

On the Structure and Composition of Copper and Tin Ingots Excavated from the Shipwreck of Uluburun

ANDREAS HAUPTMANN

Deutsches Bergbau-Museum
Forschungsstelle Archäologie und
Materialwissenschaften
Hernerstraße 45
D-44787 Bochum
Germany
andreas.hauptmann@bergbaumuseum.de

ROBERT MADDIN

The Jefferson
900 North Taylor Street
Arlington, VA 22203
bobmaddin@comcast.net

MICHAEL PRANGE

Deutsches Bergbau-Museum
Forschungsstelle Archäologie und Materialwissenschaften
Hernerstraße 45
D-44787 Bochum
Germany
michael.prange@bergbaumuseum.de

We report on the structural and chemical composition of copper and tin ingots from the Late Bronze Age shipwreck of Kas/Uluburun, found at the southern coast of Anatolia. The ship carried ten tons of copper and one ton of tin. The cargo thus represents the "world market" bulk metal in the Mediterranean. It is the aim of this paper to evaluate the quality of metal traded during this period and to discuss the making of these ingots. Cores drilled from a number of ingots show an extraordinary high porosity of the copper. Inclusions of slag, cuprite, and copper sulfides suggest that the ingots were produced from raw copper smelted in a furnace and, in a second step, remelted in a crucible. Internal cooling rims point to multiple pouring. We doubt that the entirety of an ingot was made from one batch of metal tapped from a Late Bronze Age smelting furnace. The quality of the copper is poor and needed further purification before casting, even if the chemical composition shows that it is rather pure. The copper was not refined. The tin ingots in most cases are heavily corroded. The metal is low in trace elements except for lead.

INTRODUCTION

Perhaps the earliest (archaeological) account of a copper ingot comes from an 1858 report by Giovanni Spano. This ingot was excavated in Sardinia; today it would be classified as what is known as an oxhide ingot. However, it was not until 110 years later that Buchholz (1959) and Bass (1967) provided accounts of these ingots. In two subsequent publications Buchholz (1966; 1967) sug-

gested a more detailed classification based upon stylistic features. The excavation by G. F. Bass (1967) of the Cape Gelidonya shipwreck off the coast of Turkey directed much attention to this form of ingot. As is now readily known, the 12th century B.C.E. ship carried a number of oxhide ingots and may have carried tin as well.

The discovery of the Uluburun shipwreck off the coast of the Anatolian fishing village at Kas in 1982, and its underwater excavation during the subsequent

years, have yielded the largest number of oxhide ingots, both of copper and of tin, ever discovered. The cargo exceeded that of Gelidonya by far. The ship, which sank ca. 1300 B.C.E. (Pulak 2000: 137), contained 354 oxhide-shaped ingots and 121 intact ingots of plano-convex discoid, or bun shape, altogether amounting to nearly 10 tons of copper. Additionally, about 120 ingots and fragments of tin were recovered, weighing about one ton. They were traded in the same oxhide and bun shapes as those used for copper, and in the shape of stone anchors and in a rectangular shape. With the exception of three intact ingots, nearly all of the tin oxhide ingots were cut into quarters or halves. Perhaps coincidentally, the ratio of copper to tin loaded on the ship roughly corresponds to the ratio of copper to tin in "classical" bronzes. The tin from Uluburun is, at this time, the only pre-Roman tin with a reasonable provenance (Roden 1985). Tin ingots found off the coast of present-day Israel—for example, those reported by Galili, Shmueli, and Artzy (1986)—are without secure provenance. All ingots from Uluburun were described in detail by Pulak (1997; 2000), along with an overview of all other finds from the shipwreck. This assembly, now in the Museum of Underwater Archaeology in Bodrum, Turkey, as are the ingots from the Cape Gelidonya ship, is the largest collection of copper and tin ingots anywhere. The total number of copper oxhide ingots in museums in Cyprus, Greece, Sardinia, Italy, Britain, the United States, and in private collections are still fewer than those recovered from the Uluburun shipwreck.

The discovery of the copper and tin ingots from the Uluburun shipwreck opened totally new views in the understanding of Late Bronze Age trade and gift-giving in the eastern Mediterranean. It also demonstrated that copper oxhide ingots and, to a lesser extent, bun-shaped ingots made up the overwhelming bulk of metal that was traded "worldwide" during the Late Bronze Age, both by sea and over land routes. It is a well-known fact that copper oxhide ingots were widely distributed from the eastern Mediterranean to Sardinia in the west, and these ingots were found in Anatolia, in Bulgaria (Gale 1991: 201), and they were even traded as far as southern Germany (Primas and Pernicka 1998). Even if tin might have been traded in a larger variety of shapes, as indicated also by the ingots from Israel, the cargo of Uluburun seems to represent the typical form and shape of tin of the Late Bronze Age trade.

Late Bronze Age copper ingots and in a few cases tin ingots, therefore, have been subject to several scientific investigations. Maddin and Muhly (1974) reported on the metallographic and chemical characteristics of some ingots from the Cape Gelidonya shipwreck. They studied their microstructure and the chemical composition in order to obtain clues to the origin of the ingots and to shed light on the origin of the ship and the origin of the copper. The study of these particular ingots answered few of these questions but did stimulate further investigations of this class of ancient copper. In 1976, Tylecote published an investigation on Late Bronze Age copper ingots from different localities in Middle Europe and in the Mediterranean. He was convinced that ingot material, in general, would derive from primary smelting products. Thus he expected to receive the best information from such materials on ancient smelting processes. Lo Schiavo et al. (1990) published an investigation of copper ingots of the bun-shaped and oxhide types from Sardinia. Part of this study was a materials analysis of ingots by Maddin and Merkel (in Lo Schiavo et al. 1990: 43–199). The authors discussed technological questions of how the ingots were made and tried to follow the path from smelting to the final product.

The question of the provenance of copper and tin has been intensively studied during the last two decades by Gale and Stos-Gale (see, e.g., Stos-Gale et al. 1998 and Stos-Gale 2000¹ for detailed literature) using measurements of lead isotope abundance ratios. The authors meticulously traced the origin of copper oxhide and bun-shaped ingots in the Mediterranean back to Cyprus and began to investigate the provenance of tin ingots too. One of the major aspects, in provenancing these ingots by lead isotope analysis, which was harshly called into question by Budd et al. (1995), was the question of whether they originated from one batch of copper produced in a smelting furnace, or, alternatively, by remelting several batches of metal or even by recycling scrap metal. Decisively, of these two possibilities, only the first alternative would reflect the fingerprint of the specific source. Otherwise, the lead isotope signature of the ore deposit would be blurred and would match the average of several ore deposits—that is, a mixture of them.

The present investigation is focused primarily on technological questions. We will not address ques-

¹Cited in Pulak (2000).

tions of the provenance of copper and tin. However, our study, to a certain extent, will interact and perhaps overlap with some of the questions related to the interpretation of lead isotope analyses. We will try to elucidate the quality of the copper in the oxhide and the bun-shaped ingots. This is not only because they represent *the* sort of metal that was traded "worldwide" during the Late Bronze Age. We expect that a detailed compositional investigation, in addition, will provide fundamental information to reconstruct the metallurgical processes used to produce the ingots. In texts from the Old Babylonian period (Reiter 1997: 188–92), different sorts of copper from Cyprus have been mentioned, namely "normal" copper from Alašiya, and "refined" and "washed" copper from Alašiya. To possibly identify which one is represented by the ingots, the technological origin of the ingots has to be deciphered. Were the bun-shaped ingots formed by solidification of molten copper at the bottom of a smelting furnace, as suggested by Tylecote (1976: 166, 170)? Were oxhide ingots produced by tapping metal from smelting furnaces? Do the copper ingots consist of raw copper resulting from a "primary" smelting process, or were they produced by remelting or refining copper or even (in some cases) recycling bronze objects? Is there any information "frozen" in the metal that can provide us with information on the smelting operations?

What can be learned about the solidification process from the appearance of copper grains, their shape, the extent of distribution, and the types of other phases embedded in the metal as well as other characteristics? Were the ingots cast in a solid (stone) mold, or were they cast in sand? Are the ingots homogeneous in their composition, i.e., do they derive from one batch of copper or from several batches?

How was the physical behavior of the ingots affected by qualitative differences? The physical properties of copper oxhide ingots are reputed to be miraculous, as demonstrated in depictions at the temple of Karnak. The power of Amenophis II (ca. 1447–1420 B.C.E.) is symbolized by archeries whereby arrows penetrated even oxhide ingots. He was able "to split the ingot like papyrus" (Schwaller de Lubicz 1999). How was a "ductile" metal such as copper broken up into small pieces? The metal is extremely malleable; that is, to reduce it into smaller pieces would, under normal circumstances, be extremely difficult since it, like any ductile metal,

would simply deform when subjected to an external stress. Attempting to cut copper with a saw does not work since the teeth of the saw are filled in with gummy copper, preventing further use of the saw. Attempting to break up the ingot by force at temperatures below the melting point simply deforms the copper further. Thus it is most difficult to understand how the ingots were broken as described in Hittite letters (Kempinski and Košak 1977) and evidenced by hundreds of excavated fragmented pieces found throughout the Middle East, particularly in Sardinia (Lo Schiavo 1989), and in Germany (Primas and Pernicka 1998).

SAMPLING AND MEASUREMENT

Most of the material both for metallographic and chemical analyses was taken by breaking off small chunks with a steel chisel and cutting off pieces with carbide cutting disks at high speed from both the mold surface and the rough surface of the ingots.² In this way, specimens of approximately 0.2–0.5 cm³ were used. In some cases, samples were taken from the edge of an ingot. These kinds of samples are similar to those used in other such studies. However, they provide information primarily about the composition of the surface of the ingots. Altogether, 151 copper ingots were sampled in this way.

To gain additional information about the structure and the homogeneity of the inner part of the copper ingots, we were given permission to obtain drill cores from throughout three oxhide (KW 1548, 2379, 3695) and one bun-shaped ingots (KW 963), from the top to the bottom. These were obtained by using drills with an inner diameter of 6 mm. Four to six cores were taken from the edges and from the middle part of the oxhide ingots, and one was taken from the bun-shaped ingot.

From all these specimens, mounted samples were prepared for phase and texture analyses. They were etched with a 1:1 mixture of NH₄OH and H₂O₂. Microscopic observations were made using a Zeiss Axiophot microscope. From all mounted samples (including the cores), only a selected sequence of photomicrographs is shown in the text to demonstrate the most characteristic textural details. These

²Cutting or chiseling distorts the structure of the copper to about 60 microns (μm) on either side of the cut or chisel. Removing those layers by standard metallographic methods leaves the undistorted structure.

micrographs are taken at a magnification of 100x unless otherwise specified.

Samples of tin in the form of drillings were taken by drilling into the ingots with a 6-mm carbide drill. Thirty-two tin ingots were sampled. Four specimens were used to prepare mounted samples. They were etched with diluted (3%) FeCl_3 .

All samples were submitted for chemical analysis by optical emission spectrometry using an inductively coupled plasma (ICP-OES/IRIS/AP, Thermo Jarrell Ash) in Bochum. Standard measurement conditions were used for copper as described by Prange (1998). Tin, arsenic, and nickel concentrations of copper ingots were analyzed, in addition, by flame-atomic absorption spectroscopy (Perkin Elmer) to cross-check the values obtained by ICP. Calibration curves for elements measured in copper ingots were set up by standard aqueous solutions. For tin analyses, the Pig-Tin Standards Cat. No. NF-54/1, 2, 3, 4, 5, Alpha Analytical Laboratories, Inc. were used.

The elemental analyses of copper ingots are compiled in tables 1 and 2, and those of the tin ingots in table 3 (see appendix of tables).

RESULTS AND DISCUSSION

Metallography of Copper Ingots

There are two persistent metallographic characteristics in just about all of the 151 samples of both the oxhide and bun-shaped copper ingots. One is the constant porosity, some large and some small, generally present in all the samples studied so far. The other is the ubiquitous presence of different phases and compounds inside the copper matrix.

Porous Volume of the Copper Ingots. Throughout the samples we observed the porous volume typical for "blister copper." The ingots contain numerous cavities that can be classified in sizes of a few micrometers up to several millimeters. It can be demonstrated by the plugs drilled from the ingots that copper oxhide and bun-shaped ingots of the Late Bronze Age have an enormous porous volume that exceeds by far our previous ideas on their inner structure (figs. 1–5). The volume locally reaches up to 20% or even higher. In general, cavities like these are caused by the effervescence of gases such as oxygen, carbon monoxide, and carbon dioxide, by water from burning charcoal, as well as by sulfur dioxide from oxidation of sulfide inclusions in the

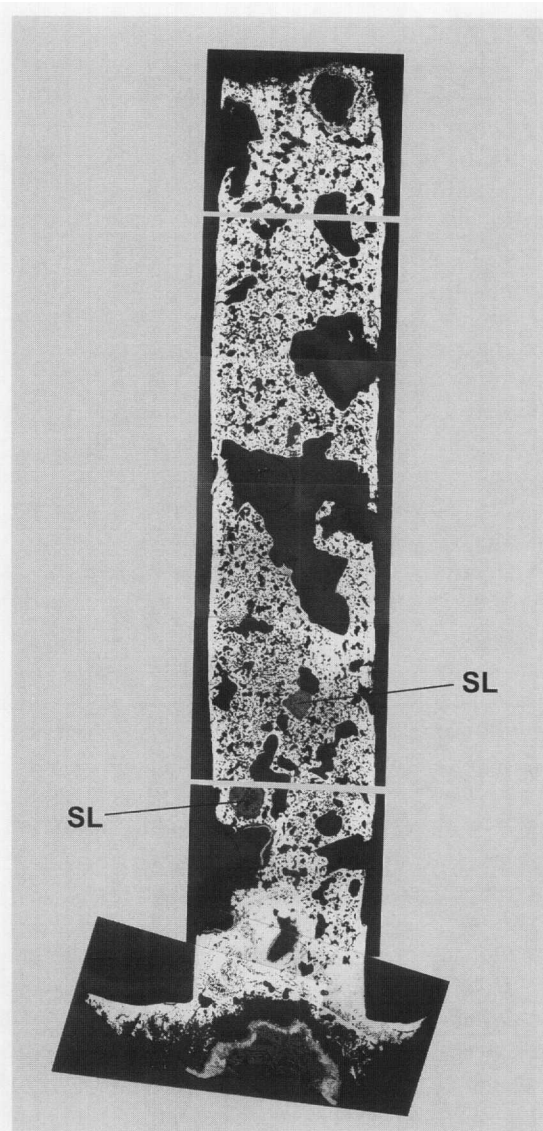


Fig. 1. Bun-shaped ingot, KW 963. Core drilling from surface (top) to bottom (below), showing large, irregularly shaped voids and tiny voids throughout the entire sample, except in the lower part which shows densely solidified copper. There are few slag inclusions (SL). The higher density of copper along the rim of the core is from compression due to drilling. Length of the sample: 4.2 cm.

copper in the liquid state. The gases dissolve violently during solidification, a phenomenon known in metallurgy as "Spratzen." In addition, porous volume is caused all over the ingots by interdendritic shrinkage (fig. 6). The porosity is high in the upper part of the ingots. Near the bottom, the porous volume is low, the structure is more dense and hence

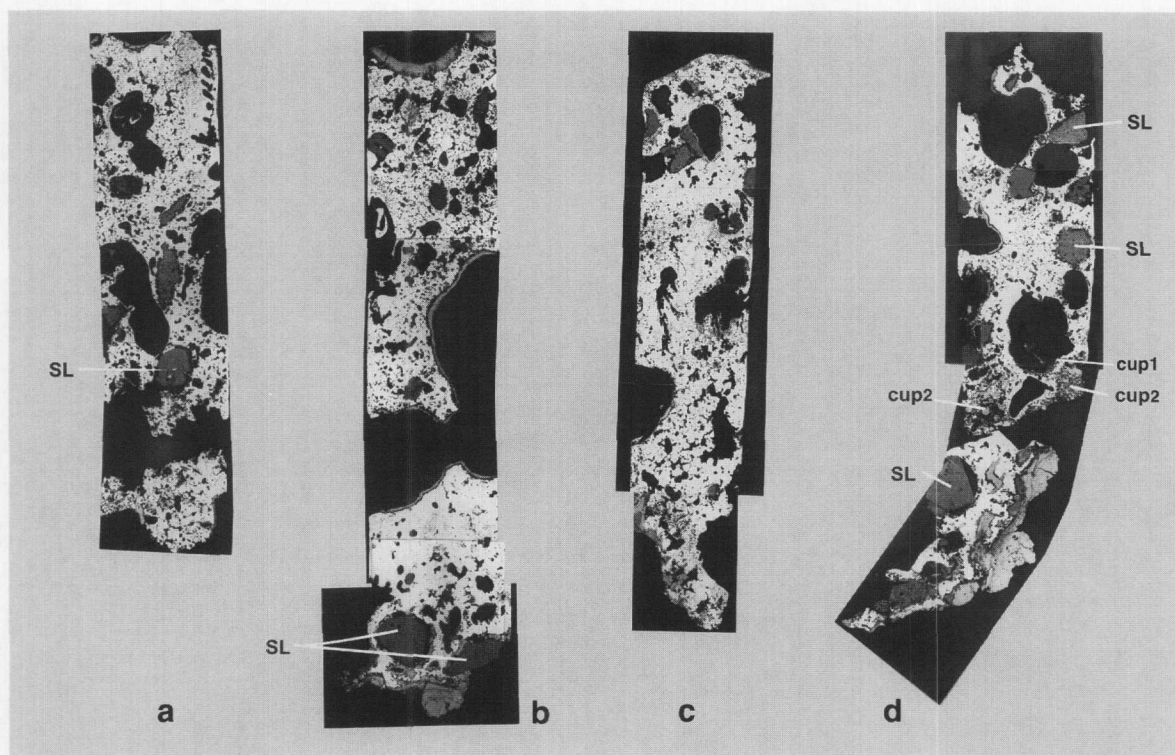


Fig. 2. Oxhide ingot, two handles (one handle broken), KW 1548. Four cores (a–d) taken near the edges of the rectangular ingot. They have in common an extremely high porosity with large voids, often encrusted by cuprite (cup1). There is a formation of primary cuprite at core KW 1548/d, middle (cup2). The cores show compositional heterogeneities: KW 1548/4 is extremely rich in angular slag inclusions (SL), while KW 1548/3 is made up of relatively dense metal, and in KW 1548/2 dense and porous metal are next to each other. Core drilling from surface (above) to bottom (below). Length of the samples: a: 2.4 cm; b: 3.1 cm; c: 3.4 cm; d: 2.8 cm.

much less affected by corrosion over the millennia. The distribution of the porous volume, in addition, is irregular. This is exemplified in the oxhide ingot KW 1548/7b, where parts of dense copper alternate with those high in bubbles and cavities (fig. 2) and are sharply separated from each other. This could be caused by pouring several batches of metal into the mold to complete an ingot, an observation supported by macroscopic evidence (Pulak 2000: 142, fig. 6).

