Tin Processing at Göltepe, an Early Bronze Age Site in Anatolia

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Abstract

This paper presents the archaeological contexts and results of analyses of slags, surface residues, and earthenware refractories from the third-millennium B.C. site of Göltepe in south-central Turkey. These materials are only part of a workshop/habitation assemblage at the site, which also includes ore nodules, multifaceted molds, and metal fragments as well as groundstone tools utilized in ore dressing and beneficiation. Twenty-four ceramic fragments of bowl-shaped crucibles were analyzed as a representative sample from some 250 examples excavated in the 1990 season. Analysis suggests the intentional production of tin metal by reduction firing of tin oxide (cassiterite, SnO_2) in crucibles. Tin oxide was identified on the interior surfaces of the crucible fragments by x-ray fluorescence, x-ray diffraction, scanning electron microscopy coupled with energy dispersive x-ray analysis, and wavelength dispersive microprobe analysis. The results of these tests have a direct bearing on the question of tin sources in ancient Anatolia.*

INTRODUCTION

The history of metal technology, as well as early craft specialization in the formative periods of metallurgy, has recently been afforded a renewed interest.[1] This is evident from the extensive application of modern techniques of materials science to excavated metals and metal production residues. In addition to intensive microscale artifact analyses, the organizational strategies of metal industries at archaeological sites are being scrutinized as well.[2] These investiga-

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The following abbreviations are used:

Early History	R.F. Tylecote, *The Early History of Metallurgy in Europe* (London 1987).
Iron	T.A. Wertime and J.D. Muhly eds., *The Coming of the Age of Iron* (New Haven 1980).
"Kestel"	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.
Kuantitatif	U. Esin, *Kuantitatif spektral Analiz yardımıyla Anadolu'da Başlangıcından Asur Kolonileri Çağına kadar Bakır ve Tunç Madenciliği* 1 (Istanbul 1969).
Muhly	J.D. Muhly, "The Bronze Age Setting," in *Iron* 25–67.
Search	A.D. Franklin, J.S. Olin, and T.A. Wertime eds., *The Search for Ancient Tin* (Washington, D.C. 1978).
Tarsus	H. Goldman, *Excavations at Gözlü Kule, Tarsus* II: *From the Neolithic through the Bronze Age* (Princeton 1956).

[1] P. Craddock, "The Scientific Investigation of Early Mining and Smelting," in J. Henderson ed., *Scientific Analysis in Archaeology and Its Interpretation* (Oxford 1989) 178–212; R. Maddin ed., *The Beginning of the Use of Metals and Alloys* (Cambridge, Mass. 1988); M. Goodway and P. Vandiver, "Metal and Frit Processing: Analysis of Ceramic Crucible Residues," in J.S. Crawford ed., *The Byzantine Shops at Sardis* (Cambridge, Mass. 1990) 129–34.

[2] M. Tosi, "The Notion of Craft Specialization and Its Representation in the Archaeological Record of Early States in the Turanian Basin," in M. Spriggs ed., *Marxist Perspectives in Archaeology* (Cambridge 1984) 22–52; K. Kristiansen,

tions aim to delineate and understand changes in production strategy and its socioeconomic consequences through time.

The Anatolian Early Bronze Age is characterized by dramatic technological, political, and economic changes on both regional and interregional scales. Several developments in metallurgy are evident in the late fourth and throughout the third millennium B.C. The production of metal ornaments and trinkets characteristic of Neolithic and early Chalcolithic assemblages changes with the appearance of larger, more functional, technologically superior tools and weapons.[3] Of the 233 copper-based artifacts examined at Stuttgart from this period in Anatolia, 69% contain significant amounts of arsenic or tin.[4] By 2000 B.C., the Middle Bronze Age, metallurgical practice was no longer at the level of a small local craft, but approached the efficiency and scale of an established industry, with mastery of the arts of smelting, melting, annealing, forging, working sheet metals and alloying, refining gold and silver by cupellation of lead, and the use of iron.[5] A dramatic economic threshold was also breached in the variety, quality, and quantity of metals manufactured, as well as in the variety of sources exploited.[6]

Although arsenical copper continued to be used in the third millennium, tin-bronze gained precedence.[7] On the basis of archaeological evidence, the process appears to be "a long, irregular transition from preponderant use of arsenic to preponderant use of tin, perhaps dependent upon the gradual introduction of improvements in refining techniques."[8] The early alloyed coppers from Anatolia contain tin; whether or not intentionally added as metallic tin or cassiterite mineral, some form of the element was involved in their production. Some of the earliest tin-bronzes in Anatolia come from the Amuq area near the southern coast and date to the late fourth/early third millennium. A pin and an awl with 7.79% and 10% tin, respectively, and fragments of slag (with 5% tin content) found in crucibles were excavated from Judeidah level G.[9] Other early examples of tin-bronzes occur at Early Bronze I Kusura A, where several pins and needles show alloying with tin, while from Kusura B, analyses indicate that four out of 18 artifacts sampled from mid-third millennium levels have 4.8–6.7% tin.[10] By the mid-third millennium, relatively good tin-bronzes are found in most areas of Anatolia. Early Bronze II levels at Tarsus have revealed copper-based artifacts of which 24% are tin-bronzes, and good tin-

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"From Stone to Bronze: The Evolution of Social Complexity in Northern Europe, 2300–1200 B.C.," in E. Brumfiel and T.K. Earle eds., *Specialization, Exchange and Complex Societies* (Cambridge 1987) 30–51; R.K. Evans, "Early Craft Specialization: An Example from the Balkan Chalcolithic," in C.L. Redman et al. eds., *Social Archaeology: Beyond Subsistence and Dating* (New York 1978) 113–29; A.B. Knapp, *Copper Production and Divine Protection: Archaeology, Ideology and Social Complexity on Bronze Age Cyprus* (*SIMA-PB* 42, Göteborg 1986); M. Tosi, "The Distribution of Industrial Debris on the Surface of Tappeh Hesar as an Indication of Activity Areas," in R.H. Dyson and S.M. Howard eds., *Tappeh Hesar: Reports of the Restudy Project, 1976* (Florence 1989) 13–24; V.C. Pigott, "Archaeo-Metallurgical Investigations at Bronze Age Tappeh Hesar, 1976," in Dyson and Howard eds. (supra) 25–34.

[3] D.B. Stronach, "The Development and Diffusion of Metal Types in Early Bronze Age Anatolia," *AnatSt* 7 (1957) 30–125; D.L. Heskel, "A Model for the Adoption of Metallurgy in the Ancient Middle East," *CurrAnthr* 24 (1983) 362–66.

[4] See analyses in *Kuantitatif* and also D.L. Heskel, "Early Bronze Age Anatolian Metal Objects: A Comparison of Two Techniques for Utilizing Spectrographic Analyses," *Annali. Istituto Oriente di Napoli* 40 (1980) 473–502.

[5] R. Maxwell-Hyslop, *Western Asiatic Jewellery, c. 3000–612 B.C.* (London 1971); *Search*; K. Prag, "Silver in the Levant in the Fourth Millennium B.C.," in P.R.S. Moorey and P. Parr eds., *Archaeology in the Levant. Essays for Kathleen Kenyon* (Warminster 1978) 36–45; J. Yakar, "Regional and Local Schools of Metalwork in Early Bronze Age Anatolia, Part I," *AnatSt* 34 (1984) 59–86; Yakar, "Regional and Local Schools of Metalwork in Early Bronze Age Anatolia, Part II," *AnatSt* 35 (1985) 25–38; P.S. de Jesus, *The Development of Prehistoric Mining and Metallurgy in Anatolia* (*BAR-IS* 74, Oxford 1980); and *Iron*.

[6] K.A. Yener, E.V. Sayre, E.C. Joel, H. Özbal, I.L. Barnes, and R.H. Brill, "Stable Lead Isotope Studies of Central Taurus Ore Sources and Related Artifacts from Eastern Mediterranean Chalcolithic and Bronze Age Sites," *JAS* 18 (1991) 541–77; E.V. Sayre, K.A. Yener, E.C. Joel, and I.L. Barnes, "Statistical Evaluation of the Presently Accumulated Lead Isotope Data from Anatolia and Surrounding Regions," *Archaeometry* 34 (1992) 73–105.

[7] J.A. Charles, "Determinative Mineralogy and the Origins of Metallurgy," in P.T. Craddock and M.J. Hughes eds., *Furnaces and Smelting Technology in Antiquity* (London 1985); P.T. Craddock, "Three Thousand Years of Copper Alloys: From the Bronze Age to the Industrial Revolution," in P.A. England and L. van Zelst eds., *Application of Science in Examination of Works of Art* (Boston 1985) 59–67.

[8] R. McC. Adams, review of M.T. Larsen, *The Old Assyrian City-State and Its Colonies* in *JNES* 37 (1978) 268.

[9] R.J. Braidwood and L. Braidwood, *Excavations in the Plain of Antioch* I: *The Earlier Assemblages, Phases A–J* (Chicago 1960) 300–15, dated approximately 3200–3000 B.C.; R.J. Braidwood, J.E. Burke, and N.H. Nachtrieb, "Ancient Syrian Coppers and Bronzes," *Journal of Chemical Education* 28 (1951) 87–96.

[10] W. Lamb, "Excavations at Kusura near Afyon Karahisar," *Archaeologia* 86 (1936) 1–64; *Kuantitatif* 136; Z.A. Stós-Gale, N.H. Gale, and G.R. Gilmore, "Early Bronze Age Trojan Metal Sources and Anatolians in the Cyclades," *OJA* 3 (1984) 26. The authors have reanalyzed Anatolian Early Bronze tin-bronzes sampled by Esin and have noted that these early analyses "underestimate the quantity of tin present by factors varying from 1.2 to 2.5."

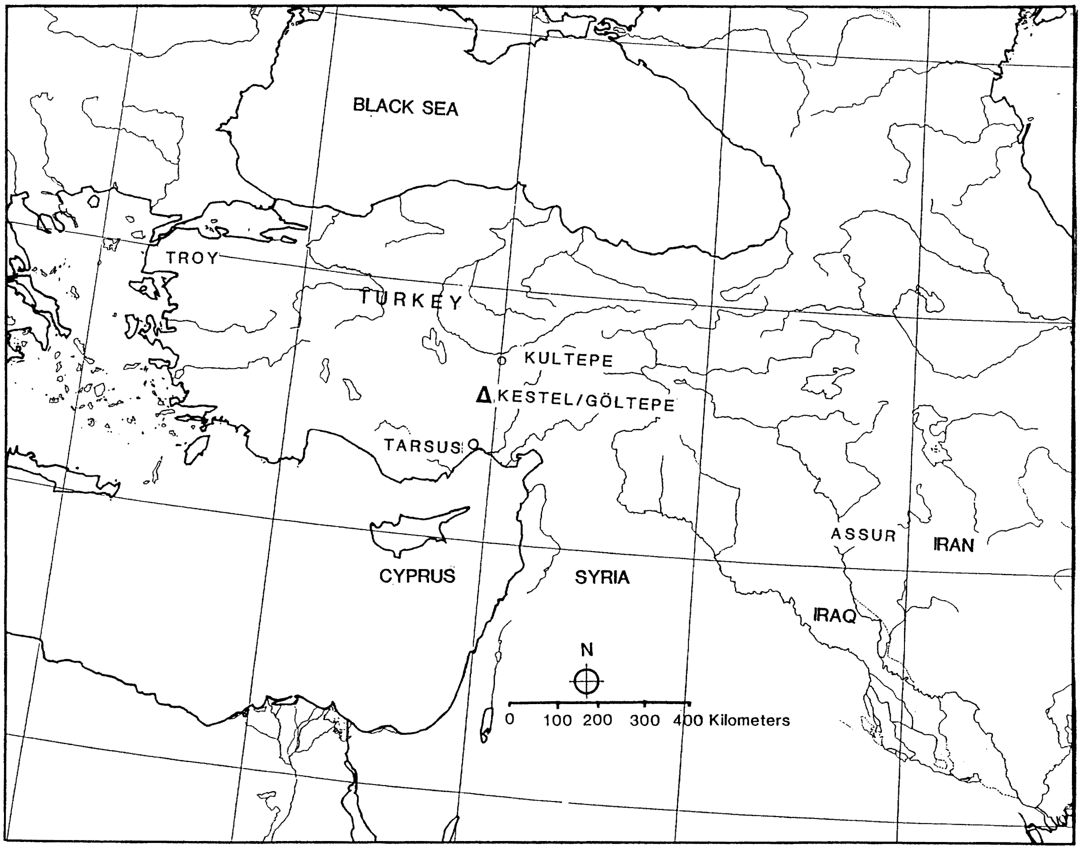

Fig. 1. Map of the eastern Mediterranean showing location of Göltepe and the Kestel mine

bronzes are present at Early Bronze III Tarsus as well.[11] These EB III bronzes have up to 6% tin. There are also high-grade tin-bronzes from the coeval phases H and I in the Amuq.

