Reply to J.D. Muhly, "Early Bronze Age Tin and the Taurus"

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Abstract

This response to J.D. Muhly's essay (supra pp. 239–53) focuses on a series of key issues that have arisen concerning the chronology, technology, and archaeological context in which prehistoric metallurgy developed.

Additional radiocarbon dates and information on EBA ceramics from soundings in the Kestel mine are presented, which are relevant to the dating of the operations. The tin-bronze industry at Tarsus and the question of "intentionality" in the manufacture of bronze alloys are further discussed. No data exist to support Muhly's contention that gold and iron were produced at Göltepe and Kestel. It is stressed that although particles of cassiterite and tin metal are small, they are dense and characteristically colored, and hence easily identified. Replication experiments in 1992 have suggested a method of producing tin metal compatible with the analyses of the crucibles and coatings.

In an appendix, Lynn Willies discusses the geological nature of tin deposits in general and at Kestel in particular, and considers Muhly's interpretation of the deposits in the Eastern Desert.*

Professor Muhly is to be thanked for devoting serious attention to the question of Early Bronze Age tin, a topic that has so many significant implications. We believe that his commentary and the widespread interest shown by scholars, and by the lay scientific press, all reflect the importance of our findings to the field.[1] We welcome the opportunity to respond to his points, each of which touches on issues that we have considered in depth and have discussed in print. Muhly seems to have overlooked some of the empirical data that we have published in the past and in this issue,[2] but he has also not had access to our new findings from the 1992 season at Göltepe. In this reply we present some new data and discuss the larger question of tin metallurgy and metal exchange in Anatolia. In an appendix, Lynn Willies focuses on local geology and the Kestel mine.

Muhly has often argued for a scheme whereby metallurgy was a "unique" discovery in only one area followed by radial diffusion from the center of origin. Although he applauds the passing of traditional ideas such as stimulus-diffusion and "ex orient lux," he nevertheless insists that the inspiration for metallurgical development came from a single restricted area, such as Troy or Mesopotamia, and then spread outward through "indirect relations" between metal-producing regions.[3] We expect that as intensive research in metal-rich highland regions of the world increases and their sophisticated indigenous metal technologies are documented, Muhly's unilinear, monodimensional reconstruction will be replaced by a more complex model.

"INTENTIONALITY" AND DEFINITION OF BRONZE

One of the most contentious issues in archaeometallurgy has been the definition of "intentionality" in the manufacture of bronze. Muhly dismisses the presence of a local bronze industry in south-central Ana-

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[1] See J.D. Muhly, "Early Bronze Age Tin and the Taurus," in this issue, supra pp. 239–53.

Publications both lay and scholarly have presented our findings: see esp. P. Craddock, "A Short History of Firesetting," *Endeavor* n.s. 16 (1992) 145–50; C. Michel, "Durhumid, son commerce et ses marchands," in D. Charpin and F. Joannes eds., *Marchands, diplomats et empereurs. Études sur la civilisation mésopotamienne offertes à Paul Garelli* (Paris 1991) 253–73; T. Bass, "Land of Bronze," *Discover* 12:10 (1991) 62–66; L.L. Jobe, "Finding the Evidence," *Aramco World* 43:1 (1992) 18–19; C. Holden, "Clues to a Tin Age," *Science* 256 (1992) 1136; and E. Pennisi, "Turkish Tin Mine Revises Bronze Age History," *Science News* 141 (1992) 309.

[2] See bibliography supra p. 208 n. 6, p. 209 n.12, and p. 215 n. 38. See also K.A. Yener and H. Özbal, "The Bolkardağ Mining District Survey of Silver and Lead Metals in Ancient Anatolia," in J.S. Olin and M.J. Blackman eds., *Proceedings of the 24th International Archaeometry Symposium* (Washington, D.C. 1986) 309–20; K.A. Yener, H. Özbal, E. Kaptan, A.N. Pehlivan, and M. Goodway, "Kestel: An Early Bronze Age Source of Tin Ore in the Taurus Mountains, Turkey," *Science* 244 (1989) 200–203; P.B. Vandiver, K.A. Yener, and L. May, "Third Millennium B.C. Tin Processing Debris from Göltepe (Anatolia)," in P.B. Vandiver, J. Druzik, and G.S. Wheeler eds., *Materials Issues in Art and Archaeology* 3 (Pittsburgh, in press) 545–69; and E.V. Sayre, K.A. Yener, and E.C. Joel, reply to "Evaluating Lead Isotope Data: Further Observations," *Archaeometry* (in press).

[3] J.D. Muhly, *Copper and Tin: The Distribution of Mineral Resources and the Nature of the Metals Trade in the Bronze Age* (Hamden, Conn. 1973) 322–23; Muhly, "The Bronze Age Setting," in T.A. Wertime and J.D. Muhly eds., *The Coming of the Age of Iron* (New Haven 1980) 28; and R. Maddin ed., *The Beginning of the Use of Metals and Alloys* (Cambridge, Mass. 1988) 2.

tolia by questioning the tin-copper ratios analyzed in the Early Bronze assemblage from Tarsus. Contrary to our view and those of his collaborators[4] that 1% or more tin content in a bronze is significant, he has concluded that there was no bronze industry at Tarsus. With such a view of the as yet little-known Cilicia, he also discounts the contemporary and nearby Amuq bronzes. Even if one were conservatively to consider 2% tin content in a bronze as the "intentionality" limit, as Muhly suggests, then 12% of the objects from Tarsus should be considered intentional bronzes, and one would have to explain the origin of the added tin. Furthermore, the remaining 12% (of our stated 24%) of objects that "unintentionally" contain 1–2% tin clearly indicate that the ores used in Tarsus are rich in tin and, when smelted, yielded a so-called "natural" tin-bronze.