As shown by previous studies (see above), the high porosity seems to be a characteristic feature of Late Bronze Age copper ingots with a provenance from Cyprus. Already at this point we observe a striking contrast in quality with copper from other periods and other localities. At Oman, during the first half of the third millennium B.C.E., copper with a very low porous volume was produced from sulfate

copper ores and was melted to bun-shaped ingots (Hauptmann 1985: 81, fig. 63; 1987: 210). This was the traditional bulk metal traded in the Bronze Age in the Persian Gulf area. Raw copper and ingots produced for export—e.g., from Timna, Israel (Roman 1990), and Feinan, Jordan (unpublished results Bochum)—reveal an excellent density compared with those from Uluburun or Cyprus, respectively. This is certainly due to the oxidic nature of the ores which prevents unwanted degassing of sulfide inclusions from ores such as chalcopyrite. However, as exemplified by bar ingots from the end of an Early Bronze Age (ca. 2300 B.C.E.) metal factory at Khirbet Hamra Ifdan, Feinan (see also Levy et al. 2002), the high quality of the copper is due not only to the nature of the ores, but to improvements effected by repeated remelting of lumps of raw copper into batches large enough to cast an ingot of 250–300 g.

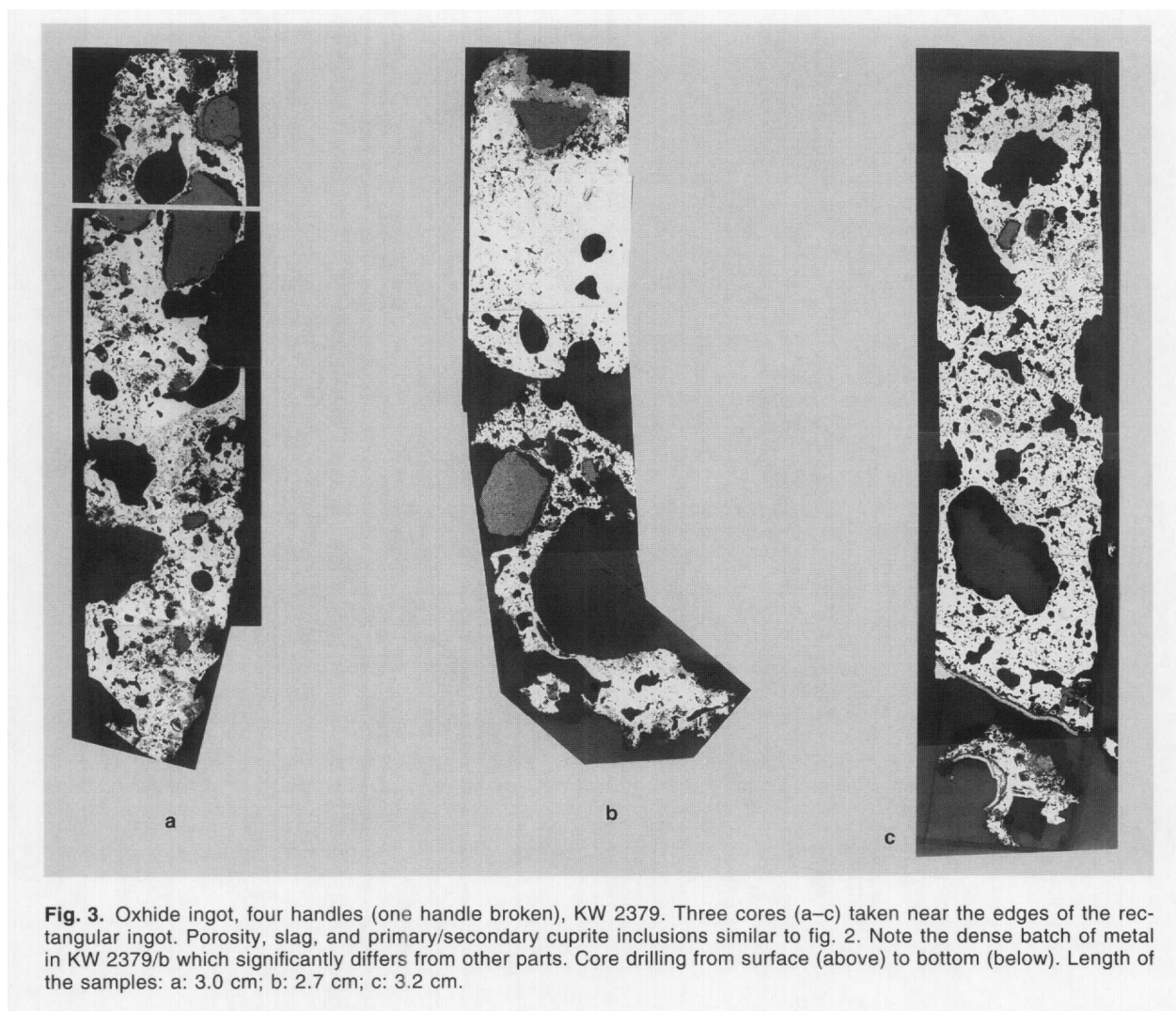


Fig. 3. Oxide ingot, four handles (one handle broken), KW 2379. Three cores (a–c) taken near the edges of the rectangular ingot. Porosity, slag, and primary/secondary cuprite inclusions similar to fig. 2. Note the dense batch of metal in KW 2379/b which significantly differs from other parts. Core drilling from surface (above) to bottom (below). Length of the samples: a: 3.0 cm; b: 2.7 cm; c: 3.2 cm.

Grain Size and Structure. The grains of the copper are, for the most part, equiaxed and may be characterized on an ASTM (American Society for Testing Materials) as size 3 (3–6 grains per square inch at 100x). This is true for the samples taken from the surfaces of the ingots and for the plugs as well, where the structure could be observed from the surfaces down into the middle of the ingots. Only occasionally is slight coring of the grains visible (fig. 9). This was checked by profile microanalyses, but no chemical variation phenomena were found. The grain boundaries are slightly separated from each other. Droplets of cuprite and of sulfide inclusions are visible along the grain boundaries. The equiaxed nature of the grains suggests that the cooling of the ingots was relatively slow, and there are no columnar characteristics as would be expected if

the cooling had occurred in a mold material with a thermal conductivity greater than stone or earth. In this respect, we could not confirm the observations of Tylecote (1976) made by his investigation of two copper oxide ingots from Mathiati (Cyprus) and from Kea (Greece).

The samples investigated do not show signs of distortion—e.g., strain bands or elongation of inclusions—which could be indicative of physical impact such as being beaten with a heavy tool to break the ingot into several pieces, as observed by Pulak (2000: 145).

Slag Inclusions. All ingots contain angular-shaped inclusions of iron-silicate slags that may reach a size of up to 5 mm in diameter (figs. 2, 4–5). They consist mainly of an olivine with a com-

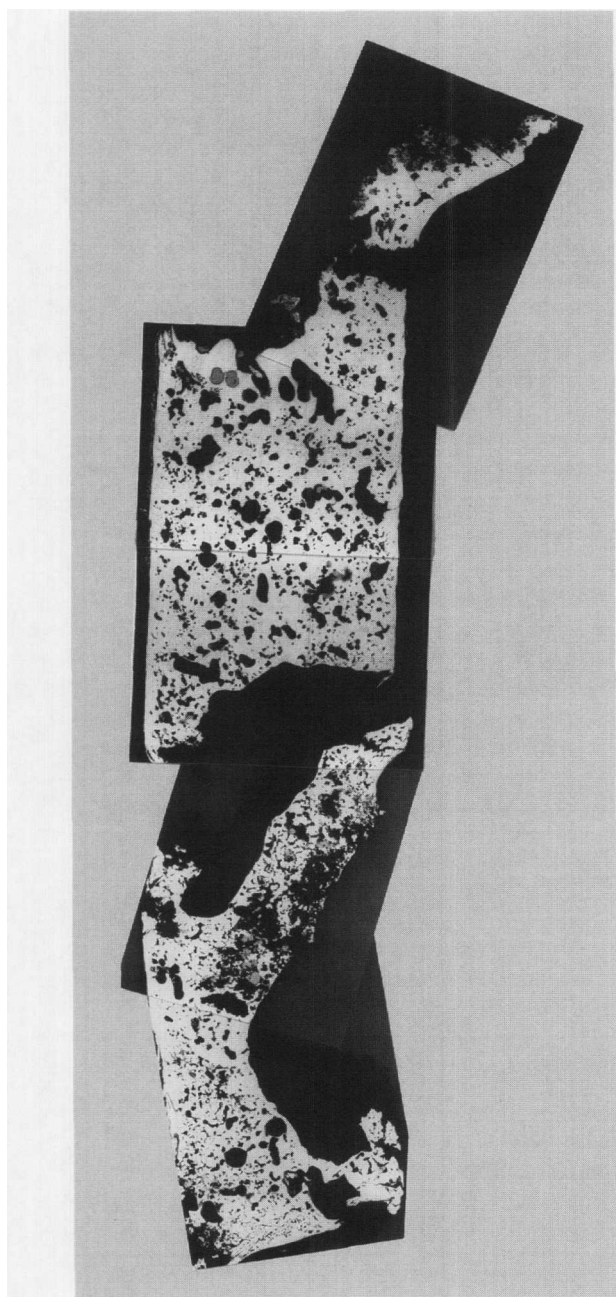


Fig. 4. Oxhide ingot, four handles, KW 2711. Partly broken due to large voids. Considerable porosity by millimeter-sized gas bubbles. No major slag inclusions. The higher density of copper along the rim of the core is from compression due to drilling. Core drilling from surface (above) to bottom (below). Length: 3.5 cm.

position close to fayalite (Fe_2SiO_4) and magnetite (Fe_3O_4); occasionally we identified copper sulfides (chalcocite, nearly Cu_2S) or mixed copper-iron sulfides (nearly chalcopyrite, CuFeS_2). There are striking similarities to slag inclusions described by

Zwicker, Viridis, and Ceruti (1980) from copper oxide ingots from Sardinia. Our slag inclusions show typical structures of cooling from a liquid—i.e., lath- or needle-like skeletons of olivine and dendrites of magnetite (fig. 7)—to be expected from slags tapped from a furnace. In parts, however, they contain a mineralogical phase with the name iscorite ($\text{Fe}_7\text{SiO}_{10}$), which is typical for reheating iron silicates. In addition, they exhibit features comparable with natural rocks that were affected by contact-metamorphism, i.e., an impact of high temperatures in the solid state. Here we observe a granoblastic structure with isometric mineral grains caused by a recrystallization due to reheating. Those slag inclusions show coronas of iron oxides formed by oxidation of iron silicate slags at high temperatures. It is obvious that the copper used to cast these ingots has characteristics of raw copper produced by a primary smelting process and was not completely separated from adhering slag. There was apparently no interest in a thorough purification³ of the metal to remove these slag inclusions. This suggestion is supported by both the archaeological and the experimental evidence which indicates that a complete separation of slag to remove a piece of clean copper seems to have been not easily understood in ancient metallurgy. Striking examples are given by Bamberger and Wincierz (1990: 134, fig. 132). The metal produced by experimental smelting is covered by a thin layer of slag. The same is true for a piece of copper from Beer Ora, Timna (Tylecote and Bachmann 1990: 76, fig. 105) that is covered by slag. Also at Feinan, lumps of copper found at smelting sites usually show adhering remains of slag (unpublished results Bochum). As observed by Bisson (2000: 141–43) from an ethnoarchaeological context in Africa, such adhering slag crusts have to be removed by hammering the lumps produced by smelting, and by repeated melting processes in order to obtain high-quality metal. The author points out that these were regular steps in copper production he observed at many metallurgical sites all over the middle and southern part of Africa. Obviously, the Uluburun oxhide and bun-shaped ingots were not processed in such a way.

Cuprite Inclusions. Almost all copper samples investigated contain cuprite (Cu_2O) distributed in

³As it might be indicated in the Old Babylonian texts when “washed” or “refined” copper is mentioned (see Reiter 1997: 188–92).

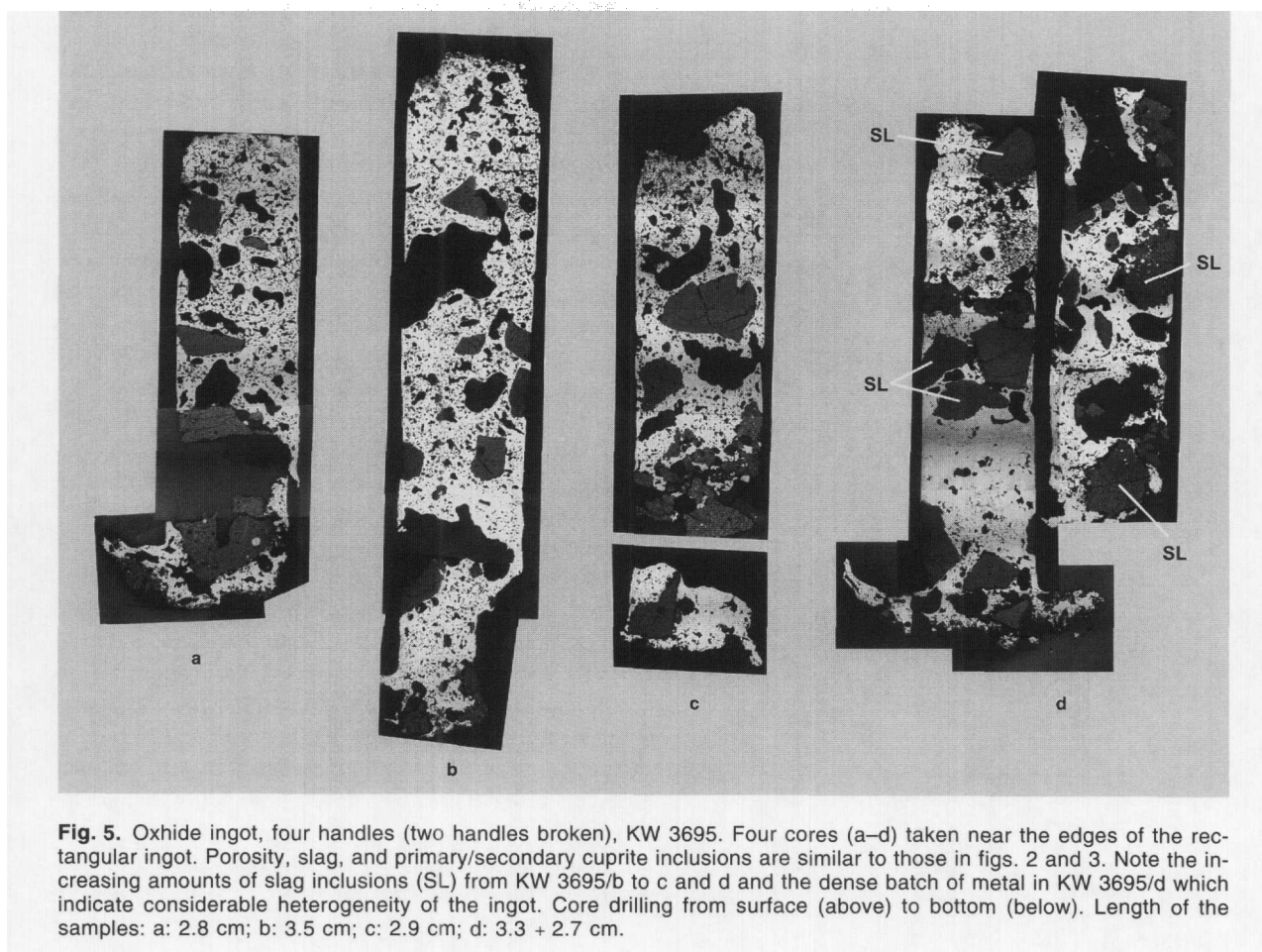


Fig. 5. Oxhide ingot, four handles (two handles broken), KW 3695. Four cores (a–d) taken near the edges of the rectangular ingot. Porosity, slag, and primary/secondary cuprite inclusions are similar to those in figs. 2 and 3. Note the increasing amounts of slag inclusions (SL) from KW 3695/b to c and d and the dense batch of metal in KW 3695/d which indicate considerable heterogeneity of the ingot. Core drilling from surface (above) to bottom (below). Length of the samples: a: 2.8 cm; b: 3.5 cm; c: 2.9 cm; d: 3.3 + 2.7 cm.

changing amounts throughout the ingots. It occurs in two different textures that allow us to distinguish its conditions of formation. Of subordinated interest for our investigation is the formation of cuprite by corrosion processes that represent the weathering of the ingots in the sea since the ship sank in the Late Bronze Age. Cuprite of this origin shows layers and protrusions (fig. 8), in some cases small crystals preferentially formed at the surfaces or in the pores of the ingots. The corrosion does not penetrate the copper ingots for more than 5 mm or so, and in every case they are much less affected than the tin ingots. This is a conservator's problem, but it does not provide any information about the pyrotechnological processes by which the ingots were formed.