In order to contribute to the reconstruction of the regional dynamics of a particular metal supply zone and its metal industry, the specialized-function site of Göltepe and its contemporary tin mine, Kestel, were chosen for investigation in 1990. The sites span the earliest inception of tin-bronze use in southwest Asia, the late Chalcolithic and Early Bronze Ages (3200–2000 B.C.). Both Göltepe and Kestel are located in the central Taurus mountain range, 4 km west of Çamardı, Niğde province, and 80 km north of Tarsus, in Turkey. The sites are strategically situated along the north–south Ecemiş fault zone, providing access both to central Anatolia and to the Cilician plains and Mediterranean coast to the south (fig. 1). A combined program was undertaken in this area, integrating the results of excavations and regional studies with a technical study of the material evidence.[12] The relevance of these investigations is demonstrated by the connec-

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[11] *Kuantitatif* 131–33.

[12] See "Kestel"; Yener et al. (supra n. 6); Sayre et al. (supra n. 6); E.V. Sayre, K.A. Yener, and E.C. Joel, "Reply" to "Evaluating Lead Isotope Data: Comments on E.V. Sayre, K.A. Yener, E.C. Joel, and I.L. Barnes, 'Statistical Evaluation of the Presently Accumulated Lead Isotope Data from Anatolia and Surrounding Regions'," *Archaeometry* 34 (1992) 330–36; K.A. Yener and H. Özbal, "Tin in the Turkish Taurus Mountains: The Bolkardağ Mining District," *Antiquity* 61 (1987) 220–26; K.A. Yener, H. Özbal, A. Minzoni-Deroche, and B. Aksoy, "Bolkardağ: Archaeometallurgy Surveys in the Taurus Mountains, Turkey," *NatGeogRes* 5:4 (1989) 477–94; K.A. Yener, "Niğde-Çamardı'nda Kalay Buluntuları," *IV. Arkeometri Sonuçları Toplantısı* (Ankara 1989) 17–28; K.A. Yener, "Arkeometri Projesi: Çamardı 1988 Çalışmaları," *V. Arkeometri Sonuçları Toplantısı* (Ankara 1990) 1–12; E. Kaptan, "Türkiye Madencilik Tarihine ait Celaller (Niğde) Yöresindeki Sarıtuzla-Göltepe Buluntuları [Finds Relating to Mining Found at Celaller (Niğde), Sarıtuzla-Göltepe]," *V. Arkeometri Sonuçları Toplantısı* (Ankara 1990) 13–32; Kaptan, "Türkiye Madencilik Tarihine ait Çamardı-Celaller Köyü Yöresindeki Buluntular [Finds Relating to Mining History at Çamardı-Celaller Village]," *IV. Arkeometri Sonuçları Toplantısı* (Ankara 1989) 1–16. K.A. Yener, "Archaeological Survey in a Metal-rich Region: An Early Bronze Age Example from Çamardı, Niğde, Turkey," in preparation.

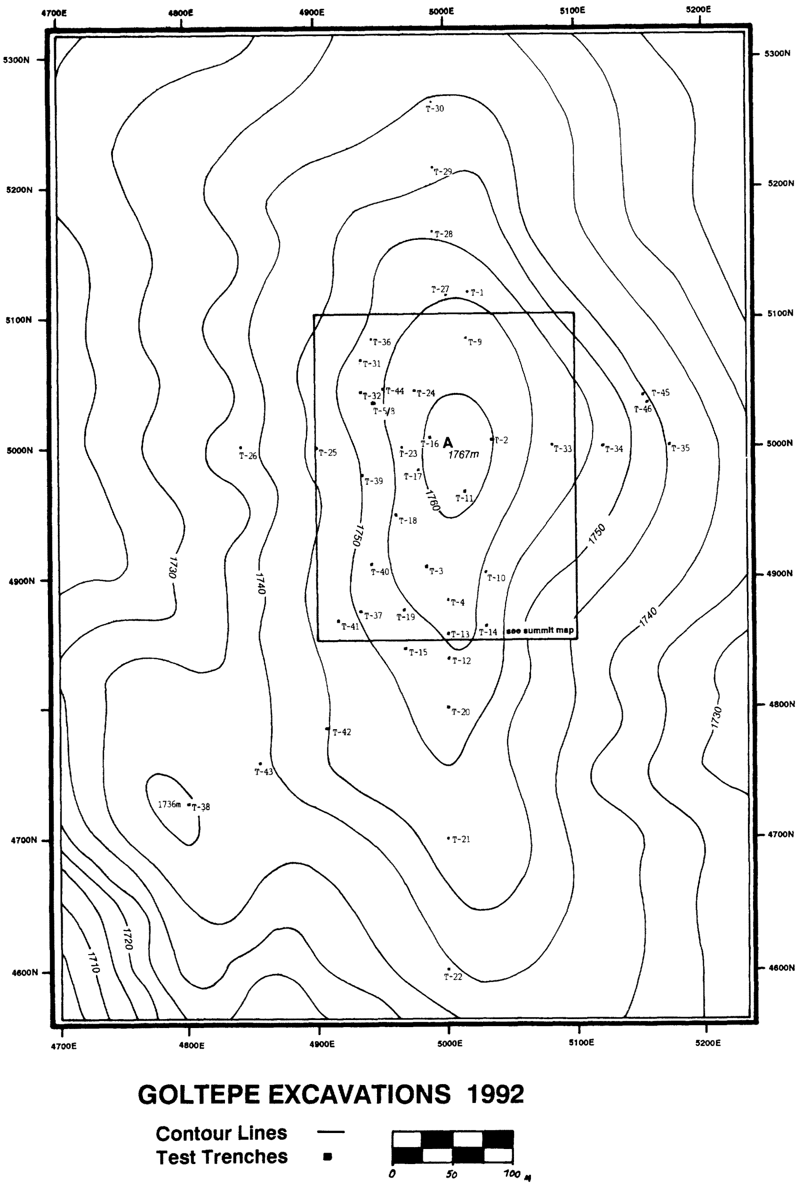

Fig. 2. Göltepe 1992 site plan. (Drawing T. Chadderdon and C. Ott)

tions of the central Taurus mines with sites yielding early tin-bronzes. The sourcing of metal artifacts to these multimetallic mines was accomplished through an extensive lead isotope characterization program at the Conservation Analytical Laboratory of the Smithsonian Institution. The preliminary results have suggested that the central Taurus metal sources were being utilized in the Chalcolithic period by sites such as Tarsus, Tell Judeidah, and Hassek Höyük. In the subsequent Early Bronze Age, Troy, Tarsus, Aššur, Khafajeh, Tell Asmar, Tell Leilan, Tell al-Raqā'i, Tell Selenkahiyeh, Hamam et-Turkman, Kurban Höyük, Tepecik, and Tarsus may also have utilized metals from these highland sources. The main conclusions drawn from this program have led to a much more unambiguous interpretation of metal industries than has hitherto been possible. Glimpses can now be caught of the ingenious ways that tin and other metals were manipulated and manufactured, as well as the role the industry and their trade played in the increasingly complex societies of the Early Bronze Age. The extensive deposits of copper, iron, silver, and gold, in addition to the presence of alloying materials, all formed the materials for an incipient industrial revolution that subtly altered the way the environment was manipulated and in turn provided the backdrop for a number of other changes in Anatolian institutional systems.

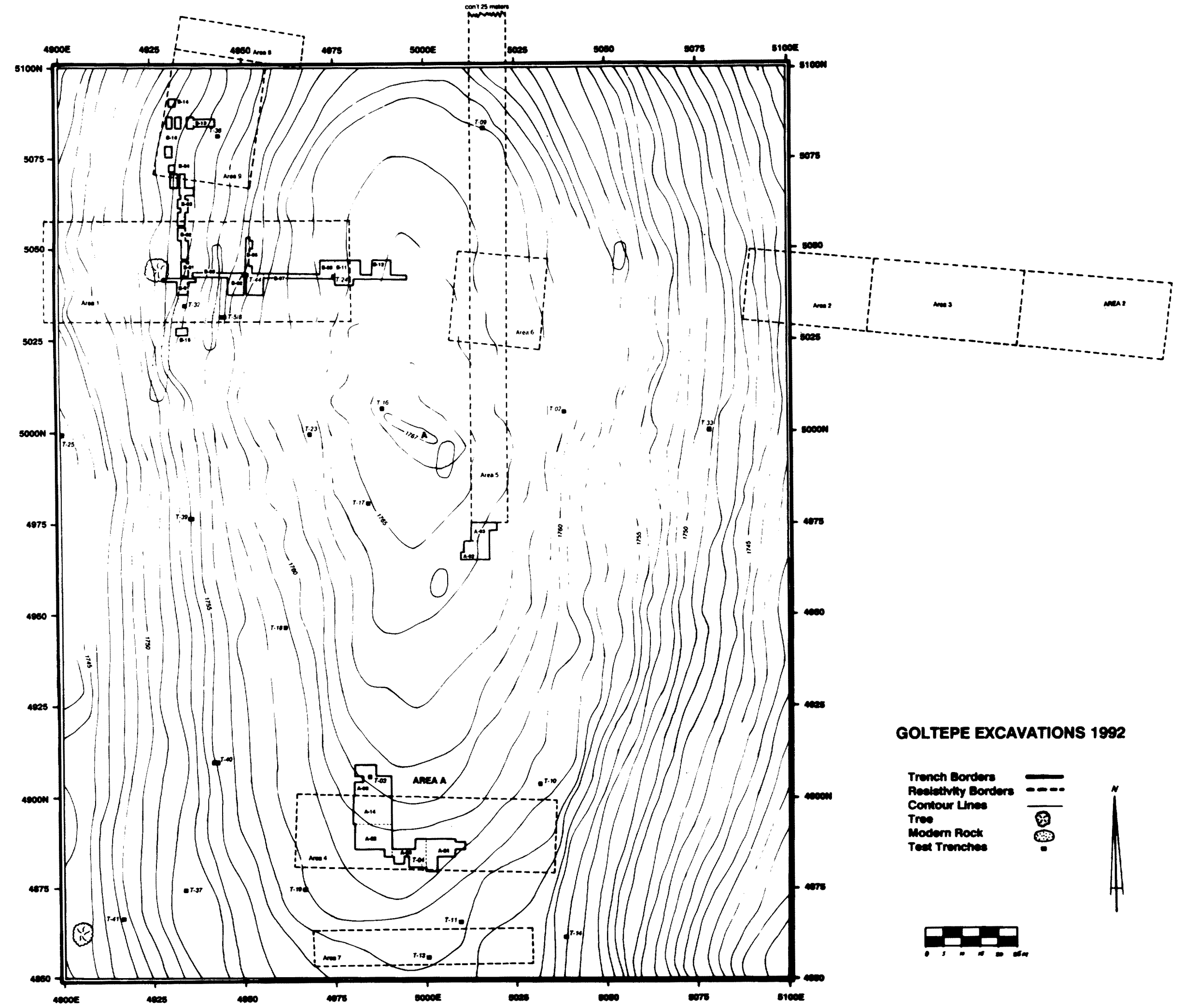

Fig. 3. Detail of Göltepe 1992 site plan. (Drawing T. Chadderdon and C. Ott)