This evidence of a bronze industry at Tarsus is corroborated by the presence of local tin-rich ores, which we have documented just to the north of Tarsus in the Taurus Mountains. The 24% figure for tin-bronzes at Tarsus is not insignificant either for the amount of tin utilized as an alloying additive or as evidence for the use of local tin-rich ores. Notwithstanding Muhly's arguments in the preceding article, tin-bronzes do occur in a variety of locations in Anatolia from the late Chalcolithic through the third millennium B.C. Their sources as well as the nature of their technology are being investigated. Our analytical program in collaboration with the Turkish Geological Survey carried out over a span of 10 years clearly demonstrates that a number of tin sources in Turkey existed during the formative periods of bronze metallurgy. We are now researching the mosaic pattern of interactions from the highlands to the urban centers utilizing analytical methods such as elemental characterization of metals and the sourcing of ores by lead isotope ratios. Characterization of ceramics and analysis of their clay sources, as well as obsidian sourcing, have illuminated complex networks and exchange patterns operating concurrently with metal trade. The exact nature of the interactions, both of local and interregional exploitation, should become more evident in the near future.

SOURCES OF TIN

Over the years Muhly has suggested a number of areas as the "primal source" of tin. In earlier papers he regarded the source of Near Eastern tin to be in central and southeast Asia and Cornwall.[5] Later he favored Afghanistan over the more remote southeast Asia.[6] Also, and despite evidence to the contrary, he has discounted the Eastern Desert of Egypt, Erzgebirge, Yugoslavia, as well as the other small pockets in the Black Sea sands, Cyprus, and the Troad, which have all yielded tin.[7]

There have also been inconsistencies in his assessment of the Taurus sources. At one time he regarded them as important candidates for a tin source,[8] reluctantly accepting Taurus tin;[9] later he totally rejected their existence,[10] then moved back to acceptance,[11] and finally, in this issue of *AJA*, he turns negative once again. Muhly has also interpreted the metallic nature of the Taurus Kestel mine in several ways. Initially he congratulated us for having discovered the legendary "Silver Mountains" of the Akkadians;[12] later he applauded us for having discovered the oldest gold mine of antiquity.[13] Now he suggests that we may have discovered an ancient iron mine.[14]

These are not matters for conjecture, but empirical data. The ore mined at Kestel *was* tin, as confirmed and published by a number of local and foreign specialists.[15] Muhly's former coauthor and local expert, Ö. Öztunalı, has now abandoned his former reserva-

[4] E. Pernicka, F. Begemann, S. Schmitt-Strecker, and A.P. Grimanis, "On the Composition and Provenance of Metal Artefacts from Poliochni on Lemnos," *OJA* 9 (1990) 272.

[5] Muhly 1973 (supra n. 3) 262–88; Muhly, "Tin Trade Routes of the Bronze Age," *American Scientist* 61 (1973) 409–12.

[6] J.D. Muhly, "Sources of Tin and the Beginnings of Bronze Metallurgy," *AJA* 89 (1985) 281; Muhly, review of R.D. Penhallurick, *Tin in Antiquity*, in *Archeomaterials* 2 (1987) 102.

[7] Muhly 1973 (supra n. 3) 102–103, 277–88, esp. 283.

[8] Muhly 1973 (supra n. 3) 290–91.

[9] Muhly 1973 (supra n. 3) 102.

[10] J.D. Muhly et al., "The Bronze Age Metallurgy of Anatolia and the Question of Local Tin Sources," in E. Pernicka and G. Wagner eds., *Archaeometry '90* (Basel 1991) 209–20.

[11] J.D. Muhly, "Copper in Cyprus: The Earliest Phase," in J.P. Mohen and C. Éluère eds., *Découverte du métal* (Paris 1991) 361.

[12] Muhly et al. (supra n. 10) 212.

[13] J.D. Muhly and E. Pernicka, "Early Trojan Metallurgy and Metals Trade," in J. Herrmann ed., *Heinrich Schliemann. Grundlagen und Ergebnisse moderner Archäologie 100 Jahre nach Schliemann's Tod* (Berlin 1992) 315.

[14] Muhly (supra n. 1) 252.

[15] L. Willies, "An Early Bronze Age Tin Mine in Anatolia, Turkey," *Bulletin of the Peak District Mines Historical Society* 11:2 (1990) 91–96; Willies, "Report on the 1991 Archaeological Survey of Kestel Tin Mine, Turkey," *Bulletin of the Peak District Mines Historical Society* 11:5 (1992) 241–48; Willies, "Reply to Pernicka *et al.*: Comment on the Discussion of Ancient Tin Sources in Anatolia," *JMA* 5 (1992) 99–103; Willies, "Report to Sponsors: Early Bronze Age Kestel Tin Mine in Turkey: 1992 Expedition," *Bulletin of the Peak District Mines Historical Society* (in press); A. Çevikbaş and Ö. Öztunalı, "Ulukışla-Çamardı (Niğde) Havzasının Maden Yatakları [Ore Deposits in the Ulukışla-Çamardı (Niğde) Basin]," *Jeoloji Mühendisliği Dergisi* 39 (1991) 22–40; A.