Most characteristic, and visible in almost every specimen, are copper–cuprite intergrowths that result from the nearly complete immiscibility of oxygen in copper both in the liquid and in the solid

states. This is exemplified by varying amounts of cuprite inclusions in copper. If oxygen is low, cuprite globules are formed like pearls on a string along grain boundaries (fig. 9). The eutectic intergrowth (fig. 10) indicates an oxygen concentration of 0.39 wt.%. These structures are formed during solidification at 1065° C, slightly below the melting point of copper itself. They are visible throughout the ingots and are associated with large voids. A considerable surplus of oxygen in the gaseous atmosphere of the reaction vessel caused further oxidation of the copper far above the eutectic (> 0.39 wt.% oxygen) and led to extensive precipitation of lumps and larger, equiaxed crystals of cuprite (hypereutectic composition; fig. 11). In parts, they are embedded like a dispersion in the copper matrix (fig. 12) with beginning dendritic crystallization. Often these crystals show breakage due to deformation during and/or after solidification. These oxide particles, of course, affect

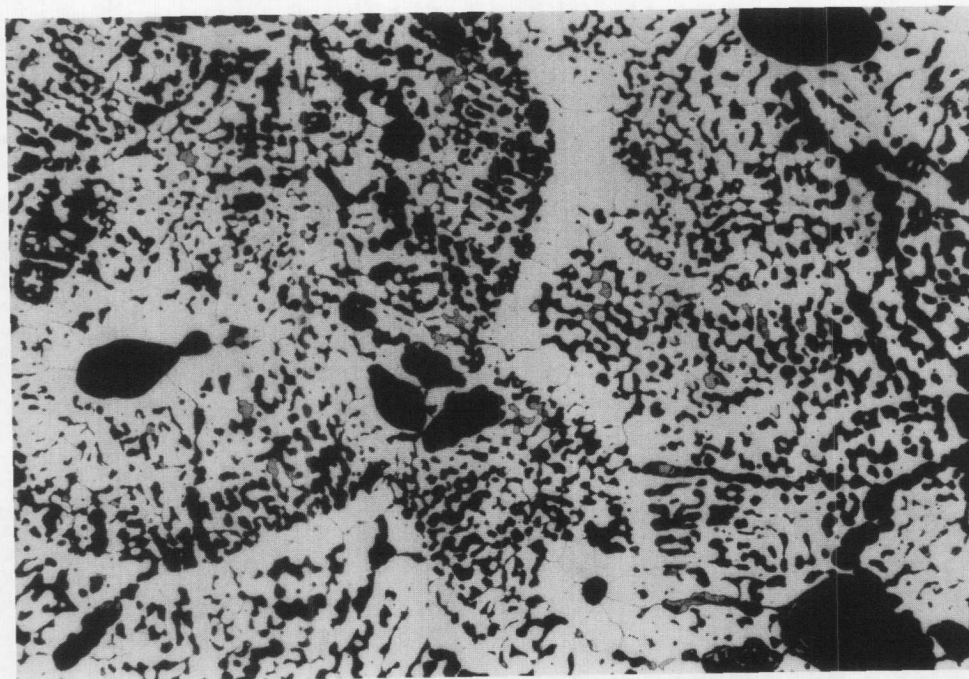


Fig. 6. Sample KW 3421. Porous volume of a bun-shaped ingot caused by interdendritic shrinkage and gas bubbles. Note several interfaces of dense metal which point to different batches during casting. Magnification 100x.

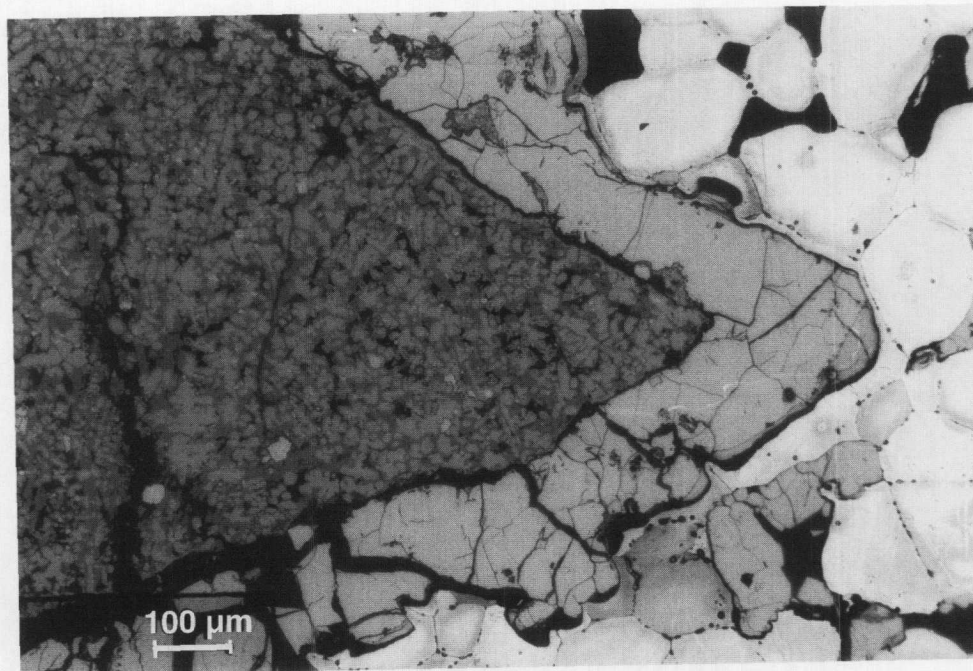


Fig. 7. Sample KW 3012. Inclusion of angular-shaped slag fragments in copper. The slag consists of magnetite (Fe_3O_4), fayalite (Fe_2SiO_4), and iscorite ($\text{Fe}_7\text{SiO}_{10}$) and reveals inclusions of copper iron matte. It is wrapped by a layer of cuprite. Magnification 100x.

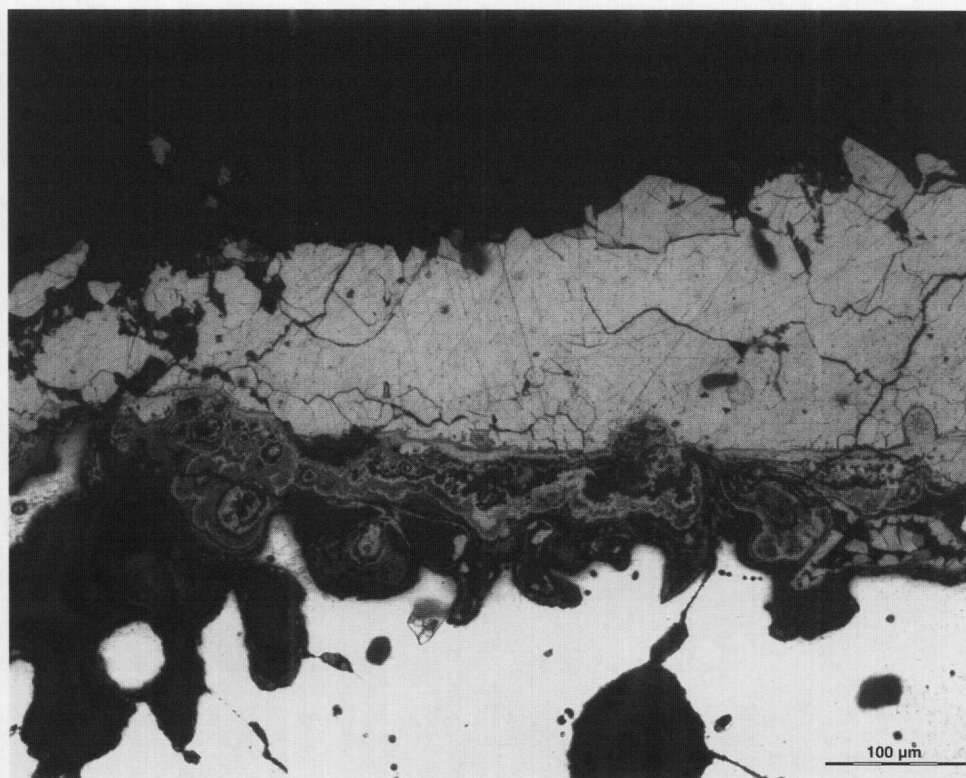


Fig. 8. Sample KW 1548/core 3. Cuprite formed by the course of weathering. Note the characteristic layering and protrusions of cuprite into the metal. Magnification 100x.

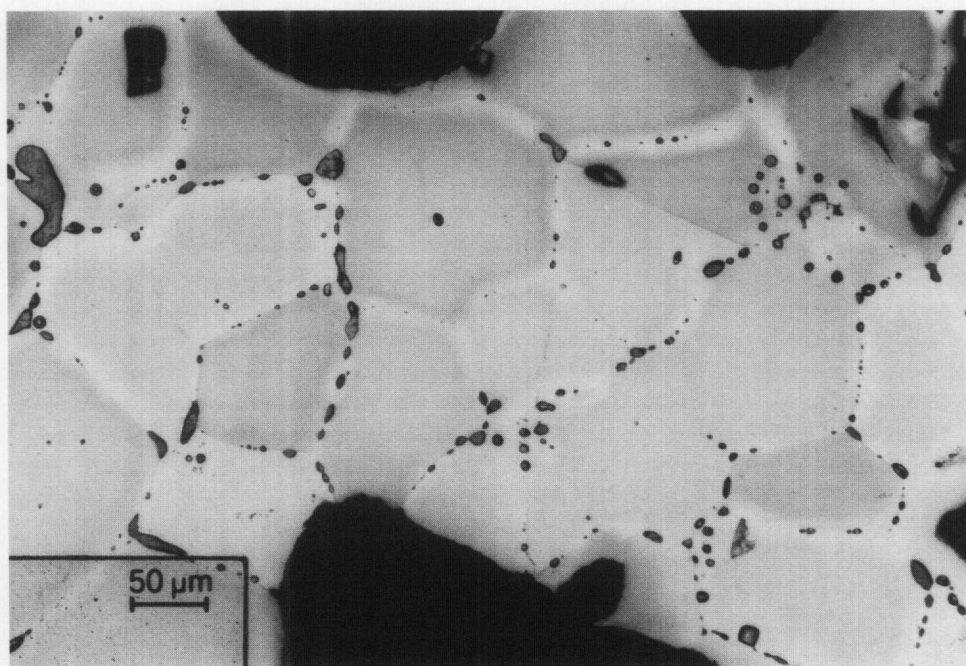


Fig. 9. Sample KW 2730. Network of cuprite between grain boundaries of copper, precipitated from the liquid metal due to immiscibility of the two phases. Minor concentrations of oxygen (around 0.05 wt.% oxygen, hypoeutectic composition). Note the slight coring of copper crystals (which, however, could not be verified by microanalysis). The voids are black. Etched, oil immersion, magnification 200x.

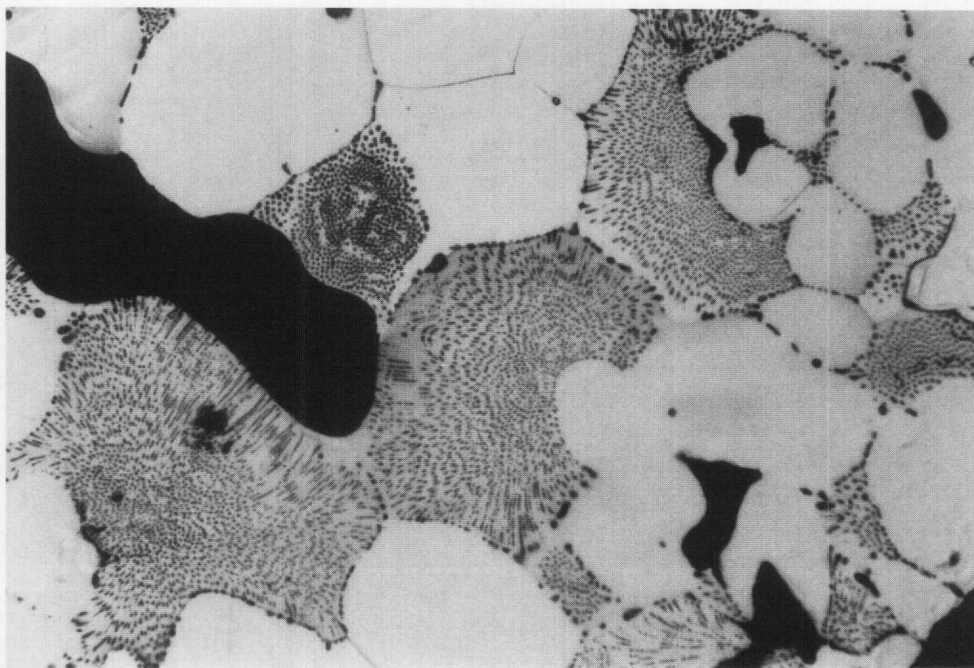


Fig. 10. Sample KW 1396. Equiaxed grains of copper and copper cuprite eutectic intergrowth ($\text{Cu-Cu}_2\text{O}$; oxygen concentration = 0.39 wt.%), an omnipresent texture in almost all the samples. The voids are black. Etched, oil immersion, magnification 200x.

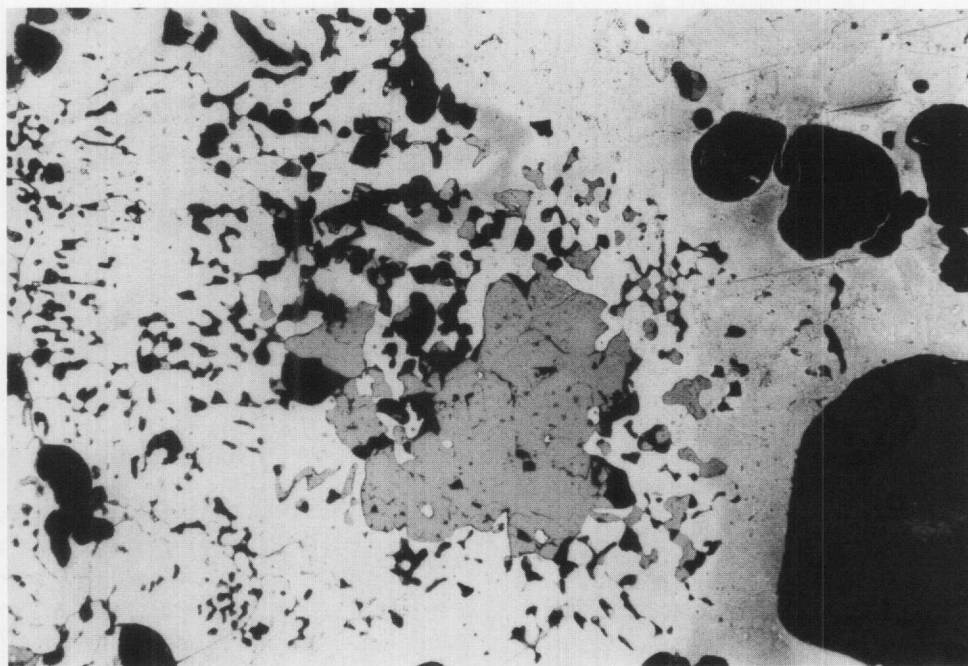


Fig. 11. Sample KW 3474. An agglomeration of cuprite formed by a surplus of oxygen in the liquid copper during casting. Note the interdendritic shrinkage of copper. Etched, magnification 100x.

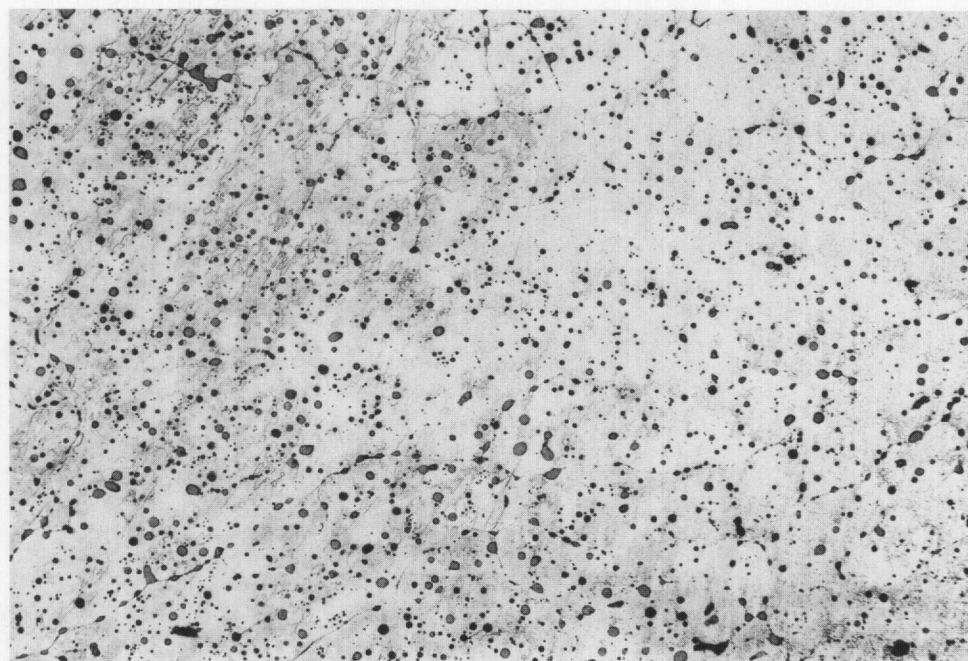


Fig. 12. Sample KW 510. Finely dispersed globules of cuprite (Cu_2O) in copper matrix and along the grain boundaries of copper crystals. Hypereutectic composition with about 0.5 wt.% oxygen. Magnification: 100x.

the malleability of the copper and make it brittle. Relatively pure copper today—for example, electrolytic copper, 99+ wt.% pure—may contain no more than 0.02–0.07 wt.% oxygen. If the copper is heated in a reducing atmosphere to temperatures above about 370° C, the oxygen concentrations can be diminished, but the copper is subject to embrittlement. If hydrogen or carbon monoxide is present, the embrittlement may be rapid (Tyler and Black 1990).