Excavations at Göltepe (figs. 2–3) and Kestel are critical in shedding light on the earliest development of high technology, i.e., the use of tin for bronze manufacture, and the relationships of this development to the socioeconomic and political role of this region as a highland resource zone for the major complex societies of Anatolia, Syria, the Aegean, and Mesopotamia. The analysis of materials from these sites documents the strategies of a metal industry and the innovative trajectories in the industry during the crucial period of early state formation in Anatolia, the third millennium B.C. In so doing, the impact of an innovative technology in this resource zone on the major civilizations of the eastern Mediterranean, during periods when bronze first appears in the archaeological records of these areas, will become apparent. The strategic importance of a tin source is manifest. Understanding the effects of the demand for tin on the producers of what became a critical and valuable commodity is the emphasis of this research into the production of tin metal.

A detailed report on excavations at Göltepe will be published elsewhere. This paper presents the findplaces and analyses of 24 ceramic fragments thought to represent crucibles (see below); the fragments are a representative sample of approximately 250 found during the 1990 excavation season at Göltepe. These fragments come from sealed deposits inside subterranean rooms in several areas of the site as well as from dump contexts at the foot of a circuit wall (or terrace wall). Elemental identification of tin in the earthenware fragments was initially identified by Yener who carried out x-ray fluorescence and scanning electron microscopy (SEM) coupled with energy dispersive x-ray analysis (EDS). Vandiver subsequently expanded the analysis with additional SEM analyses, x-ray diffraction, and wavelength dispersive microprobe analysis.

THE PROBLEM OF TIN SOURCES

The earthenware fragments with tin slag accretions from the site of Göltepe provide important data with which we can address several questions, including the sources of tin in the Near East and the method of producing tin metal for the alloying of bronze. The possibility also arises of addressing questions pertaining to the factors that influenced and the elements that constituted the formation of craft specialization in a metalliferous zone containing a source of tin. The existence of tin, one of the most important components of the "high-tech" industry of its age (bronze), surely affected the socioeconomic structure of the producer highland societies in the Taurus during peak periods of demand, or conversely in periods of stagnation. Despite the importance not only economically but certainly strategically of tin, sources for the metal immediately accessible to the eastern Mediterranean have until recently remained unknown.

Most of the evidence about tin sources derives from early second-millennium B.C. cuneiform texts found at the major trading center of Kültepe (ancient Kanesh). These tablets written in Old Assyrian by merchants mostly living in Anatolia document a highly complex commercial network revolving around the export of silver and gold to Aššur and the import to Anatolia of textiles and *annaku*. This term has generally been translated as tin, but recent reassessments suggest that at times it may have meant alloying metal.[13] Although the source of the *annaku* is never stated in the texts, several cities are mentioned, such as Susa in Iran, which suggested a source to the east of Aššur. Strict interpretation of these tablets has prejudiced scholars from accepting the possibility of other sources. The articulation of this trade by the foreign merchants and the muteness of the local Anatolians about their own activities have added to this biased view. Nevertheless, tantalizing glimpses can be caught in these texts of a local, often troublesome intra-Anatolian trade over which the merchants had no control even during this period of intense colonization and economic pressure. There is no doubt that a strong local trading system existed in copper, iron, Anatolian textiles, and other commodities. Attempts to monopolize local textile trade, restrict iron trade, and penalize smuggling and tax evasion are often the topics documented in the cuneiform tablets. It is important not to lose perspective of intra-Anatolian commodity networks, while postulating the appearance of exotic items from long distances. It is neither surprising nor distressing that *annaku* was being traded to certain Anatolian cities despite the existence of local tin. The quantities of tin in the Kestel mine in the second millennium may not have been sufficient to supply the increasing demands for this alloying material. Moreover, a restricted, more localized exploitation pattern may have prevailed. Enterprising Assyrian merchants could have been operating within a separate network, bringing in tin from an eastern source, perhaps Afghanistan, while Kestel or even other sources were supplying other regions. It would not be surprising to find such a mosaic of interregional connections and commercial sophistication during this highly entrepreneurial period.

The desire to identify one exclusive source exacerbates the problem of tin sources. Irrespective of the tendency in the literature to search for a single "primal source" that supplied the entire ancient Near East, it is proposed here that the sources of tin were numerous. Our thesis differs from earlier interpretations of tin sourcing and arises from differing underlying assumptions about the magnitude of tin deposits significant in antiquity. Small pockets of tin are still to be found today even after 5,000 years of exploitation (see below). To be sure, even though some of the ancient sources played a larger role in provisioning urban polities than others, the data indicate the functioning of several contiguous metal exploitation and exchange systems, which fluctuated through time and space.[14] The results of recent lead isotope analyses suggest a pattern of resource procurement reflective of wide networks of interaction operating concurrently with the exploitation of local metal deposits near the settlements. It is now evident

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[13] M.T. Larsen, *Old Assyrian Caravan Procedures* (Leiden 1967). *Annaku* has been variously translated as tin or lead. B. Landsburger, "Tin and Lead: The Adventures of Two Vocables," *JNES* 24 (1965) 285–96 argued that it meant lead. Although several scholars have argued persuasively that the exclusive meaning had to be tin, a recent reassessment based on a thorough comparison of tin and copper prices in bronzes from cuneiform documents now suggests that *annaku* may not always have meant tin. The price of the parts are more expensive than the whole; see M. Powell, "Identification and Interpretation of Long Term Price Fluctuations in Babylon: More on the History of Money in Mesopotamia," *Altorientalische Forschungen* 17 (1990) 76–99. For recent assessments of the Colony materials see T. Özgüç, "New Observations on the Relationship of Kültepe with Southeast Anatolia and North Syria during the Third Millennium B.C.," in J.V. Canby, E. Porada, B.S. Ridgway, and T. Stech eds., *Ancient Anatolia: Aspects of Change and Cultural Development* (Madison 1986) 31–47; M.T. Larsen, "Commercial Networks in the Ancient Near East," in M. Rowlands, M.T. Larsen, and K. Kristiansen eds., *Centre and Periphery in the Ancient World* (Cambridge 1987) 47–56.

[14] Yener et al. (supra n. 6) and Sayre et al. (supra n.6).

that localized use and small-scale exploitation of a number of tin sources in what geologists today call "ma and pa" operations coexisted with and perhaps supplied larger, interregional trade networks.

Modern and ancient sources of tin today exist in Erzgebirge in central Europe as well as in Afghanistan, Southeast Asia, Africa, and Central Asia.[15] Several authors in the past have noted the assays of tin said to exist in the early 20th century in various locations in Turkey.[16] Several attempts were made by U.S. researchers in the 1970s to collect samples from sites in Iran and Turkey where tin was reported.[17] But these limited surveys, which often lasted only a short time, failed to find evidence for tin deposits. Even in ore samples taken by the Turkish Geological Survey (MTA) for their regular field programs of analysis, much too often tin was not even analyzed; thus the "absence" of tin was merely due to the lack of comprehensive analytical programs addressed specifically to the sourcing of heavy minerals, including tin. The initial, unsuccessful excursions into these highly metalliferous zones, with or without local geological aid, only furthered the mystique of the "missing source of tin."

Modern assays have substantiated high trace levels of tin in Yugoslavia,[18] and up to 1% in the Black Sea sands.[19] Bursa Handere-Madenbelenitepe,[20] close to Troy, has close to 1% stannite, while 0.27% was tested and found in the stanniferous gossans of the copper deposits of Ergani Maden in eastern Turkey.[21] Even the native coppers of Cyprus have high trace levels of tin.[22] An Egyptian source of tin in the Eastern Desert[23] is another important location often dismissed,[24] despite the presence (although rare) of tin-bronzes from third-millennium B.C. contexts in Egypt. Intensive, well-equipped archaeometallurgical and geological surveys and improved sampling techniques are clearly needed to evaluate more correctly the concentrations of tin accessible to exploitation in the past. This review provides fairly compelling grounds for arguing that tin was more abundant than was previously believed.

The most recent findings of tin, which were located as a result of a series of intensive archaeometallurgical surveys in Turkey, were discovered first in the Sulucadere region of Bolkardağ (Taurus Mountains) in 1985.[25] Alluvial cassiterite (SnO_2, tin oxide) was subsequently identified in the streams of the Niğde Massif area about 40 km to the north.[26] The Kestel tin mine was discovered in 1987 above the cassiterite-bearing Kuruçay stream, and contains two primary mineralizing episodes, an earlier tin-bearing episode and a later hematite one with weak tin. Despite the earlier

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[15] Muhly; *Search*; T. Stech and V.C. Pigott, "The Metals Trade in Southwest Asia in the Third Millennium B.C.," *Iraq* 48 (1986) 39–64; S. Cleuziou and T. Berthoud, "Early Tin in the Near East," *Expedition* 24 (1982) 14–19; J.D. Muhly, "Sources of Tin and the Beginnings of Bronze Metallurgy," *AJA* 89 (1985) 275–91; R.D. Penhallurick, *Tin in Antiquity: Its Mining and Trade throughout the Ancient World with Particular Reference to Cornwall* (London 1986); J.D. Muhly, review of Penhallurick, *Tin in Antiquity*, in *Archeomaterials* 2 (1987) 99–107.

[16] S. Przeworski, *Die Metallindustrie Anatoliens in der Zeit von 1500–700 vor Chr.* (Leiden 1939) 138–55; C.W. Ryan, *A Guide to the Known Minerals of Turkey* (Ankara 1960); *Kuantitatif*; E. Kaptan, "The Significance of Tin in Turkish Mining History and Its Origin," *MTA Bulletin* 95/96 (1983) 164–72; and de Jesus (supra n. 5). See also a recent attempt in the Sakarya region: H.-G. Bachmann and K.L. Weiner, "Zinnvorkommen im Sakaryatal?" in M. Korfmann ed., *Demircihüyük: Die Ergebnisse der Ausgrabungen 1975–1978* II: *Naturwissenschaftliche Untersuchungen* (Mainz 1987) 37–40.

[17] T.A. Wertime, "A Metallurgical Expedition through the Persian Desert," in J.R. Caldwell ed., *Investigations at Tal-i Iblis* (Springfield, Ill. 1967) 327–39; T.A. Wertime, "The Beginnings of Metallurgy: A New Look," *Science* 182 (1973) 875–87; and *Iron*.