tions and acknowledges the important tin mineralization at Kestel.[16] Necip Pehlivan of the Turkish Mining and Research Institute (MTA), the geologist who actually discovered the Kestel mine, panned out alluvial cassiterite from the Kuruçay stream running immediately below the mine entrance.[17] Contrary to Muhly's insistence that alluvial cassiterite does not exist at Kestel, hundreds of sand-sized brilliant red cassiterite grains have been easily separated by manual means such as a pan or a vanning shovel, and very little water. Due to its high specific gravity, particles of tin will sediment out from the less dense magnetite, hematite, and quartz. This simple process was replicated a number of times at Celaller in the summer of 1992 by Bryan Earl of Cornwall (see below). As of this writing, we have not been able to penetrate further into the strata in the stream to arrive at the original concentrations of cassiterite available to the miners of antiquity, if those concentrations even still exist, because they are buried in this mountainous area, according to the Turkish Geological Survey, by perhaps as much as 30–40 m of accumulated sediment. Deforestation in the region through the millennia has contributed to the erosion of the slopes, which has produced this overlying sediment. Coring to these levels is thus an important, but costly and labor-intensive, future aim. We would not expect to see the concentrations found in the third millennium B.C. on the surface anywhere today. This is also the case in Cornwall, England. Earl, with Yener present, vanned the formerly tin-rich alluvial deposits in a Cornwall stream and arrived at precisely the same results as at Kuruçay—up to 0.15% tin concentration in the vanned sample.

THE EVIDENCE OF THE GÖLTEPE CRUCIBLES

At one time Muhly was an advocate of archaeometallurgy based on fieldwork and technical analysis. Unfortunately, he has recently relied heavily on theoretical approaches that do not spring from an empirical data base. Our data base consists of over 500 excavated tin-containing crucible fragments from the processing and habitation site of Early Bronze Age Göltepe; we have intensively analyzed 24 of these, i.e., 10% of the 250 excavated in the 1990 field season. Twenty-three of these crucible fragments are typical of the larger sample and one was selected because it was abnormal. There is no gold or silver in the slags or deposited on the crucibles' surfaces, as analyzed by x-ray fluorescence, which has a detection limit of hundredths of a percent over an area 1 cm^2 by 200–300 μ in depth. A trace of copper was found only on the one atypical crucible, but only present in a concentration of hundredths of a percent. Oxidized tin prills are present in the slags. These prills have the needle-like, or acicular, morphology of a molten metal, although they have corroded or oxidized to the oxide, cassiterite. No naturally occurring cassiterite has been found in a glass with this acicular morphology anywhere else. In addition, cassiterite is present as a fine powder with a brownish to purplish and reddish tint on the inner surfaces of many of the crucible fragments. This cassiterite deposit is further evidence of tin processing at an elevated temperature, because of the presence of tin and also for its morphology: the fine, nearly spherical particles in this powder are characteristic of particles produced by condensation from a vapor. We have identified some peaks of tin metal by x-ray diffraction, but there are many other phases present, some of which overlap and so obscure the peaks that identify tin metal. In addition, these other phases are better crystallized and present in far greater amount, and thus detection is extremely difficult. The theoretical argument for the presence of tin metal in the slag is that it is surrounded in glass through which oxygen diffuses very slowly, at about 10^{-23} cm/cm/°C, and thus some of the original metal may remain.

The amount of tin oxide that has been consistently analyzed in the slags by wavelength dispersive microprobe analysis is about 30 wt% average, although some areas contain over 90 wt%. The controversy here is not about tenths of a percent of tin, or about "infinitesimal" amounts, but instead data are presented in which the presence of tin as an element is found by three different and well-established techniques in amounts far beyond the detection limits of the techniques and in 24 individual samples. The

Çağatay and A.N. Pehlivan, "Celaller (Niğde-Çamardı) kalay cevherleşmesinin mineralojisi [Mineralogy of the Celaller (Niğde-Çamardı) Tin Mineralization]," *Jeoloji Mühendisliği Dergisi* 32–33 (1988) 27–31; Craddock (supra n. 1) 145–50; E. Kaptan, "Türkiye Madencilik Tarihine ait Çamardı-Celaller Köyü Yöresindeki Buluntular," *IV. Arkeometri Sonuçları Toplantısı* (Ankara 1989) 1–16; Kaptan, "Türkiye Madencilik Tarihine ait Celaller (Niğde) Yöresindeki Sarıtuzla-Göltepe Buluntuları," *V. Arkeometri Sonuçları Toplantısı* (Ankara 1990) 13–32; Kaptan, "Finds Relating to the History of Metallurgy in Turkey," *MTA Bulletin* 111 (1990) 75–84; and Kaptan, paper delivered at the 14th International Symposium of Excavations, Surveys and Archaeometry, 25–29 May 1992, Ankara.

[16] Çevikbaş and Öztunalı (supra n. 15) 22–40.