A gas atmosphere necessary to produce cuprite in an amount observed in our samples does not prevail during the smelting of (roasted) ores. This must be conditioned toward the reduction to metal in (at least partial) equilibrium with a fayalite slag (fig. 13) (Eugster and Wones 1962; Abs-Wurmbach et al. 1983). It would exclude the formation of cuprite. We therefore can eliminate the conclusion that the ingots consist of as-smelted raw copper tapped directly from a smelting furnace (contra Tylecote 1976). Our explanation is that the copper, before being cast into oxhide or bun-shaped ingots, underwent a subsequent remelting process in a smaller reaction vessel, perhaps in a crucible which led to the precipitation of cuprite. This seems to have been a widely distrib-

uted phenomenon, as Cooke and Nielsen (1978) and Zwicker (1984) demonstrated by investigations on archaeometallurgical finds from casting workshops at Nichoria (Late Helladic period) and Olympia (fifth century B.C.E.). The slag inclusions observed can easily be interpreted as relics from a primary smelting process that were not removed. Their granoblastic structure and oxidation coronas are in accord with a reheating during remelting.

Copper Sulfide Inclusions. The third type of inclusion is made up of nearly pure copper sulfides as observed already in the slag inclusions. They form droplets aligned along the grain boundaries of copper, very similar to the cuprite inclusions. These are relics of the sulfidic ore used for smelting. This seems to have been a well-developed technology at Late Bronze Age Cyprus. The sulfides probably have been roasted, either before the first smelt, or, if matte was produced, after it, because most of the ore available on Cyprus is of chalcopyritic composition, and this mixed sulfide does not occur in the copper. In every case, relics of sulfides remained in the roasted material, as it is quite difficult to completely remove the sulfur content of such an ore.

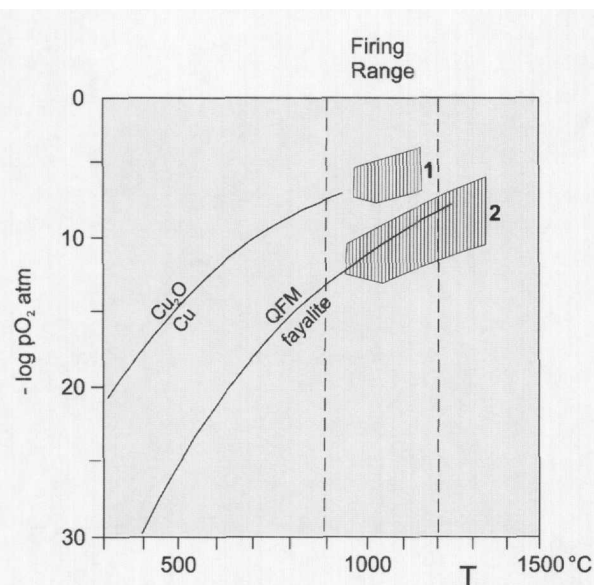


Fig. 13. The approximate smelting conditions to produce copper (or matte) in equilibrium with a fayalitic slag (2) as shown in the pO_2 - T diagram of the systems Fe-Si-O and Cu-O (after Eugster and Wones 1962). Note the physical differences of cuprite formation (1). Primary cuprite is found in copper ingots; hence, they must have been formed by a different process than the slag.

Chemical Composition of Copper Ingots

The two types of ingots are made of pure copper. With the exception of iron, the trace element content is below or approximately about 1 wt.%, and all the ingots show a homogeneous composition. The total elemental content of the ingots is sometimes well below 100 wt.%. This is mainly due to the inclusions of silicate slags, but also of cuprite as explained above. Silica and oxygen were not analyzed. From the chemical point of view, the purity of this copper is extraordinary in comparison with other sorts of copper distributed in the Late Bronze Age Old World. For instance, copper from the Wadi Arabah is much higher in lead (up to several percent; Leese et al. 1985/1986: 97–102; Hauptmann 2000: 232), copper from the Caucasus area is extraordinarily high in arsenic (up to several percent; see Chernykh 1992: 145–53; Gambaschidze et al. 2001), and copper from Oman usually contains arsenic and nickel in the percentage level (Prange 2001: 63–64).

Two points are essential for the interpretation of these data. First, as shown by our metallographic investigations, we are able to exclude a conscious purification or even refining process of the copper to produce the ingots. Second, we know from experi-

mental work (Merkel 1990: 103, 105, 108) and from analytical data of ore and copper derived from this ore (Hauptmann 2000: 133) that the concentrations, for instance, of lead, arsenic, antimony, nickel, or silver do not change very much during smelting (even if a roasting process was carried out before smelting; see Pernicka 1987: 638). We therefore conclude that the ingots reflect the composition of “pure” copper ores that were smelted to produce the metal, and with but a few exceptions we see few indications that bronze scrap could have been added, as has been suggested. This statement is made based on observations of the tin concentrations. The median of tin in the oxhide ingots is 0.008 wt.%, that in the bun ingots 0.001 which is the detection limit (table 4). Most of the samples reveal tin concentrations below the detection limit at < 0.001 wt.%; the maxima are at 0.24 and 0.37 wt.%, respectively. Unfortunately, there are virtually no ore analyses available from Cyprus that could serve as a basis for our considerations. However, Prange (2001: 110, table 36) published almost 100 analyses of copper ores from massive sulfide deposits in ophiolitic rocks of Oman that, due to their origin, are perhaps comparable to Cyprus. The maximum tin concentration analyzed there was 0.0093 wt.%. Three out of 38 bun ingots (KW 510, 514, 841), and 10 out of 114 oxhide ingots (KW 627, 997, 1169, 3079, 3110, 3141, 4374, 4460, 4507, 6795) slightly exceed this level. If bronze was added to the ingots, then it was only an infinitesimal amount. In contrast, the Gelidonya copper ingots seem to contain somewhat higher tin concentrations: at least five of the ingots show between 0.4 and 0.5 wt.% (Maddin and Muhly 1974: 3); still another, additional ingot, according to qualitative analysis, obviously is in the percentage level (Han 1967: 169).

Iron is the only element that exceeds (in a few samples) the percentage level. It shows large ranges of concentrations in both types of the ingots, but somewhat more in the oxhide ingots. In the histograms shown in figure 14, there are 113 samples of oxhide ingots with iron concentrations between 50 ppm and 1.69 wt.%, and in one case it is even higher than 5 wt.%. Thirty-eight samples of bun ingots show iron concentrations between 30 ppm and 0.89 wt.%. In tables 1 and 2, iron is calculated as metallic iron, but in reality, no α -iron is present in the copper ingots from Uluburun. The iron contents are primarily due to slag inclusions. In our cases they are not caused by a strong reducing gas atmosphere during smelting or melting as suggested by Craddock

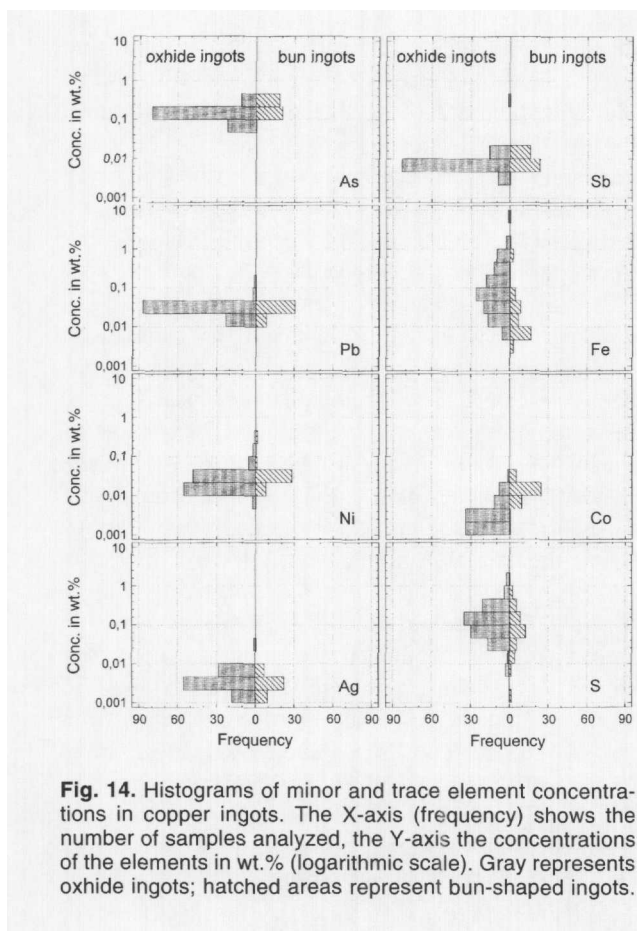


Fig. 14. Histograms of minor and trace element concentrations in copper ingots. The X-axis (frequency) shows the number of samples analyzed, the Y-axis the concentrations of the elements in wt.% (logarithmic scale). Gray represents oxide ingots; hatched areas represent bun-shaped ingots.

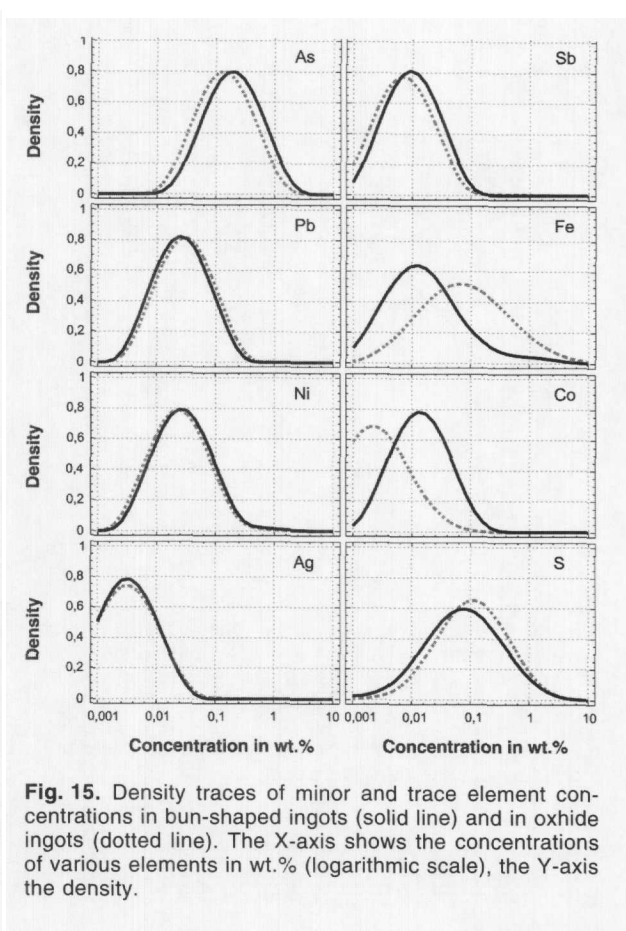


Fig. 15. Density traces of minor and trace element concentrations in bun-shaped ingots (solid line) and in oxide ingots (dotted line). The X-axis shows the concentrations of various elements in wt.% (logarithmic scale), the Y-axis the density.

(1995: 139–40) to explain increased iron concentrations for Late Bronze Age copper and bronze artifacts. The iron concentrations in the copper ingots do not provide any information about quality and the uses of fluxes. They seem to be low in comparison with the amount of slag inclusions as shown in figures 1–5. This might be caused by an irregular distribution of slag within the entity of the ingots: the cores were taken from the inner part, while the samples used for chemical analyses were taken from the surface or the rim of the ingots.

We also recognize very similar medians in both types of ingots (0.076 wt.% in oxide and 0.012 wt.% in bun-shaped ingots; see table 4). The histogram in figure 14 shows a small change in the distribution of the Fe. But it clearly indicates, as the distribution of the peak values show (fig. 15), that, if at all, bun ingots served only partially as material remelted to obtain the larger oxide ingots, as suggested by Maddin and Merkel (in Lo Schiavo et al. 1990: 43–199): the amount of iron, here identified as slag inclusions, would hardly be increased by a remelting process.

Incidentally, the medians are quite similar to those of the copper oxide ingots from Mathiati and Skouriotissa, from Cape Gelidonya, and from Hagia Triada (Crete) (compiled in Primas and Pernicka 1998).

The statistics for sulfur are somewhat similar to those for iron. Here too, the values for the 113 oxide ingots are substantially greater than those for the 38 bun ingots. The histogram in figure 14 shows essentially the same distribution as do the density traces (fig. 15).⁴ However, as better indicated by the calculation of the medians (table 4), sulfur is slightly higher in the oxide than in the bun ingots. This is hardly compatible with a remelting of bun ingots to produce oxide ingots.

Arsenic concentrations vary between 0.06 and 0.41 wt.%. As earlier measurements in copper in-

⁴Density traces are a plot to better view the distribution of the data presented in the histogram, especially the variations in density over the range of data. Unlike a histogram, the density traces use overlapping intervals to smooth the densities, resulting in a continuous line rather than a group of rectangles in a histogram.

gots from Uluburun (Maddin 1989) were partly higher than the results presented in this study, and as far-reaching conclusions were drawn from these values, we cross-checked our ICP measurements by atomic absorption spectrometry. The deviations are max. ± 0.02 wt.% (= 7 %) and, therefore, can be neglected. The medians of the oxhide and of the bun-shaped ingots are 0.13 and 0.2 wt.%, respectively (table 4). Even if our values still are lower than arsenic concentrations in oxhide ingots from different localities on Cyprus ($\bar{O} = 0.34$ wt.%) and from Cape Gelidonya ($\bar{O} = 0.46$ wt.%; see Muhly 1991; Gale 1991), they do not have a significantly different composition and are not in contradiction to an origin from Cyprus as suggested by Muhly (1991). This is substantially supported by lead isotope abundance ratios as presented by Stos-Gale (2000; Stos-Gale et al. 1998). The histogram (fig. 14) shows an almost identical distribution of arsenic between the two types of ingots, although the density plot (fig. 15) indicates a slight shift to decreasing distribution in the bun ingots.

A similar behavior is noted for antimony. The concentrations are identical between the two types of ingots. The concentrations of antimony are in the same low range as arsenic.

The histogram in figure 14 shows that silver values in both types are nearly identical. The median in both types of ingots is 0.004 wt.%. In the oxhide ingots, among 113 values, it varies from 0.001 to 0.044 wt.%, and there are a number of samples that are higher in silver than the bun ingots. The variation among 38 samples of bun ingots is from 0.001 to 0.006 wt.%. The density traces (fig. 15) show essentially no differences.

Nickel is also nearly identical in both types of ingots (figs. 14–15), while cobalt appears anomalous. This seems surprising as the two elements have comparable geochemical properties and should behave in a similar way. There are notable differences shown in the histogram (fig. 14) and in the density traces (fig. 15). We note, however, that the elemental values in both the oxhide and the bun ingot cases are low (0.005 to 0.31 wt.% for the oxhide and 0.005 to 0.75 wt.% in the bun ingots).

In the case of lead, most of the samples show only slight differences between the two ingot types (figs. 14–15). But as with iron and sulfur, some oxhide ingots high in lead are not consistent with a remelting of bun ingots to produce oxhide ingots.

The concentrations of phosphorus were determined in 25 samples, both of oxhide and of bun

ingots. This element, rarely included in chemical analyses of ancient copper, was found to be in all cases below the detection limit at 50 ppm. This seems worthy of note, because the notorious absence of phosphorous measurements in chemical analyses of copper ingots from Cyprus led Karageorghis and Kassianidou (1999: 180–83) to suggest that exactly these missing data (!) could be an indication for the utilization of bone ash as a deoxidizer for copper during a remelting process. The basis for this hypothesis was the considerable amount of bone ash found at the sacred precinct of Late Bronze Age Kition with its copper-metallurgical remains, which otherwise would be inexplicable. The apparent absence of evidence, however, does not substantiate this idea—as our analytical data show. If indeed phosphorous had been added, its concentrations would be considerably higher than the concentrations we analyzed. Also, Karageorghis and Kassianidou's conclusion (in reference to Maddin 1989: 99)—that the eutectic of Cu/Cu₂O is absent in some (and not “many”!) of the Uluburun ingots and, hence, would be indirect evidence for the use of bone ash as a deoxidizer—cannot be correct. The metallographic investigation of the ingots in this study shows that, if the eutectic is not formed, the copper always contains larger globules of Cu₂O. Incidentally, if larger concentrations of phosphorus are present, distinct phosphides both of Cu and of Fe should be visible under the microscope. This was shown to be so for Feinan copper by Hauptmann (2000: 130–36).

Metallography of the Tin Ingots⁵

In contrast to the copper ingots, the tin ingots revealed a considerably higher degree of corrosion. In a number of cases, the weathering nearly destroyed the entity of the ingots, leaving nothing more than a centimeter-sized core of metal which was surrounded by a 5–7 cm white crust of secondary tin minerals. By x-ray diffraction, we identified this crust as consisting of minerals formed by corrosion of tin, by interaction with nearby deposited copper,

⁵The grain structure of metals such as tin, lead, zinc (some of the so-called metals of antiquity) cannot reveal what hammering had been done on them because the hammering was most likely done at the ambient temperature. This is above their recrystallization temperatures and, hence, they are (in effect) “annealed” at the ambient temperature and change their grain structure which would have revealed the initial hammering.

and by precipitation from the seawater. These are tin oxide chloride hydroxide ($\text{Sn}_{21}\text{Cl}_{16}(\text{OH})_{14}\text{O}_6$, ASTM 35-0907); romarchite (SnO); synthetic cassiterite (SnO_2 , not clear, ASTM 41-1445); cuprite (Cu_2O); various copper sulfides (Cu_xS); magnetite (Fe_3O_4); aragonite (CaCO_3)⁶; copper-tin ($\text{Cu}_{5,6}\text{Sn}$, ASTM 31-487); and halite (NaCl).