[18] P. Glumac, *The Advent of Prehistoric Metallurgy in Southeast Europe* (Diss. Berkeley 1991); V. McGeehan-Liritzis and J.W. Taylor, "Yugoslavian Tin Deposits and the Early Bronze Age Industries of the Aegean Region," *OJA* 6 (1987) 287–300.

[19] R.F. Tylecote, "Iron Sands from the Black Sea," *AnatSt* 31 (1981) 137–39.

[20] A. Çağatay, B. Arman, and Y. Altun, "Madenbelenitepe (Soğukpınar-Keles-Bursa) stannitinin incelenmesi," *Jeoloji Mühendisliği Dergisi* [*Geological Engineering*] 13 (1982) 23–26. This is a stannite (tin pyrite Cu_2FeSnS_4) occurrence located in the Bursa area in northwestern Turkey.

[21] R.F. Tylecote, "Chalcolithic Metallurgy in the Eastern Mediterranean," in J. Reade ed., *Chalcolithic Cyprus and Western Asia* (London 1981) 41–52.

[22] G. Rapp, Jr., "Native Copper and the Beginning of Smelting: Chemical Studies," in J.D. Muhly, R. Maddin, and V. Karageorghis eds., *Early Metallurgy in Cyprus, 4000–500 B.C.* (Nicosia 1982) 34. In fact, four out of 366 native copper samples from Cyprus contained significant amounts of tin. One sample was even 0.74% tin.

[23] M.F. El Ramly et al., "Tin-Tungsten Mineralisation in the Eastern Desert of Egypt," in O. Moharram et al. eds., *Studies on Some Mineral Deposits of Egypt* (Cairo 1970) 43–52.

[24] Muhly 31 states that no evidence exists of pre-second millennium use of the desert source. This statement is based on a limited surface survey.

[25] Yener and Özbal (supra n. 12); Yener et al. (supra n. 12); A. Çağatay, Y. Altun, and B. Arman, "Bolkardağ Sulucadere (Ulukışla-Niğde) kalay içerikli Çinko-kurşun cevherleşmesinin minerolojisi [Mineralogy of the Tin-Bearing Bolkardağ Sulucadere (Ulukışa-Niğde) Lead-Zinc Mineralization]," *Türkiye Jeoloji Bülteni* [*Geological Bulletin of Turkey*] 32 (1989) 15–20. The source described here is a high trace level of stannite (3400 ppm) in a sphalerite/galena ore.

[26] "Kestel"; A. 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.

efforts to locate tin in Anatolia, the reserves remaining from mining tin in antiquity were discovered only as a result of the analysis of hundreds of ore and slag samples, often obtained from steep slopes and high altitudes, such as a 1,740 masl source of stannite-rich galenas at Bolkardağ. Establishing the presence of alluvial cassiterite in the Niğde Massif by the Turkish Geological Survey involved sifting through 80 tons of alluvial stream sediments in the central Taurus in the course of a five-year research project investigating the sources of heavy minerals.[27]

In order to pinpoint the sources of tin exploitable in antiquity, it is first necessary to think not in terms of millions of tons of reserves necessary for modern extractive technologies, but in terms of very much smaller deposits, as Lechtman realized in her research on ancient Peruvian metallurgy.[28] Furthermore, even low levels of tin are, according to Cornish tin miners, significant. Recently in Cornwall a stream deposit holding 0.2% tin ore (even less cassiterite than at Kestel) was considered workable by the "tin streamers."[29] There also "1% cassiterite was valued as an ore worked by 'lode mining.' These ores from both stream deposits and underground lode mining were dressed to about 65% tin metal ready for smelting."[30]

The Niğde Massif tin mineralization extends over a large area[31] and alluvial stream deposits of cassiterite are found in three rivers in this volcanic dome formation. Vanning (panning with a shovel) in the local stream beds below the mine site by sampling units was conducted by Bryan Earl of Cornwall as well as by the Turkish Geological Survey. Both found alluvial cassiterite present in sufficient percentages to consider it a feasible source in antiquity. The Kestel tin mine is a complex of multichambered galleries, now thought to be mined out, located on the Sarıtuzla slope near Celaller village, Çamardı, Niğde. Preliminary work was conducted at the mine in 1987 and 1988, where five 1 m × 2 m^2 soundings for dating and sampling purposes were initiated inside the galleries and at a workshop adjacent to the entrance. In addition to establishing cassiterite in the detritus of mining, the dating of these archaeological deposits was achieved by pottery and radiocarbon from charcoal.[32] Early Bronze Age red-black burnished, micaceous, and clinky wares, as well as charcoal, bones, and groundstone tools, were recorded from inside and outside the mine. Architectural debris emerged from the workshop sounding. The ceramics, some from sounding contexts in the mine and workshop area, were dated to the late Chalcolithic through Byzantine periods. As understood at present, the Kestel mine was first exploited around 3000 B.C., probably for open pit mining.[33] In early EB I/II, the mine was expanded into shaft and gallery systems, and workshops were set up outside the mine entrance. Göltepe reached its fluorescence in the EB II/III period. Comparable ceramics, groundstone tools, and other materials from Göltepe and Kestel demonstrate interaction between the two sites.

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[27] 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); Çağatay and Pehlivan (supra n. 26); C. Göncüoğlu, "Niğde Masifi Batı Yarısının Jeolojisi [The Geology of the Western Niğde Massif]," *MTA Report* 7856 (Ankara 1985). Earlier reports can be found in P.H. van der Kleyn, "Recommendation of Exploration for Mineralizations in the Southwestern Part of the Niğde-Çamardı Massif," *MTA Report* 4345 (Ankara 1972).

[28] Personal communication; see also H. Lechtman, "A Metallurgical Site Survey in the Peruvian Andes," *JFA* 3 (1976) 1–41.

[29] Bryan Earl, personal communication, January 1990; B. Earl, "Tin Preparation and Smelting," in J. Day and R.F. Tylecote eds., *The Industrial Revolution in Metals* (London 1991) 42.

[30] Bryan Earl, personal communication, January 1990.

[31] Çağatay and Pehlivan (supra n. 26). This article summarizes the extensive MTA report by Pehlivan and Alpan (supra n. 27). The authors report the geochemical and mineralogical results of 1,150 stream sediment samples taken from the Niğde Massif. Concentrations of alluvial cassiterite were reported in significant amounts from the streams near the villages of Celaller, Eynelli, and Kılavuz in an area encompassing 30 km^2. The results of this research and others (see now 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) that followed have now prompted the definition of these deposits as an important tin mineralization.

[32] See "Kestel." Carbon-14 dates from the Kestel mine were supplied by Teledyne Isotopes and the University of Arizona Mass Spectrometer: AA-3373, 1570 ± 60 B.P., A.D. 380 ± 60 (calibrated A.D. 347–609); AA-3374, 4020 ± 80 B.P., 2070 ± 80 B.C. (calibrated 2874–2350 B.C.); AA-3375, 3895 ± 70 B.P., 1945 ± 70 B.C. (calibrated 2576–2147 B.C.); and AA-3376, 3830 ± 65 B.P., 1880 ± 65 B.C. (calibrated 2469–2133 B.C.). Calibrations to 2 sigmas using the tree-ring curve of M. Stuiver and G.W. Pearson, "High Precision Calibration of Radiocarbon Time Scale, A.D. 1950–500 B.C.," *Radiocarbon* 28 (1986) 806–38.

[33] Yener (supra n. 12) all references. See also L. Willies, "Reply to Pernicka *et al.*: Comment on the Discussion of Ancient Tin Sources in Anatolia," *JMA* 5 (1992) 99–103.

Table 1. Göltepe Radiocarbon Dates and Excavation Loci

Main Registry Number (MRN), Findplace, Beta-Analytic Number	Sample Description	^{14}C Dates B.P.	B.C. (Libby)	Calibrated B.C.
MRN 391 A06-0100-011 Beta 42649	Charcoal from hearth 011 in subterranean pit-house in area A06	5240 ± 250	3290 ± 250	4350–3780
MRN 296 B01-0126-001 Beta 42648 ETH 7669 AMS	Charcoal from crucible dump at circuit wall in area B01	4120 ± 60	2170 ± 60	2875–2587
MRN 1400 A24-0343-006 Beta 42650	Charcoal from burnt debris on floor of pit-house 6 in area A24	4070 ± 70	2120 ± 70	2865–2498
MRN 1785 A23-0100-007 Beta 42651	Charcoal from burnt debris 20 cm above floor of pit-house 3 in area A23	3790 ± 80	1840 ± 80	2451–2050

Calibrations to one sigma (68%)

The tin in the Kestel mine is not obvious, and one may assume that only the subeconomic material remained unextracted by the miners of antiquity. Willies reports that a working presumption might be that an ancient cutoff grade of around 1% is reasonable for the mine and notes that the cassiterite ore has been extracted from disseminations within marble and quartz schist and not from the poor-value, tin-bearing hematite veins.[34] Those veins inside the mine were recently analyzed by atomic absorption analysis and, despite their poor quality, were found to contain over 1.5% tin, while 1% tin was found in the sample analyzed in England.[35] Willies notes that a "rough estimate of rock mined underground, and the much greater quantity at the surface, suggests some few hundreds of tonnes of tin concentrate could have been produced, making the mine an important contributor, possibly over some hundreds of years, to the Mediterranean production of tin-bronze."[36]

Skepticism about the usefulness of Turkish tin sources has been based on the original report of 0.6% concentrations of tin in the Kestel mine and on the results of an independent study that failed to find sites and tin resources.[37] Such skepticism should now be dismissed in light of more recent assays of the ore, and we hope also by the evidence presented below of the vitrified fragments from the workshop habitation site of Göltepe, located opposite the Kestel mine. The conclusions drawn by Muhly and his colleagues were based on their sampling techniques,[38] which appear to us to have been inadequate, and on samples taken without our knowledge or advice. Understandably, defining the original extent and quality of ore in an abandoned mine is difficult. A comparable example

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[34] Willies (supra n. 33).

[35] Hadi Özbal and Bryan Earl, personal communications, April and January 1991, respectively.

[36] L. Willies, "An Early Bronze Age Tin Mine in Anatolia, Turkey," *Bulletin of the Peak District Mines Historical Society* 11:2 (1990) 94. See also L. Willies, "Report on the 1991 Archaeological Survey of Kestel Tin Mine, Turkey," *Bulletin of the Peak Mining District Historical Society* 11:5 (1992) 241–48. Willies estimates close to 5,000 tons of tin ore to have been extracted from the Kestel mine from only one cavity. The mine complex has now been discovered to be 1.5 km long after the 1991 season, making this an important source of tin; see Willies (supra n. 33).

[37] J.D. Muhly, F. Begemann, Ö. Öztunalı, E. Pernicka, S. Schmitt-Strecker, and G.A. Wagner, "The Bronze Metallurgy of Anatolia and the Question of Local Tin Sources," in E. Pernicka and G. Wagner eds., *Archaeometry '90* (Basel 1991) 209–20; M.E. Hall and S.R. Steadman, "Tin and Anatolia: Another Look," *JMA* 4 (1991) 217–34.

[38] See K.A. Yener and M. Goodway, "Response to Mark E. Hall and Sharon R. Steadman, 'Tin and Anatolia: Another Look'," *JMA* 5 (1992) 77–90; E. Pernicka, G.A. Wagner, J.D. Muhly, and Ö. Öztunalı, "Comment on the Discussion of Ancient Tin Sources in Anatolia," *JMA* 5 (1992) 91–98; and L. Willies (supra n. 33).