[17] Yener et al., "Kestel" (supra n. 2); Çağatay and Pehlivan (supra n. 15) 27–31; and A.N. Pehlivan and T. Alpan, "Niğde Masifi Altın-kalay Cevherleşmesi ve Ağır Mineral Çalışmaları Ön Raporu [Preliminary Report of the Gold-Tin Heavy Mineral Mineralization of the Niğde Massif]," *MTA Report* (Ankara 1986).

other elements that are present as major constituents are iron, calcium, silicon, and aluminum. Although their absolute amounts vary, their proportions are relatively fixed. This indicates either a consistent, raw material composition involving careful selection of ore from the mine or, alternatively, control in sample preparation and processing for the smelting operation. Such consistent ratios argue for a consistent and intentional workshop practice. The variation in the amount of iron oxide may be related to its function as a flux, an agent that aids melting or lowers the temperature at which melting occurs. Iron oxide is found in lesser quantities in examples in which greater segregation has occurred, suggesting a more successful smelt, and in other instances, too much iron oxide is present and segregation is less pronounced, indicating a smelt that has not been as efficient.

The presence and size of the particles of purple to reddish-brown cassiterite in the sediments in the mine and the size of the tin prills in the slags are not relevant issues. One of the purple particles of pure cassiterite is pictured in figure 20 of our article (supra p. 234). A spoonful of sediment from the mine brought back from the first field season contained several different-colored particles that were identified visually. The reddish-purple ones can be easily separated as a concentrate from the black (iron oxides) and white ones (quartz and calcite) by merely swishing them around in a glass with water in it. They can also be separated by winnowing because their densities are so different. Once one learns that purple is the magic color associated with cassiterite, then it is relatively easy to identify where it is concentrated during excavation. Likewise, the crucible fragments look like vegetal fiber-tempered, coarse-ware cookpots, but with a certain brownish residue and black globules or drips on the surfaces. Recognition of their special contents also requires careful observation. Furthermore, in grinding the slags that can be detached from the surfaces of the crucibles, careful observation and separation according to color and density is a key to recognizing the tin. Concentrating fine particles of an especially dense material present as about 30 wt% of a glass requires no great skill or insight. For instance, a bottle of red iron oxide, or hematite, more commonly known as rust, consists of particles that average 0.1 μ, or 0.0001 mm, yet we have no trouble seeing the red color and identifying it as red ocher when the particles are grouped together. In fact, we can identify it as a strong red color when only 10% of the submicron hematite particles are present and mixed with 90% quartz and calcite, and the density difference of hematite is much less than that of cassiterite. The evidence is overwhelmingly positive in its confirmation that tin processing occurred at Göltepe.

REPLICATION EXPERIMENTS

Excavations at Göltepe have so far provided an extensive corpus of artifacts related to tin production. Artifacts from the Kestel slope and the mine galleries corroborate the presence of a tin production industry at Göltepe, with the possibility of functional and diachronic variation. The evidence for tin smelting relies on 1) the enormous quantities of crucible fragments and the analyses of their tin-rich slag, 2) the composition of the local ore body, 3) the presence of workshop floors with activity areas related to tin processing, and 4) the presence of bar-ingot molds. We have constructed a model for tin production at Göltepe based on data generated from the 1990–1992 field seasons, the geological survey, replication experiments, and laboratory analyses of production debris. Our research goal is to narrow the gap between theory and data using fundamental premises of physical and chemical science, which influence the structure of our investigation. Each phase of the production process from mining to finished product is in the process of being identified, its elements defined, and archaeological, metallurgical, and mineralogical implications investigated to characterize the nature of the technology. Since very little information for crucible smelting of tin existed prior to our investigation,[18] our replication experiments in the summer of 1992 helped define hypothetical manufacturing stages using local raw materials and identified the expected archaeological data associated with each stage.

The experiments were conducted in collaboration with Bryan Earl, an eminent mining engineer from Cornwall who specializes in ancient tin technologies. These experiments have demonstrated that smelting required a multistep process to produce tin metal with refining accomplished by washing, density separation, and grinding with lithic tools and subsequent remelting. Corroborating evidence was provided by tin oxide identified by scanning electron microscope on the surfaces of several grinding tools from Early Bronze

[18] See attempts by B. Earl, "Tin Preparation and Smelting," in J. Day and R.F. Tylecote eds., *The Industrial Revolution in Metals* (London 1991) 47–83; Earl, "Melting Tin in the West of England: A Study of an Old Art," *Journal of the Historical Metallurgy Society* 19 (1985) 153–61; and R.D. Penhallurick, *Tin in Antiquity* (London 1986).

Fig. 1. Bryan Earl smelting tin in a crucible, July 1992, Celaller, Turkey. (Photo K.A. Yener)

Age contexts.[19] The smelting process was simple and straightforward and did not require technical sophistication. No fixed installations were needed. A temperature range of ca. 850–1000° C is sufficient and was easily attained with a blowpipe.

The first step in the experiment entailed the identification and selection of the ore charge to be used in the smelt. In the 1990 season at Göltepe, several caches of pulverized ore were discovered that had a fine powdery consistency, and contained 0.3–1.8 wt% tin with a distinct reddish-purplish color. Vessels containing this ore had been excavated in sealed deposits on the floors of Early Bronze II/III pit-houses. This "low grade" 1% cassiterite ore mixture was then enriched to approximately 20% by vanning (panning with a shovel) with a cup of water. The enriched ore was next placed in a "homemade" crucible, using local clay and chaff temper (as described above), and covered by successive layers of charcoal. Smelting of this ore produced slag and tin prills that emerged inside the crucible after 20 minutes of blowing through a blowpipe (fig. 1). This experiment will be published elsewhere in more detail and should ease initial skepticism about the "useful" concentrations of tin in the Taurus and the technological skill required of ancient workers.