No gray tin (α -tin) was determined since the reverse transformation begins when the temperature rises above 13° C. Unlike the transformation from the β - to the α -modification which proceeds slowly at the transformation temperature and increases with decreasing temperatures to a maximum rate at -77° C, the reverse transformation proceeds quickly in comparison, once it reaches the ambient temperature. The normal variety of α -tin is highly resistant to corrosion by seawater. Indeed, some of the ingots from Uluburun, and also those recovered from the Mediterranean off the coast of Haifa, Israel, showed no corrosion after millennia buried in the sea. In contrast, little is known of the corrosion resistance of α -tin which showed notable corrosion. This phase was suggested to be the predominant phase of these crusts by Maddin (1989: 102) and by Pulak (2000: 152). It appears likely that the hydroxides analyzed here result from a decomposition of the corrosion of the α -tin.

Otherwise, microscopic observations of specimens where metal is preserved revealed homogeneous compositions with a low content of any inclusions. After etching, dislocations appeared here and there, most likely caused by shear stress during the sampling of the ingots. The Uluburun tin ingots are devoid of tin oxides and gas bubbles which both are characteristic for the copper ingots. The only inclusions within the metallic tin matrix are tiny crystals of magnetite (Fe_3O_4).

Chemical Analyses of the Tin Ingots

Except for a few analytical data published by Maddin (1989) and Begemann et al. (1999), no detailed compositional data are known from Late Bronze Age tin ingots in the Old World. Hence, the ICP analyses of 32 tin ingots as shown in table 3 provide the beginning of a database. Twenty-eight

⁶See also Dykstra (1967) who analyzed calcium carbonate on tin samples from the Gelidonya. He suggested a considerable replacement of tin by calcium hydroxide which later was transformed to calcium carbonate.

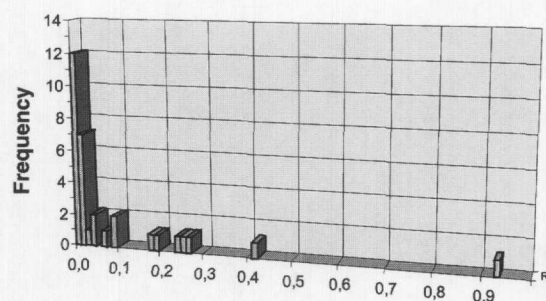


Fig. 16. Concentrations of lead in tin ingots from Uluburun. Values are given in wt.%. With but a few exceptions, the concentration of this element in the tin ingots is near or below the detection limit at 0.001 wt.%.

tin ingots from Uluburun were analyzed for their lead isotope abundance ratios by Stos-Gale et al. (1998) and four by Begemann et al. (1999). Only five out of these are included in our data set (KW 203, 2332, 2774, 2924, 3157).

Generally, the ingots' chemical composition is made up of surprisingly pure tin. Nickel and selenium, and in most cases also cobalt and zinc, are below 10 ppm. Arsenic, antimony, iron, and silver are mostly below 100 ppm.

Lead shows slight variations. In the majority of the samples, it is below the ICP detection limit at 100 ppm (fig. 16). Six of the samples analyzed are between 0.17 and 0.5%, while one ingot contains almost 1% lead. These slightly elevated values correlate with copper, which may reach up to 0.3%. These data are in accord with previously published analyses from Uluburun, as well as from Hishuley Carmel and Kefar Shamir in Haifa, Israel. Similarly low is lead in cassiterite, the most promising possibility as the source of the tin (Begemann et al. 1999: 278). The lead content of the ingots and of this tin ore is in most cases much less than would be expected if the lead in bronzes had been introduced via the tin. We conclude that all these elements are due to natural impurities of the ore sources.

Our data may possibly reflect the bimodal grouping of lead content as observed by Stos-Gale et al. (1998) (medium lead contents at 15 ppm and at 1100 ppm). This dichotomy seems to support a grouping of isotope compositions of the same samples the authors analyzed. Incidentally, the tin ingots from Hishuley Carmel were found to be identical in lead content and isotopes with the low lead Uluburun samples, while a tin ingot from Kefar Shamir with

2200 ppm (Begemann et al. 1999) matches in its isotopic composition the Uluburun ingots high in lead.

CONCLUSIONS

While there is abundant evidence for a unique mass production of copper at Cyprus, the technology of copper production has been hardly investigated. The archaeological evidence is confusing and will not provide answers for our questions. Remains of smelting furnaces, as they were excavated by Fasnacht (1989: 62–65), are extremely rare or, if they exist, remain enigmatic (Knapp, Donnelly, and Kassianidou 1998). The purpose of the famous crucible or smelting furnace from the settlement of Enkomi is debated, and neither samples investigated by Zwicker (1986) nor by Tylecote (1982: 92) could support us in determining whether ore was smelted or metal lumps were melted in this “reaction vessel.” Also, slag investigations carried out to date (Bachmann 1982; Koucky and Steinberg 1982) are too limited to finally clarify the ancient technology of copper production. We do know today that a description of ancient metallurgical processes merely in terms of modern physicochemistry cannot sufficiently answer the questions addressed by archaeology. To answer, for instance, how societies involved in metallurgy were organized needs the reconstruction by detailed scientific studies of single steps of practical craftsmanship. In this study we obtained some information that adds new data in this jigsaw puzzle.

The copper ingots exhibit characteristics of a forming process under two thermodynamic conditions: a metallurgical process, at first under reducing and, at the end, under oxidizing conditions. Hence, we can only agree in part with the previous ideas of Tylecote (1976: 169) who suggested that both the oxhide and the bun-shaped copper ingots could represent raw copper as derived from the smelting furnace without refining. Merkel's (1986) suggestion, however, that the metal from the ingots must have come from a secondary remelting, is more plausible.

Evidence in support of Tylecote's hypothesis is the existence of slag inclusions in both types of ingots. Their composition is characteristic of slags from smelting copper ores under reducing conditions, but not of those from crucible (s)melting. We could demonstrate that the iron content of the ingots is primarily due to these slag inclusions and does not permit conclusions regarding the use of

iron-rich fluxes. The angular shape of slag inclusions, the structure, and the existence of iscorite hence point to a pouring of copper into a mold when the slag was already solidified and before it was melted again in the crucible. This excludes casting directly from a smelting furnace: the slag would have left the furnace in the liquid state and would be included in the copper as globules. It also excludes an origin, or a solidification, respectively, of bun-shaped ingots on the bottom of a smelting furnace. Such inclusions of globular slag, for instance, were observed by Craddock and Meeks (1987) in the (so-called) *ramo secco* bars from Roman Italy. The angular shape indicates that the slag, or the copper, had been mechanically treated. Such a process is fairly underestimated and neglected in the literature, but is evidenced by archaeological findings from Iron Age copper production at Feinan (Hauptmann 2000) and from the Late Bronze Age copper production all over the Alps (Hohlmann, Hauptmann, and Schröder in press), and by ethnoarchaeological research (Bisson 2000: 141–43); that is, the slag was crushed after smelting to recover copper lumps and prills or copper matte, and to separate adhering slag.

Merkel (1986; 1990) demonstrated by his still up-to-date smelting experiments that, according to Bronze Age methods, masses of copper up to 10 kg, or perhaps a little bit more, were produced in a smelting furnace. He pointed out, however, that the production of 30 kg of copper in a smelting furnace to form an oxhide or a bun-shaped ingot would be extremely difficult. Following this model we suggest that remelting batches and lumps of solid copper into larger units must have been a common practice during this period and was practiced in crucibles, as pointed out by Cooke and Nielsen (1978) and Zwicker et al. (1985). In the case of Late Bronze Age Cyprus, such a crucible could have been of the type excavated at the urban settlement of Enkomi which had a capacity of about 17 L (Dikaios 1969: vol. 3a, pl. 159:20). Iron silicate slag⁷ from the inner side of the crucible does not contradict this model. Macroscopic (Pulak 2000: 142) and microscopic evidence (fig. 2; see above) of layered textures indicate that at least part of the oxhide ingots were finished up by multiple pouring.

⁷Instead of slags rich in cuprite (Cu_2O) and alkalis typical for melting copper in crucibles. Inclusions of iron-rich slags, however, were found in the ingots!

Obviously, it was not the intention to purify the copper by repeated remelting to obtain what is mentioned in Old Babylonian texts as "washed" copper (Reiter 1997: 188–92). In such a case, slag inclusions would have been removed, and the copper would have reached a level of purity and density as, for instance, the Early Bronze Age copper ready for export from Feinan (unpublished data Bochum). Slag inclusions must be removed completely before casting objects to prevent slag formation at the spout of a crucible (Bisson 2000: 141–43) and failures in the cast.

We also do not see any evidence of a deliberate refining, as it has been suggested repeatedly, for example, by Stech, Maddin, and Muhly (1985), Merkel (1986), and Karageorghis and Kassianidou (1999). The purpose of such a process would have been to diminish impurities in the metal, especially those of iron and sulfur, but also arsenic, nickel, cobalt, etc. The metallurgical principle of refining is based on the ability of these elements to be oxidized in the liquid metal before the copper itself transforms to cuprite. They then form "dross" while oxygen is blown over the liquid metal. In practice, refining is performed until cuprite appears; this is the case when all the impurities are oxidized. In traditional metallurgy of smelting copper ore, the cuprite inclusions were reduced by a process known as *poling* (stirring the molten copper with green poles or twigs). In fact, the Uluburun copper ingots contain cuprite, but the overall distribution of slag and sulfide inclusions contradict a refining process. Incidentally, the occurrence of cuprite in bun ingots is also at variance with Tylecote (1976): if this type had been formed at the bottom of a smelting furnace, the formation of cuprite would not be in accord with a fayalitic slag that clearly points to strong reducing conditions.

It was suggested by Budd et al. (1995) that significant amounts of scrap metal may also have been included among the copper (s)melted to produce the oxhide ingots. We cannot definitively rule out such a possibility, especially not for a recycling of objects made of pure copper. But the structure and composition of the ingots point to the contrary: scrap metal, once made of dense, high-quality copper (or bronze), certainly would not contain slag inclusions and gas bubbles as are observed in such quantities in the ingots! Very low tin concentrations, in addition, are evidence that at least bronze scrap was not likely added to the ingots.

Do the copper oxhide ingots result from remelting the bun ingots? Or, alternatively, were fragments of the heavy oxhide ingots (on average 23.9 kg; Pulak 2000: 143) remelted to form bun ingots with a weight of 6 kg on average, as assumed by Maddin and Merkel (in Lo Schiavo et al. 1990: 43–199) for the Sardinian ingots? There are only weak indications that suggest this was so. As shown by the abundance of trace elements in both types, and by texture and inclusions, the ingots are in most cases too similar to reach convincing conclusions. Regarding the trace element content, a differentiation between source material and final product would hardly be visible anyhow, if the copper was just remelted. As shown by Pernicka (1987), a noticeable decrease of impurities becomes visible only after deliberately refining the copper in the liquid state—and this is just what was not done.

Our observations may have consequences for the interpretation of lead isotope analyses for provenance studies, as recently discussed fully by Gale and Stos-Gale (1995). We conclude that the ingots' compositions have not been affected by remelting many ingots or scrap metal. The copper ingots, on the other hand, do not necessarily derive from a single batch of copper from one smelting process. Based on observations at an Early Bronze Age metal factory at Feinan (Levy et al. 2002), and based on the so far best smelting experiments carried out by Merkel (1990) to exemplify Late Bronze Age copper metallurgy in the Near East, we suggest that several batches of raw copper would have been collected at the "primary" smelter, close to the ore deposits. These may have been transported to urban settlements to be remelted there into larger units. Following this model, the ingots may possibly reflect the composition of a single ore deposit, but they also may be the result of batches from different sources on the island.

We can contribute little to solving the question of the casting molds utilized to make both kinds of ingots. The almost complete lack of evidence of molds made of stone or ceramics in the archaeological record (Craddock, Freestone, and Dawe 1997; Lagarde et al. 1983) has always supported the idea of casting the metal in sand. We cannot argue against it, but in such a case we should perhaps have observed particles of quartz, clay, or other fine-grained material adhering at the surface of the ingots. This was not the case, and quartz grains found in the residue after dissolving the metal in acid and

before the measurement by spectrometry is not a sufficient argument.

The material composition of the ingots provides an explanation for the previously vexing question of how an ingot of a metal as ductile as copper could have been broken up into small pieces such as those excavated in the hundreds in Sardinia (Lo Schiavo 1989). Two characteristics of the Uluburun copper stand out: the presence of a substantial degree of porosity, and a high concentration of copper oxide inclusions. While the effect of the porosity is to provide an easy path for the propagation of a crack so as to break the ingot, it is not sufficient if the copper matrix is "pure." Attempting to break such an ingot would still produce a conglomeration of copper held together by the malleable copper matrix pieces. The effect of the porosity in the case of the embrittlement on heating is simply to reduce the cross-sectional area subjected to the external stress, and the ingot may easily be broken into pieces provided that the continuous metallic structure is in itself brittle. External stresses (for example, a sharp blow by a hammer as shown on a bun ingot by Pulak 2000: 145) produce deformation that opens up holes in the structure, reducing the cross-sectional area to a point where the holes simply join up and the ingot fractures. But in the case of the Uluburun ingots, the holes (porosity) are already present within a matrix that is itself made brittle due to the presence of the oxides. Simply dropping the ingots onto a hard surface would easily shatter the ingots since the cross-sectional area is greatly reduced by the presence of the holes and the matrix is brittle. Subjecting the

ingots to a slightly elevated temperature (about 300° C) would reduce the oxide to copper and oxygen, creating still additional internal pressure for the fracture. That is, the ingots are easily broken into smaller pieces.

The conclusion to be drawn from all our observations is that the quality of this world-market copper was low. It must have undergone additional local operations to finally obtain a quality of metal suitable for casting objects. We do not know which and how many single steps might have been taken.

Unfortunately, there is not much to say on the tin ingots. The metal melts at very low temperature and, hence, all microstructures developed by metallurgical operations disappeared. We believe that the smelting or remelting process to obtain the tin ingots was carried out under not too strong reducing conditions. This is indicated by sporadic magnetite inclusions in the tin matrix. From the metallurgical point of view, this is not a difficult task as the melting point of tin is extremely low (232° C). The tin itself will be separated quickly from the stock in the liquid state. For the time being, nothing is known about ancient tin smelting, and no further conclusions can be drawn from our observations.

Regarding the cutting of tin ingots into fragments by smashing them with a hammer or other heavy tools, it was probably the much higher ductility that made it impossible to fragment them into the same small pieces as the copper. As already pointed out by Pulak (2000: 151–52), the tin ingots were just cut into two halves or quadrants.

ACKNOWLEDGMENTS

We gratefully acknowledge the overall help of Mr. Oguz Alpözen, General Director of the Bodrum Museum for Underwater Archaeology. Special thanks go to Dr. Cemal Pulak, the excavator of the Uluburun shipwreck, for his generous graciousness and attitude in many respects, and to Mrs. Kathy Hall, the conservator of the Bodrum Museum. The financial support (to RM) of the Alexander von Humboldt-Foundation during the early part of these stud-

ies is gratefully acknowledged. The Institute for Aegean Prehistory (INSTAP) provided financial support for the analyses as well as the travel and other expenses. We are most appreciative of this support. All mounted samples were prepared in excellent quality by Andreas Ludwig, and chemical analyses were performed by Wolfgang Steger, both from the Deutsches Bergbau-Museum in Bochum.

Appendix of tables follows.