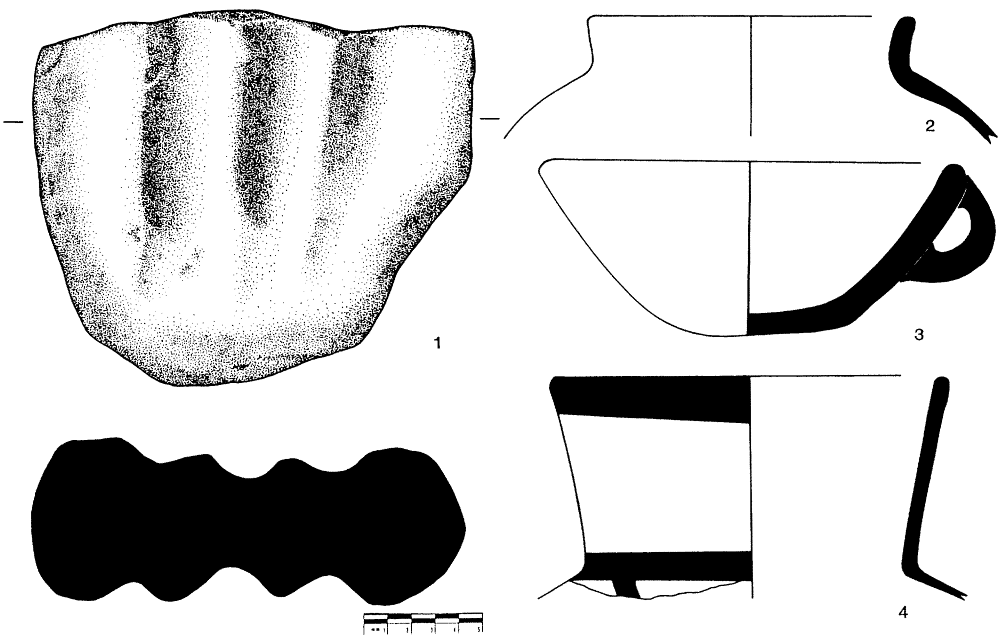

Fig. 4. Artifacts from 1990 soundings, Göltepe: 1) stone mold, possibly for ingots; 2) red/black burnished ware jar; 3) red/black burnished ware cup; and 4) clinky ware jar. (Drawings C. Ott and L. Kane)

would be an attempt to establish the richness of the original gold veins of the 1849 Gold Rush by sampling the abandoned gold mines of California. To address this problem an investigation was initiated by Yener with a combined American and Turkish team in 1990. In addition to examining the nature and magnitude of the Kestel tin source, potential industrial debris was sought and found nearby at Göltepe. Moreover, excavations at Göltepe in 1990 and 1991 provided ceramic fragments with tin-rich glassy residues in EB II/III levels.

CRUCIBLES AT GÖLTEPE AND THEIR CONTEXTS

Göltepe is located 2 km away from the Kestel tin mine on top of a large battleship-shaped natural hill. The site is situated at the juncture of active plates and consequently mineralization is abundant in the area. Shales and graywackes, a flysch deposit of Upper/Middle Palaeocene date, constitute the hilltop of Göltepe. Cultural deposition spreads across 65 ha and the site is walled at the summit.[39] Surface survey found multifaceted molds, slag, ore, and an estimated 50,000 groundstone tools for ore dressing on the site surface. A second geological subdivision, of diabase/gabbro, the source of the ore dressing stones, is situated 2 km from both sites. The third zone, the Kestel tin mine, located on a slope that is pervaded with granite, marble, gneiss, and quartzite, is geologically distinct. The relief is not particularly severe in this zone as it is in the alpine Bolkardağ area, the source of the stannite occurrence, 40 km to the south, or the Aladağ range, which is the source of silver, gold, iron, lead, and copper mines 10 km to the east.[40]

In total, 44 1-m^2 test pits (T1–T44) and four larger trenches (areas A02/A03, A06, A23/A24, B01) were opened during the 1990 excavation season (fig. 2). The principal objectives were to reconstruct 1) tin metal production processes and craft specialization; 2) the spatial distribution of these activities and the scale of the production at individual processing loci; 3) the context within which the various steps in the production processes occurred; and 4) the diachronic change of these processes.

Dating fragments identified as crucibles at Göltepe relies on two major sets of data, radiocarbon dates (see table 1) and associated ceramics found in excavated contexts. The pottery from Göltepe (fig. 4:2–4) has important parallels to that from the Cilician coast and the Aegean, as well as central Anatolia, Syria, and Mesopotamia, allowing a relative dating of the associated crucible fragments. The two most prevalent wares are dark red and black burnished ware (and an

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[39] The actual lateral extent of the site will be based on the ongoing analyses of the 1991 excavation units.

[40] Yener et al. (supra n. 12).

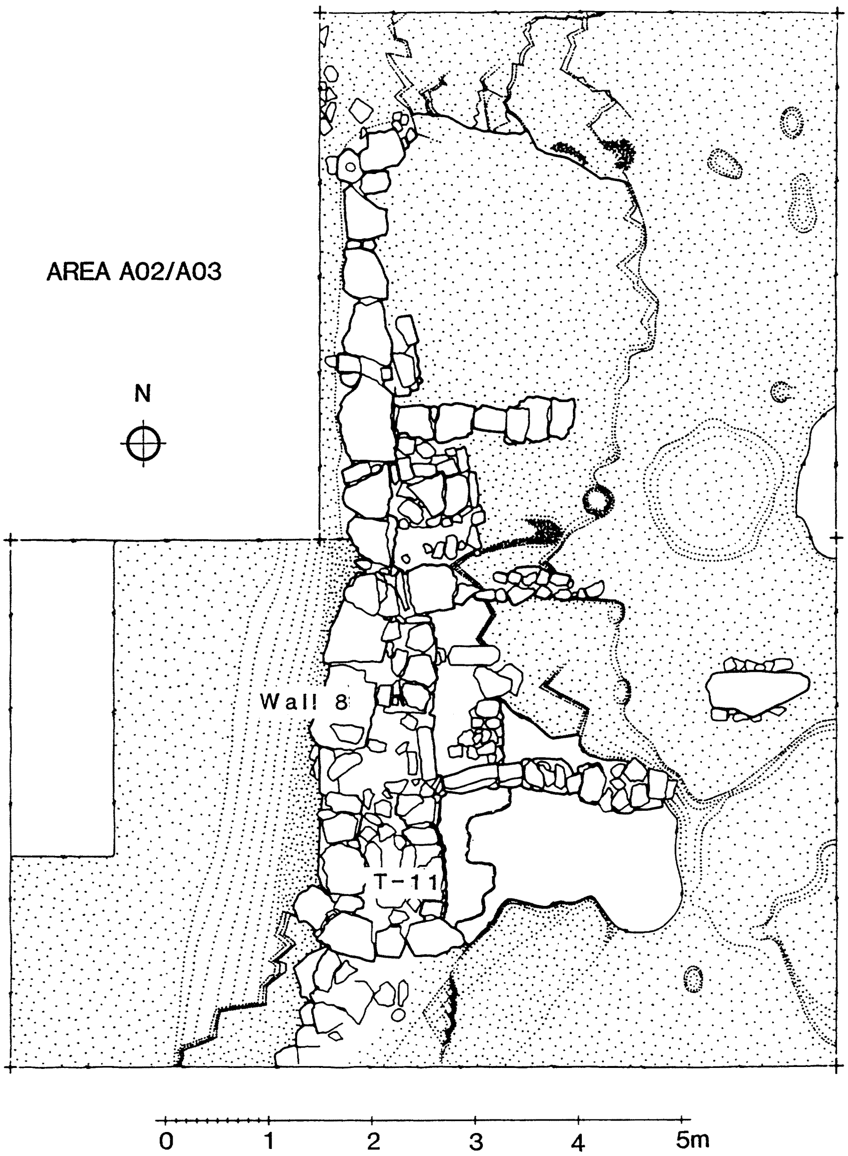

Fig. 5. Plan of Göltepe area A02/A03. (Drawing J. Knudstad)

unburnished variant) and clinky ware.[41] The clinky, or Anatolian "metallic," ware comes in small cups, jars, and bowls and is a fine, handmade ceramic. Clinky ware is found in both painted (fig. 4:4) and unpainted variants; the paint is mostly brown, or almost purple in color. The pottery is hard-fired, giving a metallic, clinky ring. This ware is referred to as "light clay miniature lug ware" at Tarsus and may also be related to the red gritty wares at that site.[42] Tarsus, located directly south along the Mediterranean coast, over the Taurus Mountains, provides the best parallels for this ware in contexts dated mainly to the Early Bronze II period. Another example of this clinky ware, now in the Ashmolean Museum, is said to come from "Bulgar Maden" (Bolkardağ).[43] Mellink[44] describes this pottery as an import to Tarsus

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[41] This ware is distributed widely in the Niğde and Konya regions as well as the central Taurus range. It is also called "metallic ware"; see J. Mellaart, "Preliminary Report of a Survey of Pre-Classical Remains in Southern Turkey," *AnatSt* 4 (1954) 191–94, 209; M. Seton-Williams, "Cilician Survey," *AnatSt* 4 (1954) 121–74.

[42] For "light clay miniature lug ware," see *Tarsus* fig. 247; "red gritty ware" 108–109.

[43] *Tarsus* 107.

[44] M.J. Mellink, "Anatolian and Foreign Relations of Tarsus," in K. Emre et al. eds., *Anatolia and the Ancient Near East: Studies in Honor of Tahsin Özgüç* (Ankara 1989) 322.

Table 2. Description of the Göltepe Crucibles and Findplaces

Sample Number	Findplace	Fragment	Measurements (cm) Dia.	Ht.	Th.	Slab Fabrics (Exterior/Interior)	Slag
1	MRN 325, circuit wall B01-0107/ 17-003	rim	—	10.0	3.0	coarse, grit and straw, light red/fine clay, dense	dark and light glassy accretion
2	MRN 325, circuit wall B01-0107/ 17-003	rim	—	5.0	1.5	coarse, grit and straw, light red	light gray, glassy spots
3	MRN 325, circuit wall B01-0107/ 17-003	rim	—	4.0	2.5	coarse, grit and straw, light red	pitted, light gray, splotchy
4	MRN 325, circuit wall B01-0107/ 17-003	rim	30.0	7.0	3.0	coarse, grit and straw, light red, brown	light gray to black
5	MRN 325, circuit wall B01-0107/ 17-003	rim	30.0–40.0	6.0	2.5	coarse, grit and straw	gray, glassy
6	MRN 325, circuit wall B01-0107/ 17-003	rim	25.0	7.0	3.0	coarse, grit and straw/fine clay, dense	splotchy, gray, glassy
7	MRN 325, circuit wall B01-0107/ 17-003	body	—	7.0	1.0	coarse, grit and straw, overfired	gray
8	MRN 325, circuit wall B01-0107/ 17-003	body	—	7.0	3.0	coarse, grit, overfired	light gray
9	MRN 325, circuit wall B01-0107/ 17-003	rim	—	5.0	1.5	coarse, grit and straw/fine clay, dense	light gray, splotchy
10	MRN 325, circuit wall B01-0107/ 17-003	rim	—	7.0	3.0	coarse, grit and straw/ pitted	porous, gray, rough
11	MRN 325, circuit wall B01-0107/ 17-003	body	—	5.0	2.5	coarse, grit and straw	gray, glassy
12	MRN 325, circuit wall B01-0107/ 17-003	rim? cover?	—	5.0	2.3	fine, clay, dense	light gray and white, splotchy

from the Taurus Mountains and adjoining plateau and suggests connections with the metal sources. This ware is indeed widely distributed in the Niğde and Konya plains as well as the central Taurus range.[45] Examples were also excavated at the Sarıkaya Palace soundings at Acemhöyük from levels X–VIII, which are dated to the Early Bronze II and III,[46] and at the related, contemporary sites of Kültepe[47] and Karahöyük level VII in the Konya plain.[48]

The dark-burnished wares come in a highly polished red and black as well as a related unburnished variant. Tempered with fine grit and some chaff, the

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[45] Yener, in prep. (supra n. 12); A. Özten, "A Group of Early Bronze Age Pottery from the Konya and Niğde Region," in Emre et al. eds. (supra n. 44).

