope ratios for a primary sulphide deposit. Sample B17528a_2_1 was tested on a corroded surface and shows alteration of δ^{65}Cu by corrosion.

values fluctuating around zero represent primary sulfide minerals as crystallized during a hydrothermal event. Negative δ^{65}Cu values show the relics of altered supergene sulfide minerals and positive δ^{65}Cu values indicate secondarily oxidized minerals, which occur in alteration zones (Markl, Lahaye and Schwinn, 2006). As the samples from Ur have δ^{65}Cu values around zero (Figure 2), the metal most probably originates from a primary hydrothermal sulfide mineral deposit.

The silver samples show δ^{65}Cu ratios close to those of the copper artifacts, but with a tendency to slightly positive values. This indicates secondary oxide mineral deposit as a source. Combined with the results of their chemical analysis the argument for silver metal produced from argentiferous lead ores of a Pb-Ag-Zn-Cu-mineralization is strengthened.

To summarize the preliminary thoughts on the provenance of the copper and silver metal, it must be stated that there are no metal deposits in the vicinity of lower Mesopotamia and Ur. It is thus obvious that the metal had to be imported from elsewhere (Zettler and Horne, 1998). Based on the analysis of the material so far, there is evidence for a hydrothermal arsenic and nickel bearing copper source, and, due to the geographic situation, an ophiolite belt has to be considered as a potential candidate. Second a more pure copper source (likely an oxide mineral deposit, due to the chemical purity of the bronzes) and is probably associated with a tin mineralization due to the association of tin and this type of copper. And third, a Pb-Ag-Zn-Cu-type deposit may be the origin for the investigated silver artifacts.

The *Tethyan Eurasian Metallogenic Belt* (*TEMB*) runs from Cyprus and Taurus Mountains across the Zagros Mountains to Oman bearing ophiolitic rocks and polymetallic ore deposits (Janković, 1997). There is archaeological evidence for large-scale copper production in Oman in the 3rd and 2nd millennium BC (estimated 2000 – 4000 tons) (Hauptmann, 1987). It is known by cuneiform texts that the land of copper *Magan* traded copper to southern Mesopotamia (Weisgerber, 2007). It has been well established that Oman is the ancient *Magan* (Prange, et al., 1999).The Omani copper shows similar arsenic and nickel contents, both up to 4 wt. %.

Begemann, et al. (2010) measured and compared lead isotope data from Oman with Mesopotamian artifacts (including Ur, Figure 3). They found that a number of artifacts they measured match the copper ores from Oman. Despite to the evidence of large-scale copper production in Oman, the geographic situation and the cuneiform texts deliver strong arguments for a copper