TABLE 1. Chemical Composition of the Oxide Ingots (Values in Wt.%)

IFA-Nr. Bochum	Inv.-Nr. Bodrum	Cu	Sn	As	Sb	Pb	Fe	Ni	Co	Zn	Bi	Se	Te	Ag	S	Total
TR-35/65	KW 2177	94.2	<0.001	0.11	0.007	0.035	0.11	0.022	0.003	<0.001	<0.001	<0.001	0.005	0.005	0.06	94.6
TR-35/66	KW 2199	93.2	<0.001	0.12	0.007	0.036	0.26	0.029	0.004	<0.001	<0.001	<0.001	0.006	0.005	0.07	93.8
TR-35/67	KW 2268	95.3	<0.001	0.11	0.007	0.034	0.18	0.018	0.004	<0.001	0.000	<0.001	0.006	0.005	0.07	95.8
TR-35/68	KW 2269	95.6	<0.001	0.087	0.006	0.037	0.049	0.019	0.006	<0.001	0.002	<0.001	0.005	0.006	0.10	95.9
TR-35/69	KW 2299	93.1	<0.001	0.091	0.003	0.032	0.92	0.021	0.004	<0.001	0.002	<0.001	0.007	0.002	0.12	94.3
TR-35/70	KW 2410	93.3	<0.001	0.11	0.006	0.028	0.081	0.016	0.001	<0.001	<0.001	<0.001	0.003	0.005	0.04	93.6
TR-35/71	KW 2412	96.3	<0.001	0.12	0.008	0.037	0.096	0.028	0.002	<0.001	0.004	<0.001	0.010	0.005	0.06	96.6
TR-35/73	KW 2719	95.2	<0.001	0.08	0.005	0.032	0.22	0.021	0.004	0.001	0.001	<0.001	0.008	0.001	0.06	95.7
TR-35/74	KW 2734	97.9	<0.001	0.08	0.008	0.036	0.19	0.025	0.004	<0.001	0.003	<0.001	0.010	0.002	0.13	98.4
TR-35/75	KW 2738	92.2	<0.001	0.18	0.009	0.034	0.50	0.025	0.003	<0.001	0.003	<0.001	0.008	0.002	0.25	93.2
TR-35/76	KW 2790	95.7	<0.001	0.10	0.007	0.033	0.096	0.028	0.003	<0.001	0.005	<0.001	0.008	0.002	0.03	96.0
TR-35/77	KW 2811	94.4	<0.001	0.08	0.005	0.036	0.070	0.14	0.003	<0.001	0.001	0.010	0.007	0.003	0.07	94.8
TR-35/78	KW 2827	90.9	<0.001	0.11	<0.001	0.034	1.44	0.033	0.016	<0.001	0.004	<0.001	0.009	<0.001	0.08	92.6
TR-35/79	KW 2828	94.0	<0.001	0.17	0.008	0.035	0.096	0.016	0.003	<0.001	0.004	0.001	0.004	0.004	0.03	94.4
TR-35/81	KW 2846	96.3	<0.001	0.15	0.006	0.034	0.20	0.019	0.002	<0.001	0.003	0.005	0.003	0.003	0.13	96.8
TR-35/82	KW 2847	95.2	<0.001	0.06	0.005	0.035	0.15	0.038	0.007	<0.001	0.002	<0.001	0.008	0.003	0.10	95.7
TR-35/83	KW 2850	97.5	<0.001	0.13	0.005	0.035	0.65	0.025	0.006	<0.001	0.002	<0.001	0.004	<0.001	0.18	98.5
TR-35/84	KW 2855	91.3	<0.001	0.23	0.014	0.036	0.005	0.009	0.002	<0.001	0.003	0.005	0.010	0.009	0.04	91.7
TR-35/85	KW 2885	95.5	<0.001	0.077	0.005	0.034	0.36	0.019	0.009	<0.001	0.002	<0.001	0.005	0.002	0.03	96.1
TR-35/86	KW 2888	93.6	<0.001	0.062	0.004	0.031	0.64	0.026	0.004	<0.001	0.002	<0.001	0.009	0.003	0.01	94.4
TR-35/87	KW 2889	96.5	<0.001	0.17	0.008	0.032	0.049	0.021	0.002	<0.001	0.003	0.004	0.003	0.003	0.11	96.9
TR-35/88	KW 2890	94.7	<0.001	0.14	0.008	0.031	0.079	0.018	0.002	<0.001	0.004	0.002	0.007	0.004	0.03	95.0
TR-35/89	KW 2894	95.7	<0.001	0.10	0.007	0.032	0.14	0.016	0.003	<0.001	0.006	<0.001	0.002	0.002	0.08	96.1
TR-35/90	KW 2904	95.2	<0.001	0.076	0.007	0.032	0.034	0.018	0.002	<0.001	<0.001	<0.001	0.006	0.003	0.05	95.4
TR-35/91	KW 2919	95.1	<0.001	0.082	0.005	0.031	0.42	0.018	0.004	<0.001	0.003	<0.001	0.006	<0.001	0.12	95.8
TR-35/92	KW 3040	97.8	<0.001	0.15	0.006	0.033	0.045	0.020	0.002	<0.001	0.002	0.002	0.007	0.001	0.03	98.1
TR-35/93	KW 3044	97.1	<0.001	0.09	0.007	0.030	0.11	0.018	0.002	<0.001	0.003	<0.001	0.002	0.003	0.03	97.4
TR-35/94	KW 3059	96.5	<0.001	0.14	0.007	0.031	0.012	0.020	0.002	<0.001	0.002	0.002	0.006	0.005	0.06	96.8
TR-35/95	KW 3072	95.5	<0.001	0.17	0.007	0.035	0.31	0.024	0.004	<0.001	0.004	0.006	0.008	0.003	0.25	96.3
TR-35/96	KW 3076	97.1	<0.001	0.10	0.003	0.033	0.53	0.030	0.010	<0.001	0.002	<0.001	0.007	0.002	0.06	97.9
TR-35/97	KW 3096	96.5	<0.001	0.13	0.006	0.032	0.23	0.028	0.003	<0.001	0.003	<0.001	0.005	0.004	0.06	97.0

IFA-Nr. Bochum	Inv.-Nr. Bochum	Cu	Sn	As	Sb	Pb	Fe	Ni	Co	Zn	Bi	Se	Te	Ag	S	Total
TR-35/98	KW 3115	97.9	<0.001	0.12	0.007	0.033	0.008	0.019	0.001	<0.001	0.003	0.002	0.012	0.005	0.08	98.1
TR-35/99	KW 3124	98.7	<0.001	0.13	0.006	0.032	0.054	0.029	0.001	<0.001	0.001	0.008	0.009	0.004	0.06	99.0
TR-35/100	KW 3251	97.6	<0.001	0.14	0.006	0.033	0.32	0.020	0.003	<0.001	0.004	0.001	0.008	0.001	0.05	98.1
TR-35/101	KW 3258	100.4	<0.001	0.13	0.010	0.036	0.094	0.019	0.003	<0.001	0.003	0.005	0.004	0.003	0.07	100.8
TR-35/102	KW 3275	98.2	<0.001	0.12	0.007	0.035	0.013	0.016	0.001	<0.001	0.002	0.003	0.005	0.003	0.19	98.6
TR-35/103	KW 3278	95.2	<0.001	0.12	0.008	0.033	0.010	0.024	0.003	<0.001	0.003	0.004	0.007	0.005	0.13	95.5
TR-35/104	KW 3420	94.6	<0.001	0.080	0.009	0.031	0.033	0.030	0.001	<0.001	0.003	0.005	0.003	0.005	0.09	94.9
TR-35/105	KW 3427	98.5	<0.001	0.088	0.004	0.036	0.065	0.034	0.008	<0.001	0.005	<0.001	0.010	0.003	0.28	99.0
TR-35/106	KW 3430	96.4	<0.001	0.18	0.009	0.032	0.007	0.015	0.003	<0.001	0.005	<0.001	0.006	0.007	0.05	96.7
TR-35/107	KW 3432	98.0	<0.001	0.12	0.007	0.033	0.020	0.049	0.001	<0.001	0.002	0.019	0.008	0.006	0.05	98.3
TR-35/108	KW 3441	92.8	<0.001	0.11	0.006	0.034	0.019	0.024	0.002	<0.001	0.003	0.010	0.010	0.003	0.11	93.1
TR-35/109	KW 3455	98.7	<0.001	0.12	0.006	0.035	0.042	0.032	0.002	<0.001	0.005	0.006	0.008	0.005	0.04	99.0
TR-35/110	KW 3465	97.6	<0.001	0.16	0.007	0.037	0.094	0.024	0.005	<0.001	0.004	0.009	0.008	0.003	0.24	98.2
TR-35/112	KW 3472	97.5	<0.001	0.13	0.003	0.034	0.96	0.059	0.004	<0.001	0.005	0.009	0.009	<0.001	0.37	99.1
TR-35/113	KW 3474	92.6	<0.001	0.11	<0.001	0.036	5.45	0.022	0.012	<0.001	0.002	<0.001	0.004	<0.001	0.41	98.7
TR-35/114	KW 3488	97.8	<0.001	0.080	0.009	0.032	0.36	0.039	0.007	<0.001	0.004	0.009	0.004	0.002	0.04	98.4
TR-35/115	KW 3504	97.2	<0.001	0.13	0.009	0.030	0.013	0.015	<0.001	<0.001	0.005	0.017	0.005	0.005	0.13	97.6
TR-35/116	KW 3524	98.3	<0.001	0.15	0.006	0.030	0.029	0.028	<0.001	<0.001	0.003	0.023	0.008	0.006	0.11	98.7
TR-35/117	KW 3534	97.9	<0.001	0.13	0.007	0.031	0.061	0.020	<0.001	<0.001	0.003	0.008	0.005	0.006	0.04	98.2
TR-35/118	KW 3543	99.6	<0.001	0.15	0.007	0.037	0.070	0.018	<0.001	<0.001	0.004	0.019	0.006	0.007	0.16	100.1
TR-35/119	KW 3579	98.1	<0.001	0.11	0.008	0.031	0.12	0.030	<0.001	<0.001	0.005	0.015	0.006	0.004	0.09	98.5
TR-35/120	KW 3584	98.2	<0.001	0.091	0.007	0.031	0.061	0.064	0.003	<0.001	0.003	0.011	0.005	0.004	0.07	98.5
TR-35/121	KW 3599	99.8	<0.001	0.18	0.009	0.033	0.035	0.018	0.001	<0.001	0.005	0.011	0.007	0.006	0.07	100.2
TR-35/122	KW 3621	99.7	<0.001	0.093	0.007	0.030	0.081	0.15	0.001	<0.001	0.003	0.018	0.003	0.006	0.13	100.2
TR-35/123	KW 3635	99.5	<0.001	0.24	0.009	0.032	0.009	0.030	<0.001	<0.001	0.005	0.021	0.010	0.007	0.28	100.2
TR-35/124	KW 3655	99.8	<0.001	0.13	0.007	0.033	0.035	0.020	<0.001	<0.001	0.004	0.021	0.006	0.006	0.12	100.2
TR-35/126	KW 3676	97.6	<0.001	0.13	0.007	0.032	0.020	0.033	0.001	<0.001	0.003	0.018	0.008	0.005	0.24	98.1
TR-35/128	KW 3692	98.7	<0.001	0.14	0.005	0.034	0.54	0.022	0.002	<0.001	0.005	0.016	0.007	0.002	0.22	99.7
TR-35/129	KW 3702	97.0	<0.001	0.17	0.012	0.033	0.071	0.020	0.001	<0.001	0.005	0.014	0.009	0.005	0.16	97.5
TR-35/130	KW 3706	97.4	<0.001	0.18	0.012	0.037	0.025	0.025	0.002	<0.001	0.004	0.012	0.004	0.003	0.08	97.8
TR-35/131	KW 3771	97.5	<0.001	0.090	0.003	0.034	0.48	0.021	0.002	<0.001	0.006	0.011	0.004	0.003	0.27	98.4

TABLE 1, continued

IFA-Nr. Bochum	Inv.-Nr. Bochum	Cu	Sn	As	Sb	Pb	Fe	Ni	Co	Zn	Bi	Se	Te	Ag	S	Total
TR-35/132	KW 3773	99.4	<0.001	0.14	0.009	0.038	0.023	0.023	<0.001	<0.001	0.006	0.013	0.003	0.004	0.11	99.7
TR-35/133	KW 3775	96.9	<0.001	0.21	0.013	0.034	0.017	0.023	0.004	<0.001	0.004	0.012	0.008	0.005	0.09	97.3
TR-35/134	KW 3776	97.2	<0.001	0.13	0.007	0.034	0.11	0.023	0.001	<0.001	0.002	0.011	0.004	0.004	0.05	97.6
TR-35/135	KW 3806	96.6	<0.001	0.19	0.009	0.034	0.083	0.010	0.003	<0.001	0.006	0.022	0.010	0.004	0.23	97.2
TR-35/136	KW 3838	97.1	<0.001	0.13	0.008	0.034	0.045	0.019	0.002	<0.001	0.004	0.017	0.005	0.004	0.23	97.6
TR-35/137	KW 3842	98.3	<0.001	0.20	0.012	0.032	0.24	0.020	0.002	<0.001	0.004	0.018	0.009	0.005	0.16	99.0
TR-35/138	KW 3918	98.1	<0.001	0.11	<0.001	0.035	1.69	0.033	0.005	<0.001	0.002	0.009	0.003	<0.001	0.17	100.2
TR-35/139	KW 3920	97.4	<0.001	0.18	0.011	0.034	0.093	0.016	0.003	<0.001	0.006	0.014	0.007	0.005	0.09	97.9
TR-35/140	KW 3931	98.6	<0.001	0.11	0.008	0.032	0.16	0.027	0.001	<0.001	0.007	0.013	0.002	0.004	0.07	99.1
TR-35/141	KW 3984	98.0	<0.001	0.16	0.007	0.032	0.19	0.022	0.002	<0.001	0.005	0.018	0.006	0.005	0.19	98.7
TR-35/143	KW 4004	97.2	<0.001	0.18	0.011	0.033	0.014	0.021	0.003	<0.001	0.005	0.016	0.007	0.005	0.01	97.5
TR-35/144	KW 4227	97.6	<0.001	0.10	0.005	0.032	0.37	0.025	<0.001	<0.001	0.004	0.015	0.002	0.002	0.07	98.3
TR-35/145	KW 4228	95.7	<0.001	0.13	0.004	0.034	0.48	0.018	0.011	<0.001	0.006	0.009	0.006	0.003	0.18	96.6
TR-35/146	KW 4241	98.0	<0.001	0.15	0.008	0.034	0.009	0.014	<0.001	<0.001	0.005	0.027	0.008	0.005	0.05	98.3
TR-35/147	KW 4242	97.5	<0.001	0.17	0.008	0.031	0.10	0.025	0.001	<0.001	0.003	0.014	0.007	0.005	0.17	98.0
TR-35/148	KW 4378	96.0	<0.001	0.13	0.008	0.034	0.35	0.053	0.001	<0.001	0.006	0.026	0.005	0.004	0.14	96.7
TR-35/149	KW 4458	97.0	<0.001	0.41	0.014	0.039	0.010	0.017	0.002	<0.001	0.006	0.029	0.012	0.008	0.32	97.8
TR-35/150	KW 4462	96.7	<0.001	0.19	0.010	0.037	0.072	0.020	0.002	<0.001	0.004	0.024	0.009	0.005	0.03	97.2
TR-35/151	KW 4486	97.8	<0.001	0.15	0.006	0.030	0.016	0.035	0.008	<0.001	0.006	0.017	0.008	0.005	0.06	98.2
TR-035/001	KW60	88.0	0.003	0.21	0.007	0.019	0.19	0.016	<0.001	0.0097	0.008	0.023	0.013	0.004	0.50	89.0
TR-035/002	KW1857	97.8	0.002	0.19	0.009	0.024	0.017	0.019	<0.001	<0.001	0.007	0.032	0.016	0.003	0.32	98.5
TR-035/003	KW187	89.8	0.006	0.16	0.007	0.022	0.077	0.022	0.002	0.023	0.007	0.018	0.008	0.002	0.21	90.4
TR-035/004	KW627	92.3	0.012	0.13	0.007	0.020	0.037	0.019	0.009	<0.001	0.008	0.016	0.012	0.002	0.17	92.8
TR-035/005	KW876	92.3	0.007	0.25	0.28	0.063	0.030	0.25	0.029	<0.001	0.005	0.028	0.008	0.006	0.64	93.8
TR-035/006	KW997	92.6	0.049	0.16	0.007	0.019	0.059	0.024	<0.001	0.0028	0.006	0.024	0.014	0.001	0.21	93.1
TR-035/007	KW1169	89.0	0.010	0.15	0.005	0.018	0.058	0.016	<0.001	0.0028	0.005	0.015	0.010	0.002	0.30	89.6
TR-035/008	KW1187	88.5	<0.001	0.16	0.006	0.017	0.039	0.021	0.001	0.0046	0.005	0.018	0.012	0.004	1.44	90.2
TR-035/009	KW1372	93.3	0.001	0.14	0.007	0.020	0.088	0.032	0.004	<0.001	0.003	0.023	0.016	0.004	0.30	93.9
TR-035/010	KW1396	92.7	<0.001	0.09	<0.001	0.019	1.55	0.021	0.011	0.064	0.005	0.004	0.011	0.002	0.03	94.5
TR-035/011	KW1400	90.7	<0.001	0.17	0.006	0.018	0.29	0.031	0.012	0.0024	0.005	0.017	0.013	0.003	0.20	91.5
TR-035/012	KW1983	96.5	0.003	0.30	0.013	0.053	0.010	0.037	0.010	<0.001	0.005	0.042	0.021	0.004	0.11	97.1
TR-035/013	KW2325	94.7	<0.001	0.28	0.010	0.021	0.14	0.019	0.001	<0.001	0.005	0.025	0.018	0.003	0.63	95.9

IA-Nr. Bochum	Inv.-Nr. Bodrum	Cu	Sn	As	Sb	Pb	Fe	Ni	Co	Zn	Bi	Se	Te	Ag	S	Total
TR-035/015	KW27307	97.5	0.002	0.10	0.008	0.020	0.095	0.027	0.011	<0.0001	0.002	0.015	0.008	0.002	0.19	98.0
TR-035/016	KW2791	91.4	<0.001	0.25	0.010	0.021	0.13	0.021	0.001	0.014	0.008	0.030	0.019	0.002	1.19	93.1
TR-035/017	KW2826	96.4	<0.001	0.24	0.010	0.018	0.032	0.020	0.001	<0.0001	0.005	0.037	0.020	0.003	0.20	97.0
TR-035/018	KW2848	99.5	0.002	0.15	0.007	0.020	0.015	0.021	0.001	<0.0001	0.004	0.014	0.010	0.001	0.04	99.8
TR-035/019	KW2867	94.8	0.000	0.10	0.005	0.019	0.15	0.019	0.007	<0.0001	0.004	0.013	0.009	<0.001	0.23	95.4
TR-035/020	KW2903	98.9	0.001	0.30	0.013	0.025	0.025	0.023	0.007	<0.0001	0.004	0.032	0.022	0.044	0.02	99.5
TR-035/021	KW3012	94.5	<0.001	0.21	0.009	0.020	0.039	0.021	<0.001	<0.0001	0.004	0.022	0.015	0.004	0.28	95.1
TR-035/022	KW3079	98.1	0.110	0.24	0.014	0.023	0.022	0.015	0.003	<0.0001	0.006	0.031	0.020	0.004	0.21	98.8
TR-035/023	KW3110	98.6	0.080	0.089	0.007	0.020	0.034	0.017	0.001	<0.0001	0.004	0.015	0.008	<0.001	0.15	99.0
TR-035/024	KW3141	96.2	0.071	0.12	0.008	0.020	0.19	0.060	0.001	<0.0001	0.003	0.021	0.010	0.002	0.27	97.0
TR-035/025	KW3407	100.0	0.001	0.11	0.008	0.019	0.011	0.021	<0.001	<0.0001	0.005	0.021	0.010	0.002	0.15	100.3
TR-035/026	KW4317	99.5	0.000	0.13	0.009	0.019	0.013	0.032	0.001	<0.0001	0.003	0.018	0.013	0.002	0.27	100.0
TR-035/027	KW3497	100.3	<0.001	0.13	0.005	0.022	0.17	0.024	<0.001	<0.0001	0.003	0.019	0.008	0.002	0.12	100.8
TR-035/028	KW4373	96.7	0.008	0.26	0.010	0.021	0.017	0.021	0.001	<0.0001	0.005	0.034	0.019	0.004	0.03	97.1
TR-035/029	KW4374	96.4	0.051	0.16	0.008	0.019	0.045	0.015	0.003	<0.0001	0.004	0.021	0.015	0.002	0.01	96.8
TR-035/030	KW4460	90.7	0.055	0.10	0.002	0.107	0.86	0.022	0.003	<0.0001	0.006	0.009	0.009	0.001	0.22	92.1
TR-035/031	KW4501	97.1	0.009	0.22	0.008	0.025	0.024	0.019	0.002	<0.0001	0.005	0.020	0.014	0.002	0.01	97.4
TR-035/032	KW4507	95.3	0.032	0.16	0.009	0.021	0.010	0.026	0.008	<0.0001	0.005	0.021	0.013	0.003	0.15	95.8
TR-035/033	KW67795	89.7	0.016	0.14	0.006	0.018	0.061	0.015	0.002	<0.0001	0.005	0.025	0.014	<0.001	0.57	90.6

Note: The total does not always reach 100%. This is because of inclusions of sand, slag, and cuprite in the matrix that were not considered in the analyses.