The second part of our hypothesis, that smelted tin was subsequently refined in "melting" crucibles and cast into standardized ingots of tin metal, is still being investigated. Production at Göltepe apparently was aimed at the production of ingots: multifaceted molds with impressions for bar-shaped ingots were excavated in pit-house workshops. Although tin-bronze pins, awls, rings, and other fragments containing 4.75–12.3% tin were found in several of the pit-houses, it is more likely that the alloying was carried out elsewhere. The presence of non-local goods such as imported pottery and the lead isotope correlations of Taurus ores with artifacts made of copper-based or silver metal from distant sites confirm exchange with neighboring regions. Given the numbers of grinding stones and crucibles and the amount of other industrial debris, however, in addition to the context of production in pit-house workshops, the quantity of tin being produced at Göltepe and Kestel was significant. Such production reflects a strong demand for

[19] R. Hard, personal communication, August 1992.

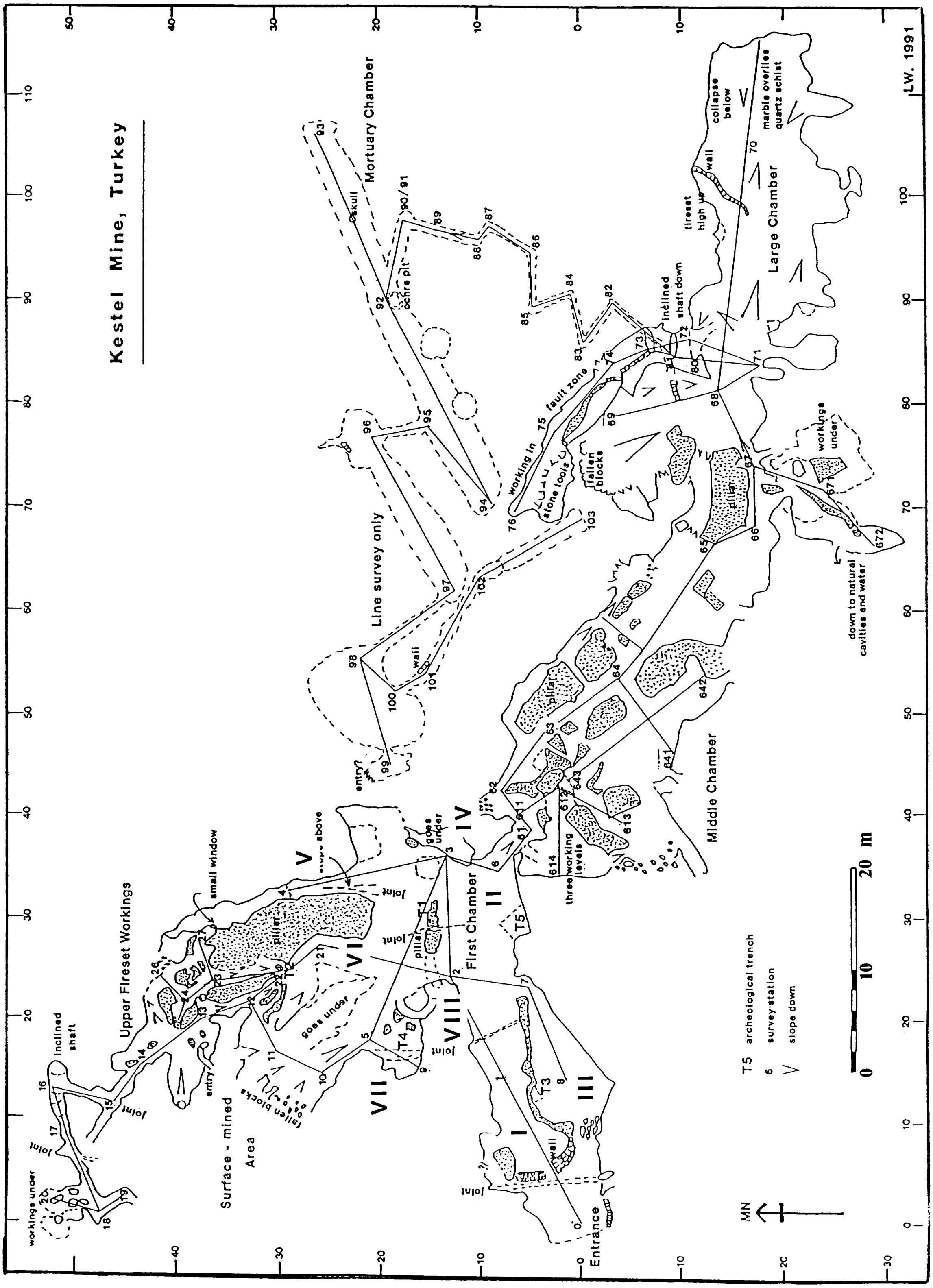

Fig. 2. Map of the Kestel mine, 1991. (Lynn Willies)

tin metal. The extent, direction, and regularity of this interaction are of particular interest, especially with respect to the role tin played in it, and we hope to trace such interactions using trace element and Mossbauer studies of tin.

DATING OF MINING ACTIVITY AND PRESENT RESEARCH STRATEGY

The initial dating of the operations at the Kestel mine relied heavily on radiocarbon dates and stylistic studies of ceramics found in five soundings from 1987 to 1988. New soundings in 1990–1992 by the collaborating mining team led by Lynn Willies expanded our knowledge of the extent of the mine (fig. 2). This material is now being prepared for publication, but a short summary is presented here. The discovery of wares from different periods on the surface of the galleries and divergent extraction techniques suggest that ore may have been removed over several periods and that a chronological sequence of mining might be reconstructible.