[46] Examples excavated at the Sarıkaya Palace soundings at Acemhöyük from levels X–VIII are dated by Özten (supra n. 45) 409 on the basis of parallels with alabaster idols from Kültepe levels 12 and 13 (EB III), and alabastron-shaped Syrian bottles similar to examples from Amuq F–J as well as sites in Syria; see, e.g., H. Kühne, *Die Keramik von Tell Chuera und ihre Beziehungen zu Funden aus Syrien-Palästina, der Türkei und dem Iraq* (Berlin 1976) 64–65.

[47] Özgüç (supra n. 13) 38–39, figs. 3–21.

[48] S. Alp, *Zylinder- und Stempelsiegel aus Karahöyük bei Konya* (Ankara 1968) 304, pl. 10.19.

Table 2. (continued)

Sample Number	Findplace	Fragment	Measurements (cm)			Slab Fabrics (Exterior/Interior)	Slag
			Dia.	Ht.	Th.		
13	MRN 325, circuit wall B01-0107/17-003	rim	—	5.5	2.5	coarse, grit and straw, blowholes/fine clay, dense	smooth, light gray
14	MRN 325, circuit wall B01-0107/17-003	rim	—	6.0	2.4	coarse, grit and straw	gray
15	MRN 325, circuit wall B01-0107/17-003	rim	—	5.4	2.3	coarse, grit and straw	light gray spots
16	MRN 536, circuit wall B01-0300-003	body	—	6.0	3.0	coarse, grit and straw/fine clay, dense	glassy
17	MRN 347, circuit wall B01-0257/97-006	rim	17.0	7.5	2.0	coarse, grit	gray
18	MRN 872, T-11 A02-0100-001	furnace lining or pit lining	—	8.0	2.0	light, porous, bisquity sand-tempered	light gray with yellow powder coating
19	MRN 1401, Cell A06-0100-011 hearth	body	—	5.0	3.0	coarse, grit	gray
20	MRN 1359, Area A24-0300-001	body	—	—	—	coarse, grit and straw	gray
21	MRN 409, A06-0100-004, fill in cell A06	rim	25.0	9.0	3.5	coarse, grit/fine clay, dense	gray
22	MRN 38, A24-0100-001	body	25.0	6.0	1.0	Granular, sandy brown, six 1-mm thin strips	—
23	surface, Ç131989	rim	12.0	7.0	0.5	Fine clay, dense (reused red clinky ware?)	glassy, splotchy, globules, accretions
24	MRN 409, A06-0100-004, fill in cell A06	rim	30.0–40.0	5.0	1.3–1.5	Friable, orange-brown clay, alternating light and dark brown layers	no slag (fine-grained material on surface)

pottery is handmade and is often slipped. Simple bowls and single-handled cups are among the predominant shapes. The closest parallels for this pottery are the plain black-burnished[49] and red-burnished types[50] from EB I and II Tarsus.

The findplace for a number of ceramic fragments identified as crucibles is a multicelled structure (area A02/A03) unearthed on the summit with a substantial north–south wall (wall 8), preserved to three courses, and constructed from irregularly shaped blocks of local stones (fig. 5). The wall foundations were accommodated in the bedrock by trenching, perhaps quarrying the same stones from the trench for the wall. Tumbled stones east of wall 8 rested on compact surfaces, varying in thickness from 40 to 50 cm, and probably represent wall collapse. A number of large crucible fragments, many ore-processing groundstones, baked clay objects with relief decoration, ore nodules, rectangular clay objects,[51] obsidian tools, and sherds were found both in the trench fill and some-

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[49] *Tarsus* 100–101, fig. 239.73–74; fig. 349.310.

[50] *Tarsus* 96, fig. 241.92–96.

[51] H. Schliemann, *Ilios. The City and Country of the Trojans* (New York 1881, repr. ed. 1968) 559; C.W. Blegen, L. Caskey, and P. Rawson, *Troy* II: *The Third, Fourth and Fifth Settlements* (Princeton 1951) fig. 53.

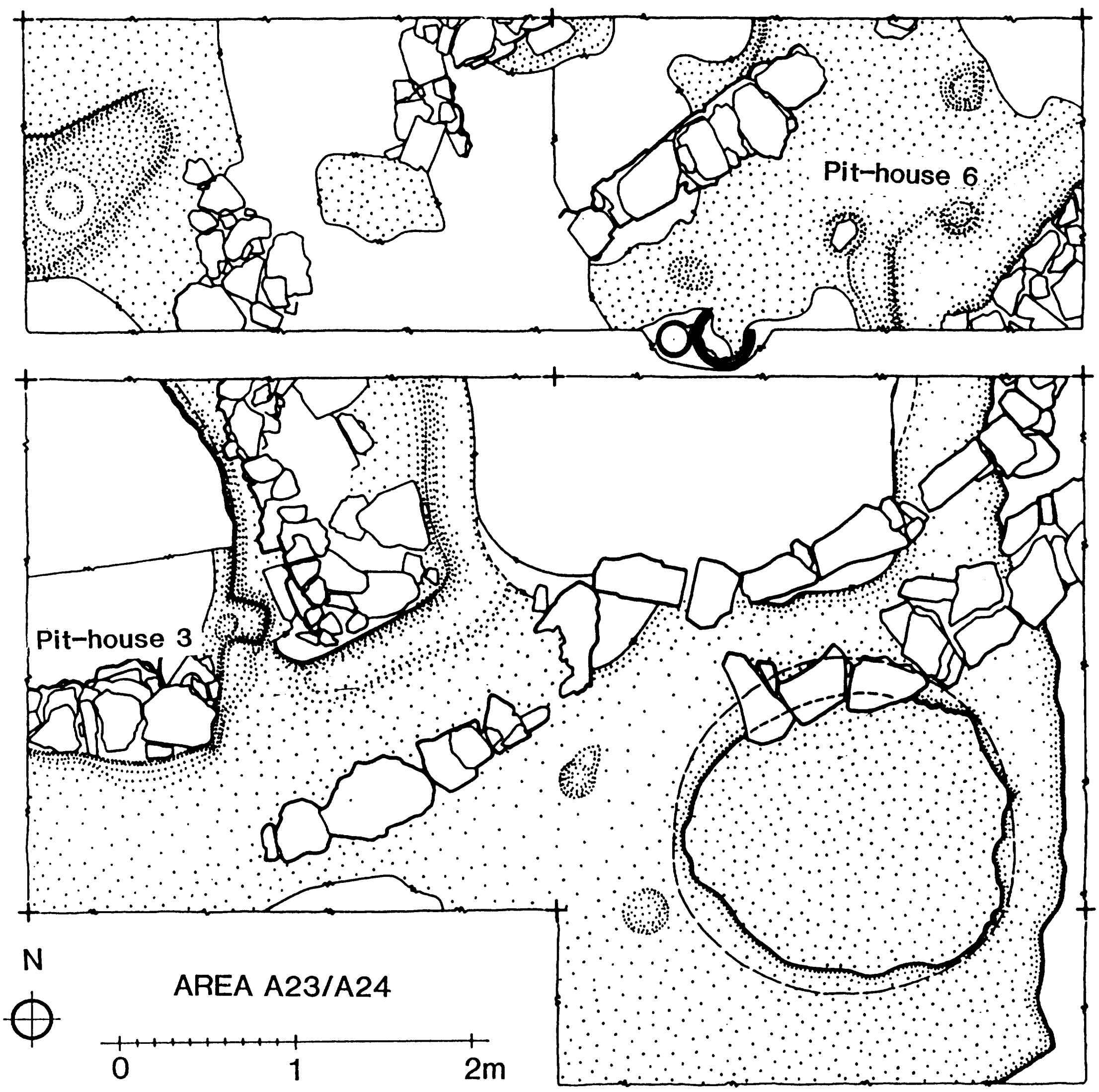

Fig. 6. Plan of Göltepe area A23/A24 and pit-houses 6 and 3. (Drawing J. Knudstad)

times embedded in the fugitive, unlaminated but nevertheless compact surfaces. A sample (table 2: no. 18) was taken from locus 001 of test pit T-11 in a dense brown earthen layer of this building. A cup with a single handle (fig. 4:3),[52] beak-spouted pitchers akin to examples examined in unpublished Karum IV levels of Acemhöyük[53] and EB III Tarsus,[54] a cup with a sharply peaked handle similar to examples from Mersin trench X,[55] and miniature vases[56] date this building to the end of the third millennium B.C.

Trenches A23 and A24 (fig. 6) on the southern part of the summit yielded a series of well-built and well-preserved subterranean and semisubterranean[57] habitation units, some with possible workshop functions.

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[52] *Tarsus* 139–40, fig 268.449.

[53] Aliye Özten, personal communication.

[54] *Tarsus* 118, figs. 248–49.

[55] J. Garstang, *Prehistoric Mersin, Yumuk Tepe in Southern Turkey* (Oxford 1953) fig. 124.4.

[56] *Tarsus* fig. 247.193–94.

[57] Troglodytic habitation in subterranean multiroomed houses cut into basal bedrock is well known in central Anatolia especially in the late Roman and Byzantine periods. The nature of the construction techniques of this subterranean house demonstrates the long continuity of building by carving out and shaping the local landscape and taking advantage of the natural volcanic topography of the area. This is characteristic of the nearby early Christian Cappadocian settlements best typified at Ürgüp, Göreme, and Kaymaklı. Although unique so far in prehistoric Anatolian architectural styles, subterranean structures of similar nature are known from earlier periods in neighboring areas such

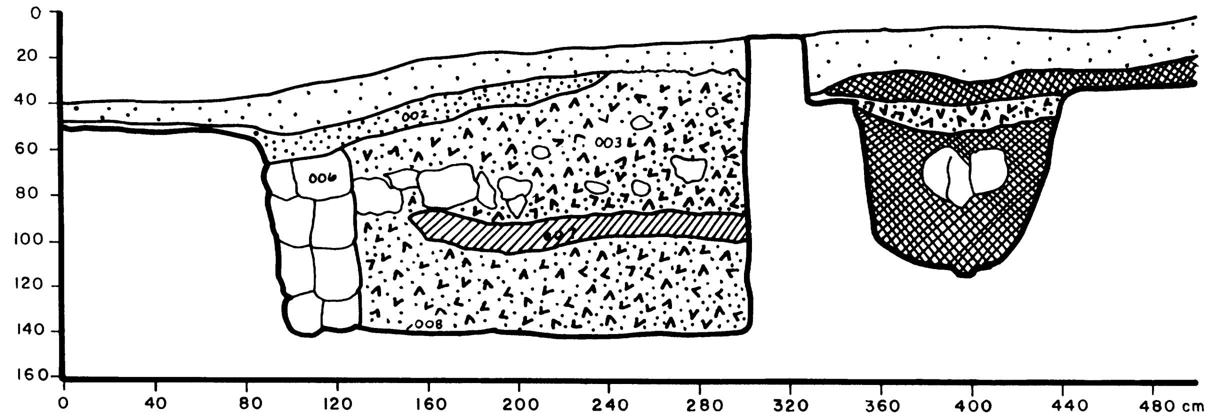

Fig. 7. Cross section of pit-house 3, west trench wall, area A23-0100. (Drawing C. Ott)