TABLE 2. Chemical Composition of the Bun Ingots (Values in Wt. %).

IFA-Nr. Bochum	Inv.-Nr. Bodrum	Cu	Sn	As	Sb	Pb	Fe	Ni	Co	Zn	Bi	Se	Te	Ag	S	Total
TR-35/63	KW 821	94.6	<0.001	0.11	0.014	0.038	0.028	0.029	0.020	<0.001	0.001	<0.001	0.005	0.005	0.07	95.0
TR-35/64	KW 2134	95.1	<0.001	0.15	0.010	0.039	0.079	0.018	0.010	<0.001	0.005	0.001	0.008	0.005	0.01	95.4
TR-35/72	KW2711	96.2	<0.001	0.10	0.007	0.033	0.005	0.025	0.012	<0.001	0.001	<0.001	0.006	0.005	0.00	96.4
TR-35/80	KW2836	96.9	<0.001	0.15	0.008	0.037	0.007	0.021	0.017	<0.001	0.003	0.006	0.004	0.005	0.09	97.2
TR-35/111	KW3466	97.9	<0.001	0.13	0.006	0.035	0.008	0.024	0.018	<0.001	0.002	0.003	0.007	0.004	0.03	98.1
TR-35/125	KW3675	99.8	<0.001	0.15	0.008	0.034	0.014	0.027	0.036	<0.001	0.004	0.013	0.010	0.005	0.07	100.2
TR-35/127	Kw3691	99.5	<0.001	0.17	0.010	0.034	0.009	0.025	0.033	<0.001	0.004	0.012	0.008	0.005	0.12	99.9
TR-35/142	KW3998	99.1	<0.001	0.17	0.008	0.032	0.055	0.024	0.021	<0.001	0.005	0.018	0.006	0.005	0.22	99.7
TR-35/152	KW4586	97.0	0.002	0.14	0.009	0.034	0.009	0.029	0.012	<0.001	0.005	0.016	0.004	0.004	0.14	97.4
TR-035/034	KW107	94.9	0.002	0.40	0.021	0.028	0.89	0.37	0.014	<0.001	0.006	0.031	0.012	0.004	0.17	96.9
TR-035/035	KW191	96.3	0.001	0.16	0.007	0.021	0.008	0.071	0.009	<0.001	0.004	0.018	0.014	0.002	0.19	96.8
TR-035/036	KW194	95.3	0.002	0.26	0.013	0.025	0.010	0.042	0.010	<0.001	0.003	0.038	0.018	0.005	0.03	95.8
TR-035/037	KW195	97.6	0.002	0.22	0.012	0.020	0.022	0.025	0.007	<0.001	0.003	0.027	0.018	0.003	0.19	98.1
TR-035/038	KW406	91.0	0.002	0.12	0.009	0.021	0.050	0.024	0.014	<0.001	0.003	0.013	0.014	0.001	0.36	91.7
TR-035/039	KW509	91.1	0.003	0.29	0.014	0.025	0.031	0.017	0.012	<0.001	0.005	0.039	0.023	0.005	0.73	92.2
TR-035/040	KW510	98.7	0.24	0.29	0.011	0.028	0.026	0.033	0.014	<0.001	0.005	0.045	0.022	0.003	0.05	99.4
TR-035/041	KW514	98.0	0.037	0.14	0.006	0.022	0.006	0.032	0.013	<0.001	0.004	0.017	0.014	0.001	0.03	98.3
TR-035/042	KW841	93.5	0.015	0.28	0.009	0.021	0.008	0.022	0.020	<0.001	0.007	0.023	0.012	0.003	0.53	94.4
TR-035/043	KW875	96.1	0.002	0.23	0.010	0.023	0.014	0.021	0.008	<0.001	0.006	0.029	0.016	0.004	0.03	96.5
TR-035/044	KW998	98.2	<0.001	0.28	0.011	0.022	0.005	0.028	0.005	<0.001	0.004	0.031	0.016	0.004	0.06	98.7
TR-035/045	KW1088	92.1	0.002	0.13	0.008	0.023	0.007	0.023	0.008	<0.001	0.004	0.018	0.013	0.002	0.07	92.4
TR-035/046	KW1535	95.4	0.005	0.24	0.010	0.022	0.023	0.029	0.017	<0.001	0.005	0.018	0.014	0.002	0.35	96.1
TR-035/047	KW1554	97.4	0.005	0.24	0.011	0.025	0.025	0.021	0.026	<0.001	0.006	0.028	0.016	0.003	0.12	97.9
TR-035/048	KW1558	93.5	<0.001	0.16	0.009	0.022	0.044	0.022	0.009	<0.001	0.003	0.020	0.012	0.002	0.13	93.9
TR-035/049	KW1564	94.3	<0.001	0.15	0.005	0.019	0.55	0.020	0.029	<0.001	0.005	0.016	0.011	0.002	0.24	95.4
TR-035/050	KW1604	99.0	<0.001	0.27	0.011	0.024	0.035	0.023	0.013	<0.001	0.003	0.030	0.020	0.004	0.06	99.5
TR-035/051	KW2178	99.5	0.001	0.23	0.012	0.024	0.059	0.032	0.013	<0.001	0.004	0.027	0.016	0.004	0.08	100.0

IFA-Nr. Bochum	Inv.-Nr. Bodrum	Cu	Sn	As	Sb	Pb	Fe	Ni	Co	Zn	Bi	Se	Te	Ag	S	Total
TR-035/052	KW2715	99.4	0.006	0.23	0.010	0.024	0.006	0.032	0.033	<0.0001	0.003	0.022	0.014	0.003	0.10	99.9
TR-035/053	KW2731	99.8	<0.001	0.39	0.015	0.030	0.003	0.017	0.009	<0.0001	0.006	0.052	0.025	0.006	0.34	100.7
TR-035/054	KW3006	99.8	<0.001	0.15	0.008	0.022	0.007	0.028	0.010	<0.0001	0.004	0.013	0.008	0.004	0.05	100.1
TR-035/055	KW3277	99.5	<0.001	0.23	0.011	0.023	0.017	0.037	0.015	<0.0001	0.005	0.022	0.015	0.002	0.02	99.9
TR-035/056	KW3421	99.8	<0.001	0.23	0.010	0.022	0.006	0.025	0.016	<0.0001	0.003	0.022	0.017	0.004	0.02	100.2
TR-035/057	KW3600	99.9	<0.001	0.31	0.013	0.025	0.005	0.026	0.012	<0.0001	0.003	0.030	0.021	0.004	0.04	100.4
TR-035/058	KW3701	98.9	0.002	0.20	0.010	0.019	0.008	0.033	0.012	<0.0001	0.003	0.019	0.018	0.002	0.05	99.3
TR-035/059	KW3758	97.1	0.002	0.20	0.008	0.022	0.013	0.021	0.010	<0.0001	0.003	0.022	0.015	0.003	0.02	97.4
TR-035/060	KW3810	99.7	<0.001	0.12	0.006	0.021	0.013	0.033	0.019	<0.0001	0.005	0.015	0.010	0.002	0.02	100.0
TR-035/061	KW4453	96.6	<0.001	0.27	0.010	0.021	0.006	0.026	0.015	<0.0001	0.003	0.026	0.016	0.003	0.08	97.1
TR-035/062	KW197/95	98.9	0.002	0.18	0.010	0.023	0.010	0.031	0.010	<0.0001	0.004	0.029	0.015	0.002	0.05	99.2

Note: The total does not always reach 100%. This is because of inclusions of sand, slag, and cuprite in the matrix that were not considered in the analyses.

TABLE 3. Chemical Composition of the Tin Ingots (Values in Wt.%)

IFA-Nr. Bochum	Inv.-Nr. Bodrum	Cu	Sn	As	Sb	Pb	Fe	Ni	Co	Zn	Ag	Total
TR-35/153	KW 201	0.097	99.3	0.004	0.007	0.24	0.007	<0.001	<0.001	<0.001	<0.0001	99.64
TR-35/154	KW 202	0.003	98.3	<0.001	0.006	0.004	0.004	<0.001	0.001	0.0010	0.0005	98.29
TR-35/155	KW 203	0.002	98.1	0.005	0.005	0.007	0.004	<0.001	<0.001	<0.001	0.0001	98.15
TR-35/156	KW 244	0.016	98.6	0.004	0.007	0.083	0.006	<0.001	<0.001	0.0022	0.0004	98.73
TR-35/157	KW 398	0.005	98.0	0.003	<0.001	0.006	0.007	<0.001	<0.001	<0.001	<0.0001	98.00
TR-35/158	KW 1932	0.005	100.2	0.004	0.005	0.007	0.006	<0.001	<0.001	0.0028	<0.0001	100.24
TR-35/159	KW 2332	0.028	98.5	0.004	0.005	0.006	0.010	<0.001	<0.001	<0.001	0.0001	98.51
TR-35/160	KW 2408	0.004	98.6	0.005	0.006	0.006	0.004	<0.001	<0.001	<0.001	0.0012	98.61
TR-35/161	KW 2739	0.005	98.1	0.003	0.003	<0.001	0.004	<0.001	0.002	<0.001	<0.0001	98.15
TR-35/162	KW 2774	0.004	98.5	<0.001	0.007	0.086	0.011	<0.001	<0.001	<0.001	<0.0001	98.56
TR-35/163	KW 2796	0.003	99.0	0.003	0.004	0.006	0.005	<0.001	<0.001	<0.001	0.0001	99.01
TR-35/164	KW 2911	0.29	90.3	<0.001	0.011	0.93	0.025	0.001	0.001	0.002	0.0014	91.58
TR-35/165	KW 2915	0.22	98.7	<0.001	0.006	0.41	0.008	<0.001	<0.001	0.001	0.0027	99.39
TR-35/166	KW 2922	0.001	98.4	0.004	0.005	0.007	0.005	<0.001	0.002	<0.001	<0.0001	98.46
TR-35/167	KW 2924	0.004	99.4	0.003	0.005	<0.001	0.010	<0.001	0.003	<0.001	<0.0001	99.38
TR-35/168	KW 3048	0.004	99.1	0.003	0.006	0.17	0.005	<0.001	<0.001	<0.001	0.0022	99.33
TR-35/169	KW 3061	0.004	98.2	0.001	0.002	<0.001	0.004	<0.001	<0.001	<0.001	<0.0001	98.17
TR-35/170	KW 3094	0.005	97.7	<0.001	0.005	0.011	0.007	<0.001	<0.001	<0.001	0.0022	97.70
TR-35/171	KW 3157	0.003	97.1	<0.001	0.005	0.007	0.010	<0.001	<0.001	0.001	<0.0001	97.09
TR-35/172	KW 3297	0.004	98.1	0.002	0.006	0.021	0.009	<0.001	<0.001	<0.001	<0.0001	98.14
TR-35/173	KW 3433	0.015	97.4	0.002	0.008	0.25	0.001	<0.001	<0.001	<0.001	0.0090	97.73
TR-35/174	KW 3703	0.015	97.7	0.003	0.007	0.26	0.011	<0.001	<0.001	0.001	0.0026	97.98
TR-35/175	KW 3935	0.015	99.1	0.001	0.15	0.19	0.004	<0.001	<0.001	<0.001	0.024	99.47
TR-35/176	KW 4000	0.17	99.9	<0.001	0.008	0.061	0.012	<0.001	<0.001	<0.001	0.0002	100.17
TR-35/177	KW 4166	0.003	98.9	0.004	0.005	0.007	0.003	<0.001	<0.001	<0.001	<0.0001	98.92
TR-35/178	KW 4265	0.002	98.8	<0.001	0.006	0.007	0.004	<0.001	<0.001	<0.001	0.0003	98.80
TR-35/179	KW 4388	0.004	97.3	0.002	0.005	0.006	0.004	<0.001	<0.001	<0.001	<0.0001	97.32
TR-35/180	KW 4419	0.006	97.7	0.001	0.006	0.040	0.004	<0.001	<0.001	<0.001	0.0002	97.79
TR-35/181	KW 4485	0.002	97.9	0.003	0.005	0.033	0.005	<0.001	<0.001	<0.001	0.0003	97.99
TR-35/182	KW 4576	0.004	97.0	0.001	0.008	<0.001	0.008	<0.001	0.003	<0.001	0.0009	97.06
TR-35/183	KW 5552	0.008	99.0	0.003	0.005	<0.001	0.006	<0.001	<0.001	<0.001	0.0001	99.05
TR-35/184	KW 9267	0.005	98.2	0.003	0.005	0.006	0.005	<0.001	<0.001	<0.001	0.0001	98.22

Note: Nickel was analyzed also but was found to be always below 0.001%.

TABLE 4. Medians, Interquartile Ranges and Other Statistical Parameters of Oxide, Bun-shaped, and Tin Ingots

a: Statistical Analysis of Measured Elements in Uluburun Tin

	Cu	As	Sb	Pb	Fe	Co	Zn	Ag	Sn
Count	32	24	31	27	32	6	7	20	32
Average	0.030	0.003	0.010	0.016	0.007	0.002	0.002	0.002	98.16
Median	0.005	0.003	0.006	0.011	0.005	0.002	0.001	0.001	98.35
Variance	0.005	0.000	0.001	0.039	0.000	0.000	0.000	0.000	2.630
St Dev	0.068	0.001	0.026	0.196	0.004	0.001	0.001	0.005	1.620
Min	0.001	0.001	0.004	0.002	0.001	0.001	0.001	0.000	90.300
Max	0.290	0.005	0.150	0.930	0.025	0.003	0.003	0.024	100.000
Range	0.289	0.004	0.148	0.926	0.024	0.002	0.002	0.024	9.900
Low Quat	0.004	0.002	0.005	0.006	0.004	0.001	0.001	0.000	97.800
Up Quat	0.015	0.004	0.007	0.170	0.009	0.003	0.002	0.002	98.900
Int Ran	0.012	0.002	0.002	0.164	0.005	0.002	0.001	0.002	1.150

b: Statistical Analysis of Measured Elements in Uluburun Copper Oxide Ingots

	As	Sb	Pb	Fe	Ni	Co	Se	Bi	Te	Ag	S	Sn	Cu
Count	114	110	114	114	114	109	89	111	114	105	114	24	114
Average	0.146	0.010	0.031	0.230	0.030	0.048	0.016	0.004	0.008	0.004	0.167	0.021	96.070
Median	0.130	0.007	0.032	0.076	0.021	0.033	0.016	0.004	0.008	0.004	0.115	0.008	96.700
Variance	0.003	0.000	0.000	0.331	0.000	0.003	0.000	0.000	0.000	0.000	0.039	0.000	7.460
St Dev	0.003	0.026	0.010	0.576	0.028	0.050	0.009	0.002	0.004	0.004	0.198	0.029	2.730
Min	0.060	0.002	0.016	0.005	0.009	0.005	0.001	0.000	0.002	0.001	0.010	0.000	88.000
Max	0.410	0.280	0.107	5.450	0.250	0.310	0.042	0.008	0.022	0.044	1.6072	0.110	100
Range	0.350	0.278	0.091	5.445	0.241	0.303	0.041	0.008	0.020	0.043	1.5707	0.110	12.400
Low Quat	0.110	0.006	0.025	0.029	0.019	0.014	0.009	0.003	0.005	0.002	0.060	0.002	94.700
Up Quat	0.170	0.009	0.034	0.190	0.028	0.062	0.021	0.005	0.010	0.005	0.210	0.041	97.900
Int Quat	0.06	0.003	0.009	0.161	0.009	0.048	0.012	0.002	0.005	0.003	0.150	0.039	3.200

c: Statistical Analysis of Measured Elements in Uluburun Copper Bun Ingots

	As	Sb	Pb	Fe	Ni	Co	Se	Bi	Te	Ag	S	Sn	Cu
Count	38	38	38	38	38	38	36	38	38	38	89	38	38
Average	0.207	0.01	0.026	0.056	0.040	0.103	0.022	0.004	0.014	0.003	0.131	0.009	97.040
Median	0.200	0.01	0.024	0.012	0.030	0.014	0.022	0.004	0.014	0.004	0.070	0.001	97.500
Variance	0.005	0.000	0.000	0.030	0.003	0.040	0.000	0.000	0.000	0.000	0.024	0.002	6.630
St Dev	0.070	0.003	0.006	0.164	0.060	0.187	0.010	0.001	0.005	0.001	0.150	0.039	2.560
Min	0.100	0.005	0.019	0.003	0.017	0.005	0.001	0.001	0.004	0.001	0.000	0.001	91.000
Max	0.400	0.021	0.039	0.890	0.370	0.750	0.052	0.007	0.025	0.006	0.730	0.240	99.900
Range	0.300	0.008	0.020	0.887	0.353	0.745	0.051	0.006	0.021	0.005	0.730	0.239	8.900
Low Quat	0.150	0.008	0.022	0.007	0.022	0.010	0.016	0.003	0.01	0.002	0.030	0.001	95.300
Up Quat	0.276	0.011	0.030	0.028	0.032	0.015	0.029	0.005	0.016	0.005	0.170	0.002	99.400
Int Quat	0.110	0.003	0.008	0.021	0.010	0.005	0.013	0.002	0.006	0.003	0.140	0.001	4.100