In order to test the assumption that cassiterite was the targeted mineral in the Bronze Age, four small (ca. 1 × 2 m) soundings (S1–S4) were initiated inside galleries II, III, VI, and VII. These soundings were not dug stratigraphically, but soil and charcoal samples were collected at arbitrary 10 cm levels for geochemical, mineralogical, and radiocarbon analyses. The assumption was that the detritus of mining activity would yield important information about dating the mine and about the original ore body composition. Sounding S2, measuring 1.0 × 1.5 m, was placed in chamber VI at the confluence of five upsloping galleries some of which measured a scant 60 cm in diameter. These galleries had circular cross-sections and differed morphologically from the larger entrance chambers I and II. Careful study of the stratified assemblage indicated that the debris of mining dates to the Bronze Age. Also supporting this view were the massive layers of rubble with third-millennium ceramics, which were overlaid by thin horizons dating to the Byzantine period but without any associated mining debris. Thus, that there are Byzantine strata in the mine dated by ceramics and radiocarbon (charcoal samples from sounding S2 at −30 cm = A.D. 380 ± 60, calibrated A.D. 347–609, 2 sigmas) does not necessarily indicate that mining took place during these later periods.

The discovery of a large diabase mortar or anvil with two circular hollows on one surface provided information about the specific tools of extraction and beneficiation in this chamber.[20] Other surface finds in chamber VI included a lamp, a diabase pestle, and third-millennium B.C. ceramics. The upper 40 cm of the sounding yielded a mixed deposit of medieval and Early Bronze Age sherds and diabase tools. The EBA sherds are predominantly dark-burnished and unburnished varieties, red-burnished, and micaceous-finished wares. Interestingly, a pink ware similar to one dated to Karum IV levels[21] at Kültepe suggests tantalizing connections to very late third-millennium central Anatolian sites. Below 40 cm, the pottery became more homogeneous with a dark, highly polished EBA ware predominating. Some cruder examples such as a hole-mouth jar and several straw-tempered types also emerged in the lowest strata, suggesting the existence of a Late Chalcolithic phase in this mine as well. It is also possible that the Chalcolithic pottery slid into this gallery from open-pit mining operations situated 50 m upslope. Open-cast mining may have preceded the shaft and gallery systems and the Chalcolithic pottery may have slipped in through the vertical shaft that was dug after the extraction pit operations. A more precise Late Chalcolithic date for this pottery must await study of comparable sequences[22] elsewhere in the Çamardı and Niğde area when they are excavated. A new radiocarbon series from soundings in 1991 and 1992 should expand our knowledge of the range of dates for the various mining operations.

A layer of rubble intermixed with EBA sherds was reached at −60 cm. This basal unit layer of collapse from −60 to −93 cm had a massive character and suggested spoil from mining activity. Only samples below the −40 cm level were utilized for radiocarbon dating and mineral identification. The radiocarbon results on samples of charcoal yielded dates of 2070 ± 80 B.C. (at −68 cm, calibrated 2 sigmas, Struiver and Pearson curves, 2874–2350 B.C.), 2030 ± 100 B.C. (−68 cm, calibrated 2 sigmas = 2870–2200 B.C.), and 1880 ± 65 B.C. (−93 cm, calibrated 2469–2133 B.C.), and suggested that strata between −68 and −93 cm should be dated to the third millennium B.C. Another radiocarbon date comparable to these dates comes from sounding S1 at −60 cm, 1945 ± 70 B.C. (calibrated 2576–2147 B.C.).

[20] Kaptan 1989 (supra n. 15) fig. 3.

[21] A. Özten, private communication: Karum IV, III = ca. 2100–2000 B.C., Middle Chronology. It is interesting to note Muhly's discussion (1973 [supra n. 3] 288–89) of pre-Sargonic texts that specify a tin-mountain called Zar-sur, and a mention of a "mine" that may be tin.

[22] G.D. Summers, "Chalcolithic Pottery from Kabakulak (Niğde) Collected by Ian Todd," *AnatSt* 41 (1991) 125–32.

Sounding S2 has identified several features of this chamber. First, cassiterite was being mined in the third millennium B.C. The technique entailed firesetting, then battering the ore with heavy hammerstones. Mortars, pestles, and bucking stones (stones with one flat surface and a hollow in the middle) indicate that some ore beneficiation was also taking place inside the mine. It is apparent from the stone tool types found inside that hammerstones for battering and pulverizing the ore were being utilized. But, surprisingly, bucking stones indicate that grinding also took place. The debris may have been used as backfill in the mine. The presence of beneficiation in the mine suggests that some fine-scale processing was essential for extraction, and may indicate that veins were small or that testing of the particular area of the deposit by empirical means was necessary and was more efficiently carried out within the mine. It may also be that some tools were stored or discarded within the mine. Therefore, the ore was battered, pecked, and enriched inside the mine. Secondly, the presence of pottery with open forms, the domestic faunal remains, and a hearth suggest a certain minimal amount of domestic activity also took place inside the mine. Larger ceramic forms, presumably to contain water for beneficiation and drinking or foodstuffs, were perhaps used for short-term storage.