One pit-house (locus 003) was defined by two built stone walls, while the other walls were constructed by cutting into the basal clay bedrock. The subterranean pit-house units had been burned, and a collapsed layer of vitrified earth and charcoal sealed the floor deposits (fig. 7). Finds included a multifaceted stone mold with cavities carved on two sides for bar-shaped implements, possibly for the casting of tin ingots (fig. 4:1), groundstone tools in great abundance and sizes, obsidian tools, burned and vitrified clay, crucible fragments (table 2: nos. 20 and 22), clay objects with chevron designs in relief, ore nodules, and ceramics. Impressions of branches on structural clay lumps with vestiges of painted plaster, and charcoal were found in the mud debris and on the floor, which lay roughly 1.40 m beneath the surface. The amount of burned structural mud debris and the position of the branches and a semicircular hollow carved in the bedrock wall, perhaps for setting vertical timber posts, indicate a wattle and daub superstructure. Sealed deposits over the floors of two separate pit-house structures (nos. 6 and 3) yielded uncalibrated radiocarbon dates of 2120 ± 70 B.C. and 1840 ± 80 B.C., respectively (table 1). The readily identifiable clinky ware with painted decoration in purplish-red paint[58] and the related red gritty ware,[59] as well as beak-spouted pitchers[60] and other diagnostic material associated with this phase, date the deposit to EB II and the pre-Akkadian period. A fine corrugated "plain simple ware" cup fragment links this phase to Tarsus[61] and sites in Syria.[62]

Area A06 defines a subterranean, perhaps multi-roomed, habitation cut into the graywacke basal bedrock. This pit-house is delimited on the north side by a stone wall made of small, roughly square limestone blocks. Patchy remnants of plaster are visible on the interior surface of the cut bedrock walls. The west side of the room was carved into a hearth, replete with groundstone tools used as hearthstones and a substantial ashy deposit. This phase was destroyed by fire, sealing the floor deposit. The uncalibrated radiocarbon date for the hearth is 3290 ± 250 B.C. (table 1).[63] A later stratum (locus 004) represents the post-burning phase, and use of the subterranean house as a refuse pit. The ceramics from the refuse pit phase are consistent with the EB II clinky wares and burnished wares. Two of the analyzed crucibles come from this locus (fig. 4:2 and table 2: no. 24).

Ringing the area of subterranean workshop/habitation dwellings was a well-built north–south wall (possibly part of a circuit wall) on the west slope in area B01, which was preserved in some places to 10 courses and a height of over a meter (fig. 8). The wall was constructed of large, irregularly shaped stones,

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as the Chalcolithic examples in Cyprus (E.J. Peltenberg, "Lemba Archaeological Project, Cyprus, 1986," *Levant* 20 [1988] 231–35) and the Beersheva culture in Israel (T.E. Levy and D. Alon, "Shiqmim: A Chalcolithic Village and Mortuary Centre in the Northern Negev," *Paléorient* 11 [1985] 71–83). Given the nature of the intermontane climate at Göltepe, perhaps the subterranean units there should be associated with dwellings suitable in inhospitable mountainous areas. Thus, the architectural style may be environmentally and not culturally determined.

[58] Cf. *Tarsus* fig. 247.

[59] *Tarsus* 108–109.

[60] Garstang (supra n. 55) fig. 122.

[61] *Tarsus* 106–107, fig. 245.178–87. For Amuq I see Braidwood and Braidwood (supra n. 9) 410–12 fig. 315.3–5, pl. 87.3, 5.

[62] See, e.g., Kühne (supra n. 46) fig. 93.

[63] This very early date for the floor level is surprising. Further charcoal samples from the same context will be analyzed for corroboration in the future.

with parts built with reused saddle querns and large groundstone mortars with hollowed surfaces.[64] A "floor" having an inclined irregular surface emerged at the base of the wall, which may be an outdoor surface contemporary to the use of the wall. Sealing the floor was a thick level of very loose large blocks, presumably from the upper courses of the wall (locus 003). This level had a very loose soil matrix and appeared to represent a relatively rapid episode of wall collapse. Pottery from this locus included clinky ware with several beak-spouted examples similar to EB II examples from Tarsus.[65] Another locus (006) was defined by a hard, compact cultural layer that was directly below topsoil. Hundreds of fragments of a crude porous ware with accretions rich in tin oxide and containing small droplets or drips of glassy slag were found discarded by this wall, both in the collapse level and in the hard, compact level. The uncalibrated radiocarbon date from this dump is 2170 ± 60 B.C. (table 1). This area may be part of a metal workshop sector abutting the wall. As mentioned above, similar wares also emerged from the pit-house cells in A02, A06, and A23, which are associated with the clinky painted ware, giving a rough contemporaneity to these implements and architectural features.

In summary, the dates of the crucibles from Göltepe rest on their stratigraphic findplaces, which are dated by pottery and radiocarbon determinations. Based on ceramic analogies and radiocarbon dates taken from excavated contexts inside the mine, the Kestel site also spans the Early Bronze Age. Considering the coeval dates of the tin mine and the production industry at Göltepe, the importance to the eastern Mediterranean of these crucibles from Göltepe is manifest.

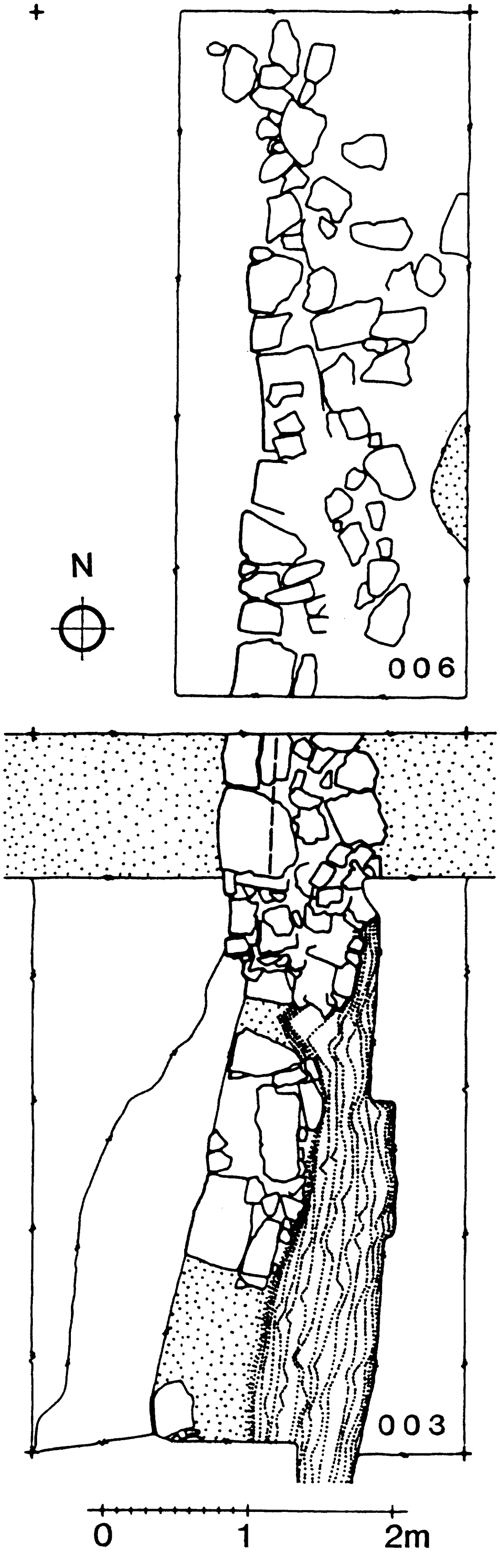

Fig. 8. Plan of Göltepe area B01-0107/17, circuit wall. (Drawing J. Knudstad)

DESCRIPTION OF THE GÖLTEPE CRUCIBLES

Twenty-four crucible fragments (five of which are illustrated in fig. 9) were chosen at Göltepe by visual examination and with a 10× hand lens for materials analysis at the Conservation Analytical Laboratory of the Smithsonian Institution (table 2). The specimens chosen were primarily rim sherds to enable reconstruction of shape, while others that were not analyzed appear to resemble furnace linings. Such distinguishable features as a reduced or blackened, hard and probably high-fired inner surface and a much softer,

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[64] When we examined aerial photographs taken by the Turkish Air Force, obtained by the staff geomorphologist, S. Ozaner, from the Geological Survey archives, wall-like features in concentric circles were apparent at the same location as the wall being excavated.

[65] *Tarsus* fig. 247.188–89.

Fig. 9a. Crucible 20 in cross section

Fig. 9b. Crucible 4 showing inner scoreaceous surface

Fig. 9c. Crucible 13 showing powdery accretions and weathering products on the surface

Fig. 9d. Crucible 5, possibly a lid, with orangish-brown powdery surface and three small droplets of slag (outlined)

Fig. 9e. Thin-walled crucible or lid no. 22, with powdery surface containing tin oxide and other elements

lower-fired, and red or oxidized exterior surface differentiated these fragments from coarse ware cookpots, which are usually harder and reduced on the exterior. In addition, a slag-like appearance of surface accretions on the interior surfaces was readily identifiable with a field microscope, making them likely candidates for crucibles.[66]

Many examples have blackened interiors with small millimeter-sized droplets or driplets of a black glassy slag (figs. 9 a–b and 10). A brownish particulate but hard residue appears in some patches on the inner surfaces. The black, glassy material poorly wetted the surface of the earthenware based on measurements of contact angles of less than 90°. The inner surfaces of many of the ceramics had been reduced to gray or black and had begun to melt and bloat to a depth of a millimeter or less (fig. 10). The exteriors are mostly red to orange, and are softer, more friable, and fired to a lower temperature than the interiors. The sizes are variable, but the average thickness is 1.2 cm and the average preserved height is 6.1 cm; the diameters are generally estimated at 20–40 cm, with a range in height of 12–40 cm at the rims. Some of the fragments were thinner, averaging 0.9 cm, leading to the conjecture that at least two functional types of crucibles were made and used. The 1991 excavation season yielded a greater variety of crucible shapes and sizes, which will be discussed in later reports.

The method of manufacture of the ceramic fragments involved slab-building, often with a strip added to form the rims. Two fabrics were observed by visual inspection. Microscopic examination revealed impressions of burned-out, fibrous vegetal material that had been intentionally added to the clay body and that had carbonized and burned during heating. The alignment of pores was generally parallel to the wall, but also tended to round at the edges where the preformed slabs were joined (fig. 10). At these joints, pores having few internal grass-like impressions were concentrated, confirming the conjectured method of manufacture.

Some of the inner layers of the ceramic fragments (nos. 1, 3, and 20) and one of the thinner-walled ones (not shown) were without vegetal temper, reinforcing the probability that the function of vegetal temper was well understood by the crucible makers (fig. 10). It is well known in the refractory brick industry that closed pores yield ceramic products with good insulation and thermal shock properties, whereas sand-tempered products with low porosity give more stable, slag-resistant refractories. Making a crucible with a sand-tempered inner layer and a fiber-tempered outer layer combines both of these features into one product. In the thicker fragments only 1, 3, and 21 are so made. In examples 1, 4, 5, and 21, the inner layer was added to the surface after the bowl was shaped and the rim coil added. The refractory and insulating functions of the various tempers were probably known, but were not consistently found in this sample of cassiterite-containing coarseware bowl fragments from Göltepe. Each crucible was made as one piece as the inner layers do not represent relining of the crucible: the joints are difficult to detect and no crack has opened at the joint, which would have resulted from differential drying shrinkage. In addition, no differences in vitrification across the joints have occurred.