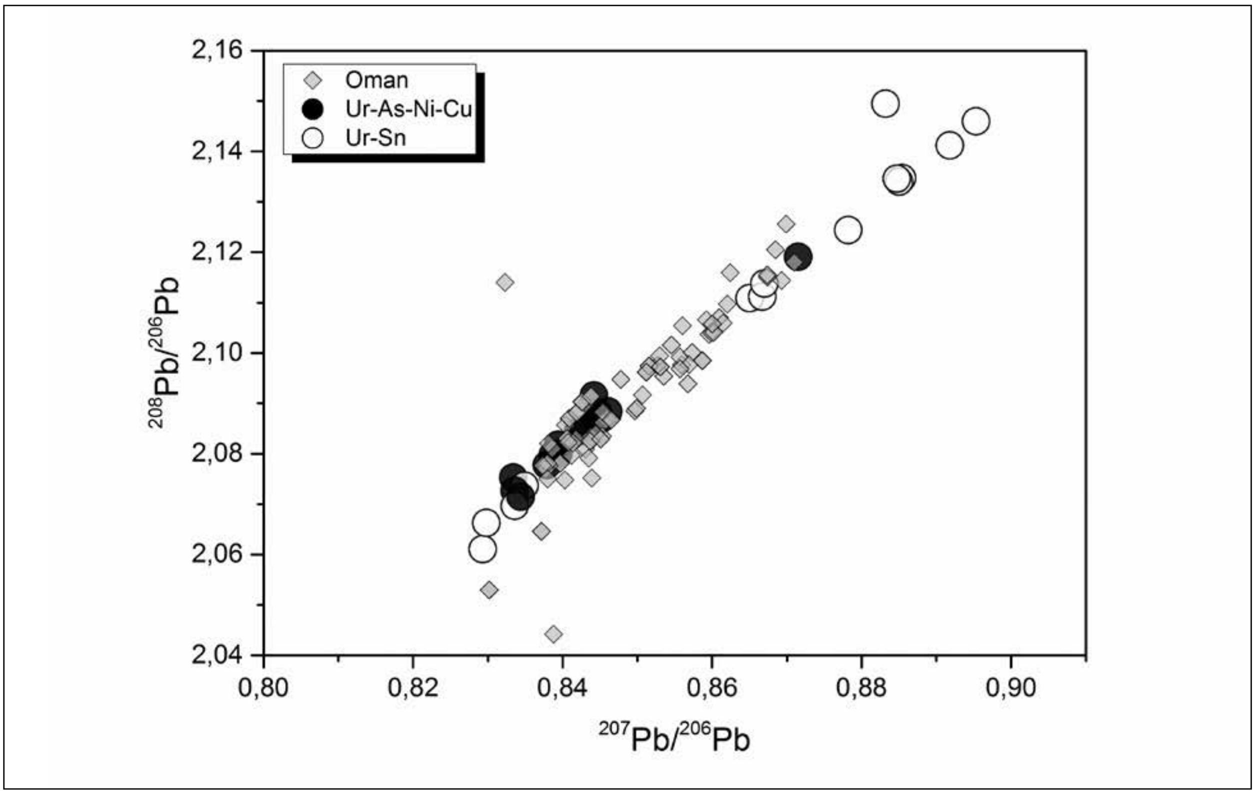

Figure 3. Lead isotope ratios ^{207}Pb / ^{206}Pb and ^{208}Pb / ^{206}Pb of arsenical nickel copper and tin bronzes of Ur measured by Begemann and Schmitt-Strecker in comparison with data from Oman (Begemann and Schmitt-Strecker, 2009; Begemann, et al., 2010).

trade from *Magan* / Oman to Mesopotamia (Begemann and Schmitt-Strecker, 2009), the lead isotope signature of Oman overlap with the Anarak region in the Iranian Plateau, where a Cu-As-Ni mineralization occurs, as well (Bagheri, Moore and Alderton, 2007). As a result, Oman is not the exclusive candidate, and Iran and others within the TEMB also have to be taken into consideration as potential suppliers for Ur.

The present results already point to the geological setting, in which the source regions for copper and silver from Ur are located. To identify the true metal sources of the Ur objects, further lead isotope analyses will be performed in future studies. Our results shall contribute to a refined understanding of structures, logistic, economy and policies of trade and exchange in the Early Bronze Age Middle East.

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Errata Metalla 22.1 (2016)

Pages 141-145, Contribution Salzmann, Klein and Hauptmann

Additional information: The *in situ* copper isotope measurements were conducted in cooperation with Marina Lazarov at the Institute of Mineralogy of the Leibniz-University Hannover according to the method published in Lazarov and Horn (2015).

Lazarov, M., Horn, I., 2015. Matrix and energy effects during in-situ determination of Cu isotope ratios by ultraviolet-femtosecond laser ablation multicollector inductively coupled plasma mass spectrometry. Spectrochimica Acta Part B: Atomic Spectroscopy 111, 64–73.

Caption figure 2. Results of copper isotope measurements with femtosecond-laserablation mass spectrometry at the Institute of Mineralogy of the Leibniz-University Hannover.

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Cover Images

1. Excavations at Troiboden the Middle Bronze Age copper ore beneficiation site in the Austrian Alps. The anthropogenic sediments resulting from ore beneficiation and subsequent weathering processes were studied with a geoarchaeological approach and give an indication that the benefication process were more effective than previously thought. See contribution Rashidian. Photo: Fabian Schapals (DBM Archiv Montanarchäologie)

2. Polished section of a crucible fragment from Dortmund Thier-Brauerei excavation with inclusions of leaded brass. The copper-based metallurgical remains from Carolingian/Ottonian levels of Dortmund and Soest were analyzed by microscopy, high-resolution ICP-MS and lead isotope analysis to reveal information about some of the earliest archaeological evidence for medieval brass production in western Europe. See contribution Merkel.

3. Royal Tombs of Ur, Mesopotamia, 3rd millennium BC. Most of the cosmetic pigments found in the tombs were stored in shell containers. They are composed of a complex mixture of bluish-greenish minerals, bone white and fats or oils. The chromophores are thought to be produced from acid or wine in copper vessels making verdigris. See contribution Hauptmann et al. on cosmetic pigments.

4. Royal Tombs of Ur, Mesopotamia, 3rd millennium BC. Wreath with golden leaves, lapis lazuli and carnelian. The golden leaves are possibly made according to the leaves of the sisso tree which is distributed in the Indo-Iranian borderlands (Iranian Plateau, northwestern India, Pakistan). Lapis lazuli comes from Sar es-Sang (northeast Afghanistan), and the carnelian beads are characteristically Harappan. See contribution Armbruster on the jewelry of Ur.

metallum, i, n:
Mine (often pl.)
Metal, also stone, mineral

μεταλλον, το:
Mine, shaft, gallery;
esp. a) Mine (usually pl.)
b) Quarry

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