The soundings in the mine have provided important information about the tools employed in the technology of Bronze Age mining and ore pulverization as well as an indication that some amount of habitation or shelter probably was provided by the mine. The Kestel excavations have helped define an interactive system between the mine and Göltepe, with its specialized sectors devoted to smelting tin. Tin smelting entailed an initial ore enrichment at Kestel, followed by grinding and washing phases at Göltepe. Fired in crucibles of various sizes, the resulting tin metal was fabricated into ingots by pouring the molten metal into molds. The data from this project have led to the irrefutable conclusion that tin was mined at Kestel and processed at Göltepe in the third millennium B.C. We can now question where the products went and what the impact of this strategic industry was on the bronze producers. In the developing field of archaeometallurgy, Muhly's careful examination of published material in the past has been an inspiration for researchers, including us. But such evaluations require continual testing and support from empirical data. Old ideas die hard, especially when not supported by empirical data.

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Appendix: Early Bronze Age Tin Working at Kestel

LYNN WILLIES

In the controversy over Kestel, my role has been that of a bit-part player, contributing from the sidelines in my own particular specialization of ancient mining.[23] I confine myself here to discussion of the mining aspects of Muhly's intriguing paper in this issue of *AJA*.[24] The controversy over EBA tin working at Kestel over the past few years has had the benefit of leading to a very close examination of almost every statement written on it, but has also led to a variety of claims, some rather frivolous, by several writers. Since Muhly's case fundamentally rests on whether tin was indeed mined at Kestel in the Early Bronze Age, and since he has, by selective quotation, inferred that I am doubtful this was the case, I hope this contribution will clarify matters.

With a small team of experienced workers, I have now been to Kestel for three successive summers, surveying and sampling the mine, with minor archaeological excavation. Interim reports have been published for the first two visits,[25] the second too late for Muhly to have seen prior to his latest commentary. I have to rely on coworkers with specialist skills for pottery examination (Sylvestre Dupré and Behin Aksoy), local geology and geochemistry (Necip Pehlivan and Ergun Kaptan of the MTA), and chemical analysis (Hadi Özbal of Boğaziçi University). Significantly, none of these specialists appear to share Muhly's doubts about Kestel. As yet, only limited accounts of the finds from the mine are published, while the results of radiocarbon dating are also awaited. Never-

23 Acknowledgments are due to the Historical Metallurgy Society and the Peak District Mines Historical Society, and above all the British Academy, which have provided much of the still very limited funding for the field investigations at Kestel.

24 See also Willies 1992, "Reply" (supra n. 15) 99–103.

25 Willies 1990 (supra n. 15) and Willies 1992, "Report" (supra n. 15).

theless, it is possible to give here an outline of mining at Kestel with reasonable confidence.

The 1992 season at Kestel established the earliest mining so far found. An inclined shaft was reopened in a mined joint to give access to an otherwise virtually inaccessible area of workings. This fortuitously went through some 5 m of material tipped into the joint from above, i.e., after the original working, containing a great deal of pottery tentatively dated to ca. 3000 B.C. The shaft gave us access to a long mined chamber reused as a mortuary chamber, which seems from the pottery scatter to have been its purpose throughout the EBA. It was originally sealed off from other mine workings, but was subsequently broken into, possibly during the Byzantine period. The mortuary chamber had been worked by firesetting, which, with stone tools, was the mode of working for most of the mine. Remains of crucibles found in the shaft infilling may indicate that contemporaneous on-site smelting occurred also at Kestel, but firm conclusions must await further examination.

Although there are a few remains of later periods, the rest of the accessible mine workings seem generally to have been used throughout the EBA, then largely abandoned. The age of the large area of openworking at the surface has not yet been ascertained, but it cuts through the earlier underground mine working. A radiocarbon date of a sample from a fire used to heat the rock should provide more definite evidence, but much more work is required.

The survey, since the first report seen by Muhly, has shown the mine and the surface-working area to be substantially larger than originally thought. There is no reason to downgrade earlier estimates of a possible output of a hundred or few hundred tons of tin metal, at 0.1% to 1% tin grades within the whole rock removed.

Samples collected in the second season (1991), designed to test various possibilities, gave very variable results, up to 2315 ppm Sn, which complement samples earlier assayed by Professor Özbal, and of course the much higher grade ore found in small pots at Göltepe. Further sampling took place in 1992. There is no doubt that the mine was capable of producing tin, though it would also have been able to produce vast quantities of iron oxides, and we may even find at some future time that some gold was produced. That all this work was to produce tin is not, in my words, cited by Muhly, self-evident (supra p. 251). It rarely is! This conclusion can only come from the related evidence, in this instance the metallurgical evidence of tin smelting found at Göltepe by Yener and her coworkers, supported by evidence of the practicability of processing a low-grade deposit, and subsequently smelting a concentrate of it.

It would not have been fundamentally difficult to locate the primary tin deposit, once its importance had been realized (very much easier, for instance, than locating silver in low-grade argento-jarosites, as was done in the Late Bronze Age at Rio Tinto in Spain). The exploration method would involve the same simple technique used for gold in streams, and the subsequent search for "shode ore" up hillslopes. Although laborious, the methods used to mine the ore were also simple, using firesetting technology well developed by EBA times, though Kestel is an early example. Processing of the ore was again laborious but simple, very similar to the production of flour, by first bruising the ore, which is very friable after firesetting, followed by a fine-grinding process using a quern. Once ground down to a fine powder it could be concentrated using water either by some refinement of panning, or by pouring thin slurries down sloping surfaces or tables. As has been shown by Bryan Earl, who will issue his own report, it is possible to van tin from the mine, and to concentrate it on the vanning shovel. Crude but effective hand-processing of finely ground, low-grade tin ores containing much hematite was a normal feature of Cornish hand methods in past centuries.