REFERENCES

- Abs-Wurmbach, I.; Peters, T.; Langer, K.; and Schreyer, W.
1983 Phase Relations in the System Mn-Si-O: An Experimental and Petrological Study. *Neues Jahrbuch für Mineralogie, Abhandlungen* 146, no. 3: 258-79.
- Bachmann, H.-G.
1982 Copper Smelting Slags from Cyprus: Review and Classification of Analytical Data. Pp. 143-52 in *Acta of the International Archaeological Symposium "Early Metallurgy in Cyprus, 4000-500 BC."* eds. J. D. Muhly, R. Maddin, and V. Karageorghis. Nicosia: Pierides Foundation.
- Bamberger, M., and Wincierz, P.
1990 Ancient Smelting of Oxide Copper Ore. Pp. 123-57 in *The Ancient Metallurgy of Copper*, ed. B. Rothenberg. Researches in the Arabah 1959-1984 2. London: Institute of Archaeo-Metallurgical Studies.
- Bass, G. F.
1967 *Cape Gelidonya: A Bronze Age Shipwreck*. Transactions of the American Philosophical Society 57, part 8. Philadelphia: American Philosophical Society.
- Begemann, F.; Kallas, K.; Schmitt-Strecker, S.; and Pernicka, E.
1999 Tracing Ancient Tin via Isotope Analyses. Pp. 277-84 in *The Beginnings of Metallurgy*, eds. A. Hauptmann, E. Pernicka, Th. Rehren, and Ü. Yalçin. Der Anschnitt, Beiheft 9. Bochum: Deutsches Bergbau-Museum.
- Bisson, M. S.
2000 Precolonial Copper Metallurgy: Sociopolitical Context. Pp. 83-145 in *Ancient African Metallurgy: The Socio-Cultural Context*, eds. M. S. Bisson, S. T. Childs, Ph. de Barros, and A. F. C. Holl. Walnut Creek, CA: Altamira.
- Buchholz, H.-G.
1959 Keftiubarren und Erzhandel im zweiten vorchristlichen Jahrtausend. *Prähistorische Zeitschrift* 37: 1-40.
1966 Talanta: Neues über Metallbarren der ostmediterranen Spätbronzezeit. *Schweizer Münzblätter* 16: 58-72.
1967 Analysen prähistorischer Metallfunde aus Zypern und den Nachbarländern. *Berliner Jahrbuch für Vor- und Frühgeschichte* 7: 189-256.
- Budd, P.; Pollard, A. M.; Scaife, B.; and Thomas, R. G.
1995 Oxhide Ingots, Recycling and the Mediterranean Metals Trade. *Journal of Mediterranean Archaeology* 8, no. 1: 1-32.
- Chernykh, E.
1992 *Ancient Metallurgy in the USSR: The Early Metal Age*. Trans. S. Wright, from Russian. Cambridge: Cambridge University.
- Cooke, S. R. B., and Nielsen, B. V.
1978 Slags and Other Metallurgical Products. Pp. 182-224. in *Excavations at Nichoria in Southwest Greece*, Vol. 1: *Site, Environs, and Techniques*, eds. G. Rapp, Jr., and S. E. Aschenbrenner. Minneapolis: University of Minnesota.
- Craddock, P.
1995 *Early Metal Mining and Production*. Edinburgh: Edinburgh University.
- Craddock, P. T., and Meeks, N. D.
1987 Iron in Ancient Copper. *Archaeometry* 29: 187-204.
- Craddock, P. T.; Freestone, I. C.; and Dawe, C. D.
1997 Casting Metals in Limestone Moulds. *Journal of the Historical Metallurgy Society* 31: 1-7.
- Dikaios, P.
1969 *Enkomi: Excavations 1948-1958*, Vol. 3a: *Plates 1-239*. Mainz: von Zabern.
- Dykstra, F. R.
1967 Analysis of Tin Sample. Pp. 171-72 in *Cape Gelidonya: A Bronze Age Shipwreck*, ed. G. F. Bass. Transactions of the American Philosophical Society 57, part 8. Philadelphia: American Philosophical Society.
- Eugster, H. P., and Wones, D. R.
1962 Stability Relations of the Ferruginous Biotite, Annite. *Journal of Petrology* 3: 82-125.
- Fasnacht, W.
1989 Excavations at Ayia Varvara-Almyras. *Report of the Department of Antiquities, Cyprus*: 59-76.
- Gale, N. H.
1991 Copper Oxhide Ingots: Their Origin and Their Place in the Bronze Age Metals Trade in the Mediterranean. Pp. 197-239 in *Bronze Age Trade in the Mediterranean*. Studies in Mediterranean Archaeology 90. Jonsered: Åström.
- Gale, N. H., and Stos-Gale, Z. A.
1986 Oxhide Copper Ingots in Crete and Cyprus and the Bronze Age Metals Trade. *Annual of the British School at Athens* 81: 81-100.
1995 Comments on "Oxhide Ingots, Recycling, and the Mediterranean Metals Trade." *Journal of Mediterranean Archaeology* 8, no. 1: 33-41.
- Galili, E.; Shmueli, N.; and Artzy, M.
1986 Bronze Age Ship's Cargo of Copper and Tin. *International Journal of Nautical Archaeology* 15: 25-37.

- Gambaschidze, I.; Hauptmann, A.; Slotta, R.; and Yalçin, Ü.
 2001 *Georgien—Schätze aus dem Land des Goldenen Vlies*. Veröffentlichungen aus dem Deutschen Bergbau-Museum Bochum 100. Bochum: Deutsches Bergbau-Museum.
- Han, M. C.
 1967 Report on Copper Ingots by Spectrographic Analysis. P. 169 in *Cape Gelidonya: A Bronze Age Shipwreck*, ed. G. F. Bass. Transactions of the American Philosophical Society 57, part 8. Philadelphia: American Philosophical Society.
- Hauptmann, A.
 1985 *5000 Jahre Kupfer in Oman*. Vol. 1: *Die Entwicklung der Kupfermetallurgie vom 3. Jahrtausend bis zur Neuzeit*. Der Anschnitt, Beiheft 4. Bochum: Deutsches Bergbau-Museum.
 1987 Kupfer und Bronzen der südostarabischen Halbinsel. *Der Anschnitt* 5–6: 209–18.
 2000 *Zur frühen Metallurgie des Kupfers in Fenan/Jordanien*. Der Anschnitt, Beiheft 11. Bochum: Deutsches Bergbau-Museum
- Hohlmann, B.; Hauptmann, A.; and Schröder, B.
 In press Der spätbronzezeitliche Verhüttungsplatz von Acqua Fredda bei Bedollo—Rohstoffbasis, metallurgische Untersuchungen und Versuch einer Prozeßrekonstruktion. In *Kupfer aus den Alpen*, eds. G. Weisgerber and G. Goldenberg. Bochum: Deutsches Bergbau-Museum.
- Karageorghis, V., and Kassianidou, V.
 1999 Metalworking and Recycling in Late Bronze Age Cyprus—The Evidence from Kition. *Oxford Journal of Archaeology* 18: 171–88.
- Kempinski, A., and Košak, S.
 1977 Hittite Metal "Inventories" (CTH 242) and Their Economic Implications. *Tel Aviv* 4: 87–93.
- Knapp, A. B.; Donnelly, M.; and Kassianidou, V.
 1998 Excavations at Politiko-Phorades 1997. *Report of the Department of Antiquities, Cyprus*: 247–68.
- Koucky, F., and Steinberg, A.
 1982 The Ancient Slags of Cyprus. Pp. 117–41 in *Acta of the International Archaeological Symposium "Early Metallurgy in Cyprus, 4000–500 BC."* eds. J. D. Muhly, R. Maddin, and V. Karageorghis. Nicosia: Pierides Foundation.
- Lagarce, J.; Lagarce E.; Bounni, A.; and Saliby, N.
 1983 Les fouilles à Ras Ibn Hanî en Syria (campagnes de 1980, 1981 et 1982). *Comptes-Rendu de l'Académie des Inscriptions et Belles-Lettres*: 249–90.
- Leese, M.; Craddock, P.; Freestone, I. C.; and Rothenberg, B.
 1985/ The Composition of Ores and Metal Objects from Timna, Israel. *Wiener Berichte für Naturwissenschaften in der Kunst* 2/3: 90–120.
 1986
- Levy, T. E.; Adams, R. B.; Hauptmann, A.; Prange, M.; Schmitt-Strecker, S.; and Najjar, M.
 2002 Early Bronze Age Metallurgy: A Newly Discovered Copper Manufactory in Southern Jordan. *Antiquity* 76: 425–37.
- Lo Schiavo, F.
 1989 Early Metallurgy in Sardinia: Copper Ox-hide Ingots. Pp. 33–38 in *Old World Archaeometallurgy*, eds. A. Hauptmann, E. Pernicka, and G. A. Wagner. Der Anschnitt, Beiheft 7. Bochum: Deutsches Bergbau-Museum.
- Lo Schiavo, F.; Maddin, R.; Merkel, J. F.; Muhly, J. D.; and Stech, T.
 1990 *Analisi metallurgiche e statistiche sui lingotti di rame della Sardegna/Metallographic and Statistical Analyses of Copper Ingots from Sardinia*. Quaderni 17. Ozieri: Torchietto.
- Maddin, R.
 1989 The Copper and Tin Ingots from the Kaş Shipwreck. Pp. 99–105 in *Old World Archaeometallurgy*, eds. A. Hauptmann, E. Pernicka, and G. A. Wagner. Der Anschnitt, Beiheft 7. Bochum: Deutsches Bergbau-Museum.
- Maddin, R., and Muhly, J. D.
 1974 Some Notes on the Copper Trade in the Ancient Mid-East. *Journal of Metals* 5: 1–7.
- Merkel, J. F.
 1986 Ancient Smelting and Casting of Copper for Oxhide Ingots. Pp. 251–64 in *Studies in Sardinian Archaeology*. Vol. 2: *Sardinia in the Mediterranean*, ed. M. Balmuth. Ann Arbor: University of Michigan.
 1990 Experimental Reconstruction of Bronze Age Copper Smelting Based on Archaeological Evidence from Timna. Pp. 78–122 in *The Ancient Metallurgy of Copper*, ed. B. Rothenberg. Researches in the Arabah 1959–1984 2. London: Institute for Archaeo-Metallurgical Studies.
- Muhly, J. D.
 1991 The Development of Copper Metallurgy in Late Bronze Age Cyprus. Pp. 180–96 in *Bronze Age Trade in the Mediterranean: Papers Presented at the Conference held at Rewley House, Oxford, in December 1989*, ed. N. H. Gale. Studies in Mediterranean Archaeology 90. Jönköping: Åström.
- Pernicka, E.
 1987 Erzlagerstätten in der Ägäis und ihre Ausbeutung im Altertum: Geochemische Untersuchungen zur Herkunftsbestimmung archäologischer Metallobjekte. *Jahrbuch des Römisch-Germanischen Zentralmuseums Mainz* 34: 607–714.
- Prange, M.
 2001 Vergleichende Untersuchungen zur Charakterisierung des omanischen Kupfers mittels

- chemischer und isotopischer Analysenmethoden. *Metalla* 8: 1–126.
- Primas, M., and Pernicka, E.
1998 Der Depotfund von Oberwiltingen. Neue Ergebnisse zur Zirkulation von Metallbarren. *Germania* 76: 25–65.
- Pulak, C.
1997 The Uluburun Shipwreck. Pp. 233–62 in *Res Maritimae: Cyprus and the Eastern Mediterranean from Prehistory to Late Antiquity*, eds. S. Swiny, R. L. Hohlfelder, and H. W. Swiny. ASOR Archaeological Reports 4. Atlanta: Scholars.
2000 The Copper and Tin Ingots from the Late Bronze Age Shipwreck at Uluburun. Pp. 137–57 in *Anatolian Metal I*, ed. Ü. Yalçın. Der Anschnitt, Beiheft 13. Bochum: Deutsches Bergbau-Museum.
- Reiter, K.
1997 *Die Metalle im Alten Orient unter besonderer Berücksichtigung altbabylonischer Quellen*. Alter Orient und Altes Testament 249. Münster: Ugarit.
- Roden, C.
1985 Montanarchäologische Quellen des ur- und frühgeschichtlichen Zinnerzbergbaus in Europa. *Der Anschnitt* 37: 50–80.
- Roman, I.
1990 Copper Ingots. Pp. 176–81 in *The Ancient Metallurgy of Copper*, ed. B. Rothenberg. Researches in the Arabah 1959–1984 2. London: Institute for Archaeo-Metallurgical Studies.
- Schwaller de Lubicz, R. A.
1999 *The Temples of Karnak*. Rochester, VT: Inner Traditions.
- Spano, G.
1858 Stele Ortuarie di Bronzo. *Bulletino Archaeologico Sardo* 4: 11–15.
- Stech, T.; Maddin, R. M.; and Muhly, J. D.
1985 Copper Production at Kition. Pp. 388–402 in *Kition*, Vol. 5: *The Pre-Phoenician Levels*, eds. V. Karageorghis and M. Demas. Nicosia: Department of Antiquities.
- Stos-Gale, S.
2000 Trade in Metals in the Bronze Age Mediterranean: An Overview of Lead Isotope Data for Provenance Studies. Pp. 56–69 in *Metals Make the World Go Round*, ed. C. F. E. Pare. Oxford: Oxbow.
- Stos-Gale, Z. A.; Gale, N. H.; Bass, G.; Pulak, C.; Galili, E.; and Sharvit, J.
1998 The Copper and Tin Ingots of the Late Bronze Age Mediterranean: New Scientific Evidence. Pp. 115–26 in *Proceedings of the Fourth International Conference on the Beginning of the Use of Metals and Alloys, May 25–27, 1998, Kunibiki Messe, Shimane, Japan*. Sendai: Japan Institute of Metals.
- Tylecote, R. F.
1976 Properties of Copper Ingots of Late Bronze Age Type. Pp. 157–71 in *Festschrift für Richard Pittioni zum siebzigsten Geburtstag*, Vol. 2: *Industriearchäologie und Metalltechnologie*, eds. H. Mitscha-Märheim, H. Friesinger, and H. Kerchler. *Archaeologia Austriaca*, Beiheft 14. Vienna: Horn.
1982 The Late Bronze Age: Copper and Bronze Metallurgy at Enkomi and Kition. Pp. 81–103 in *Acta of the International Archaeological Symposium "Early Metallurgy in Cyprus, 4000–500 bc"*, eds. J. D. Muhly, R. Maddin, and V. Karageorghis. Nicosia: Pierides Foundation.
- Tylecote, R. F., and Bachmann, H. G.
1990 Metallographic Notes on Some Ingots from the Arabah and Sinai. Pp. 74–77 in *The Ancient Metallurgy of Copper*, ed. B. Rothenberg. Researches in the Arabah 1959–1984 2. London: Institute for Archaeo-Metallurgical Studies.
- Tyler, D. E., and Black, T.
1990 Introduction to Copper and Copper Alloys. Pp. 216–40 in *Metals Handbook*, Vol. 2, ed. L. Tyler. 10th ed. Cleveland: American Society for Metals International.
- Zwicker, U.
1984 Metallographische und analytische Untersuchungen an Proben aus den Grabungen der Bronzegießerei in der Phidias-Werkstatt von Olymp und Versuche zum Schmelzen von Bronze in flachen Tiegeln. *Berliner Beiträge zur Archäometrie* 9: 61–94.
1986 Ancient Metallurgical Methods for Copper Production in Cyprus, Part I: Oxide, Sulphate and Silicate Ore. *Bulletin of the Cyprus Association of Geologists and Mining Engineers* 3: 79–91.
- Zwicker, U.; Virdis, P.; and Ceruti, M. L.
1980 Investigations on Copper Ore, Prehistoric Copper Slag and Copper Ingots from Sardinia. Pp. 135–63 in *Scientific Studies in Early Mining and Extractive Metallurgy*, ed. P. T. Craddock. Occasional Paper 20. London: British Museum.
- Zwicker, U.; Greiner, H.; Hofmann, K.-H.; and Reithinger, M.
1985 Smelting, Refining and Alloying of Copper and Copper Alloys in Crucible Furnaces during Prehistoric up to Roman Time. Pp. 103–15 in *Furnaces and Smelting Technology in Antiquity*, eds. P. T. Craddock and M. J. Hughes. Occasional Paper 48. London: British Museum.