It may not always have been necessary to concentrate the ore beyond a hand-picking stage: samples of ore found at Göltepe with up to 1.5% tin may have been just as they were when derived from the mine. A small sample was smelted by Earl, who is an acknowledged specialist on tin. There is no reason to doubt that some low-grade ore could have been smelted directly, if wastefully in terms of fuel, or it could relatively easily have been concentrated, with some loss of tin.

To conclude the case for tin processing at the Kestel mine: even after intensive exploitation, the mine bears considerable tin, which was largely worked in EBA times, using appropriate methods. There is an enormous stone tool assemblage suitable for crushing and liberating the tin from its matrix. Simple methods were available, used for gold and other minerals, suitable for concentrating the ore. Tin is relatively easy to smelt, and there is an abundance of evidence for the contemporaneous use of crucibles on a nearby site (and on-site too), some of which have been shown to have powdered tin oxide lining their inner surfaces, and which have a slag containing prills of tin now mostly oxidized to cassiterite, which could have resulted from the unwanted hematite being fluxed with locally available quartz.

The case against is not without point, but in the theoretical manner posed, it is as readily answered. It seems to be appropriate to use an old miner's saying here about the location of ore, "where it is, there it is"—in other words, it does not necessarily relate to human expectation or convenience. It does not occur at Kestel in the large pieces found elsewhere by Muhly and others (not today anyway), but he fails to show alternative sites with such large pieces that also have evidence of ancient mining. Indeed the difficulty of finding ancient tin ore sites is the underlying thread of this controversy, and obviously is a good reason for working low grades of ore in discovered deposits. In my experience of ancient mines, low-grade ore was frequently worked—compare for instance the very extensive workings at Wadi Amram[26] near Timna—for low-grade copper ore, a metal that is infinitely more plentiful than tin, and found in much higher concentrations elsewhere. Muhly raises the question of lack of evidence for the treatment of the "(hypothetical) rich ores that were all mined out during the Early Bronze Age" (supra p. 247). This in the context of his pebble-sized samples from renewable deposits (?) is *his* rather than *my* hypothesis, but I would remark that processing of high grades is not normally considered a major problem if low ones can be tackled.

Finally, I need to warn the readers of this journal not to part with good money to practical prospector Jim Muhly without a full professional examination of what might be called the prospectus for Egyptian Tin Properties, Inc. His prospectus bears all the hallmarks of selling dubious mine-stock! Consider. Exotic, faraway place (just dots on a small-scale map, no site plan); actual massive veins of cassiterite mineralization; area not previously exploited; and necessary only to walk up the bed of a dry wadi to collect several kilograms of cassiterite. Nothing could be simpler: a self-renewing source of alluvial cassiterite, easily recoverable raw material that assays at 80% tin. Plus photographs of a few formless pebbles we are asked to believe are pure cassiterite (I do really believe they are), and associated with a description of a well-known cassiterite deposit where the ore came up to the tree roots (though not on the same lode—not even on the same continent!). All published in a respected journal whose readers are known to be interested in tin mining, but who do not have professional expertise in mineral exploitation. A classic trap.

Let me add a touch of cynicism. What happens when the first few inches of wadi have been worked? Do we wait a millennium for the deposit to build up again? Perhaps the deposits or the cracks in the base of the wadi are deep—and might repay open-working by pick and shovel. Assume "Muhly and Partners" had picked up all the cassiterite they could find—he says a few kilograms, so let us call it 10 kg for convenience, in the top 10 cm of the deposit. No plan is provided, but let us assume an average width of 10 m, and a sampling length of 200 m—a pleasant walk in the hot conditions.Thus to extract his next 10 kg will entail the removal of some 500 tons of host material, and a grade of some 2% ore, or 1.6% metal in the whole rock. Still pretty good, but we can expect the promoters of such a prospectus to have chosen the best section they could, and this "proven" grade of ore might not continue far: all other grades would at best be unproven. Very soon of course, even such easily obtained ore as this would run out, and the company will need to consider mining the veins. Here the grade is likely to be lower, since it has not been processed by weathering, but the reserves are likely to be very much greater. Demand for the metal is greater than ever.

So far, of course, there has been no mention of transport facilities, timber supply, food-growing potential, population, water supply—but in the middle of the Eastern Desert? Examined in these terms, perhaps Kestel appears a more realistic prospect. We should certainly be suspicious of the viability of any easily visible, previously unworked, deposit in the ancient civilized world.

A great deal of Prof. Muhly's commentary is a useful and perceptive summary of the situation, but despite the impressive backing of the references he cites, his whole argument concerning Kestel (and much else) relies on publications of interim results—intended to allow others to share and cooperate in the work in progress. That there was EBA working of tin at Kestel is now beyond reasonable doubt. In the remaining part of the "heroic age of archaeometallurgy," Timna is taking some three decades to bring to published fruition. In more words from old miners, "When you find tail, hang on until you find t'cow." At Kestel and Göltepe the tail has been identified; defining the whole cow will take some time yet.

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[26] L. Willies, "Ancient Mining at Wadi Amram, Israel," *Bulletin of the Peak District Mines Historical Society* 11:3 (1991) 109–38.