The variations among these crucible fragments may represent, in addition to temporal and processing variations, differences in function.[67] In examples where the brown residue and very little slag are present except as submillimeter droplets, a function as a lid or superstructure is likely. Tin oxide (SnO) may have precipitated from the vapor, and small amounts of slag may have splattered. In other examples where the ceramic surface is scoriaceous, overfired, and reduced, with the top millimeter somewhat bloated, a function as a container is more likely, but surprisingly very little of the expected slag was found. Only rarely is slag present in quantities of greater volume than a cubic millimeter. No microscopic evidence of grinding or chipping of a slag from the surface was found—evidence that might have explained why so little slag was present. No crucible was found whole or nearly whole in 1990. The presence of so many thick fragments (2.5–4 cm) of nearly the same size (about 6 cm maximum), which would have been difficult to fracture into such small pieces, suggests that intentional fracture of these containers must have occurred.

Evidence from the microscopic characteristics of the crucibles shows the variation in firing temperature. A polished cross section of the bloated, blackened inte-

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[66] Only by very careful observation of these subtle traits were these potential metallurgical refractories separated from vegetal-tempered coarse wares or cooking pots. For instance, in a cooking pot one would not expect the interior to be reduced to a gray or black color or to be harder and higher-fired than the exterior. The glassy slag-like accretions on the earthenware fragments were easily observable by the naked eye, and with a 10× field lens. We thank B. Aksoy and B. Earl for lively discussions about the identity of these fragments in the field.

[67] David Killick has suggested that larger variants found in 1991 may be bowl-shaped furnaces into which smaller crucibles were placed.

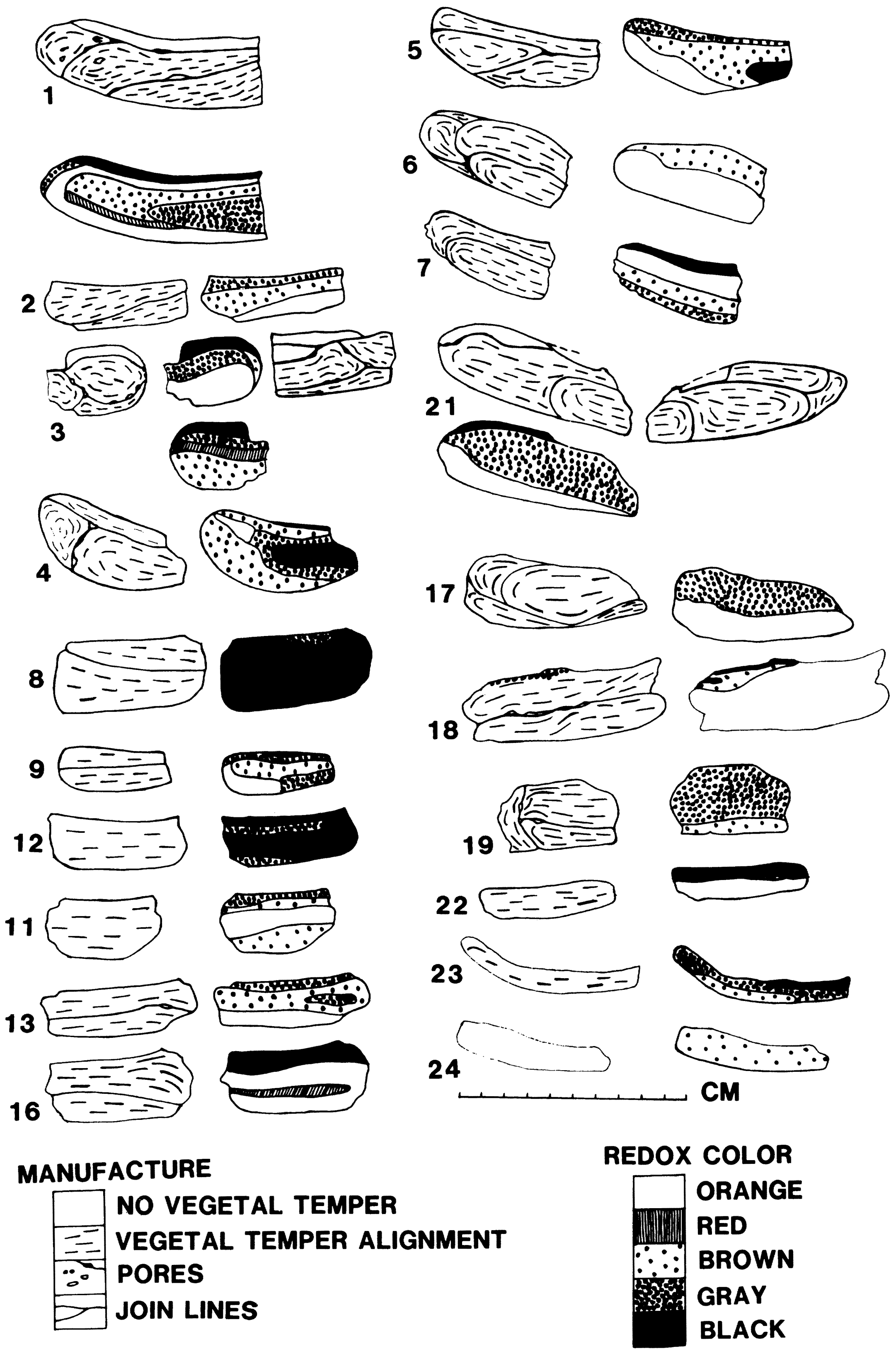

Fig. 10. Cross-sectional drawings (not stanced) of Göltepe crucible fragments showing slab construction and colors caused by oxidation (red and orange), mixed redox state (brown), and reduction (gray and black) in the ceramic body. (Drawing P. Vandiver)

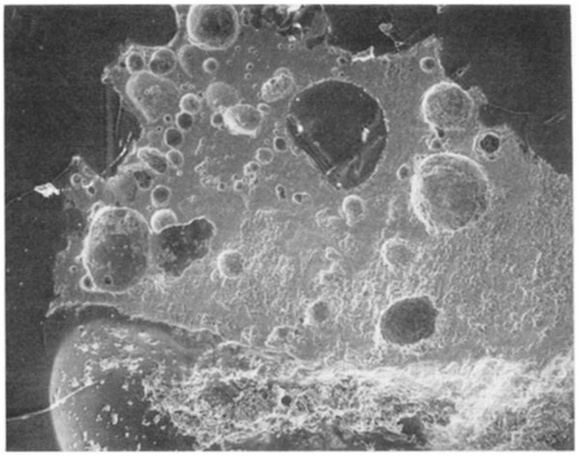

Fig. 11. Secondary or topographic SEM micrograph showing the internal ceramic microstructure in cross section of the reduced and blackened layer near the surface of crucible 4 (140×, reproduced here at 2:3)

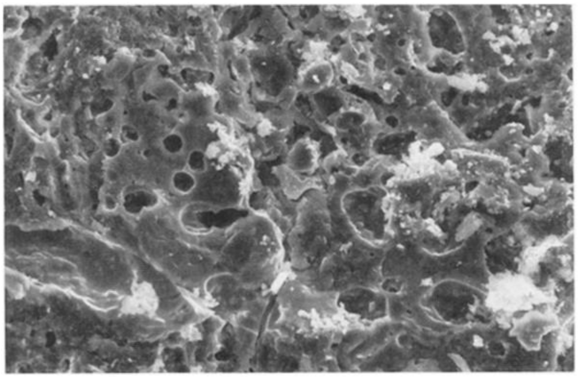

Fig. 12. Increased magnification of the surface layer of crucible 4 in fractured section at 750× (reproduced here at 1:2)

rior layer of crucible fragment 4 viewed with scanning electron microscopy (JEOL 840-II) shows the exterior surface (fig. 11, upper) and more friable, lower-fired, brown ceramic layer (lower). The fusing together of the particles and the rounding of pores can be seen in a fractured section of the higher-fired surface layer (fig. 12). A glassy appearance with rounded pores averaging about 10 microns (μ) in diameter occurs to a depth of almost 100 μ. The pores were produced by bloating or expansion of the closed-off pores during firing at relatively high temperature. By contrast the low-fired exterior (fig. 13) shows pores with irregular and rough interiors and fine, submicron- and micron-sized clay particles between which some glass has formed, thus joining them to one another.

The elemental presence of tin on the inner surfaces of the crucibles was demonstrated by SEM and EDS (Tracor-Northern energy dispersive x-ray system 1700) analyses of the interior surfaces and comparison with the exteriors and with the soil in which they were buried. A compact brown powder, adhered to the inner surfaces of some of the crucibles, is composed partly of secondary products derived from burial, such as calcium carbonate, and clay and dirt accretions, which adhere even after washing. In addition, fine particles containing tin as an element were found (figs. 14–15). Elemental identification of these particles by EDS shows tin and calcium present as the major elements with silicon, aluminum, iron, and titanium present in minor concentrations (fig. 15). The tin-containing particles were not found in the contiguous soil, and thus are believed to relate to the crucibles' use. No tin-containing particles were found on the exteriors of the crucibles. Some of the tin-containing particles are subangular to rounded; others are subangular. They measure 0.1 to almost 3 μ with the average being close to the lower limit. The small size and rounded morphology of these particles indicates that precipitation from a vapor phase is likely.

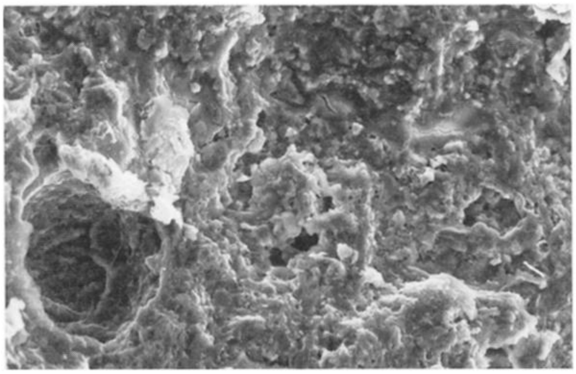

Fig. 13. Fractured section of the low-fired, red exterior of a crucible at 850×, showing a pore (lower left) with a rough irregular inner surface (reproduced here at 1:2)

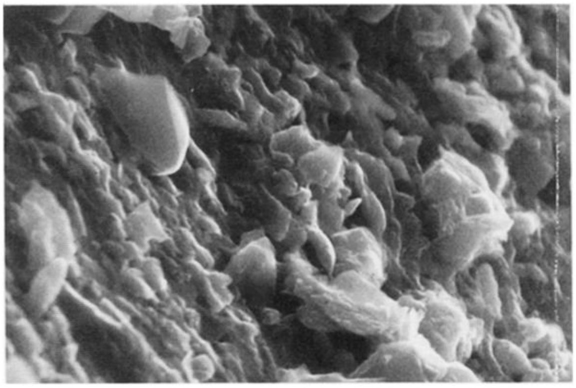

Fig. 14. Secondary SEM micrograph of the typical inner surface of crucible 7 showing a powder well adhered to the surface and composed of fine subangular to rounded particles that contain tin as an element (7,500×, reproduced here at 1:2)

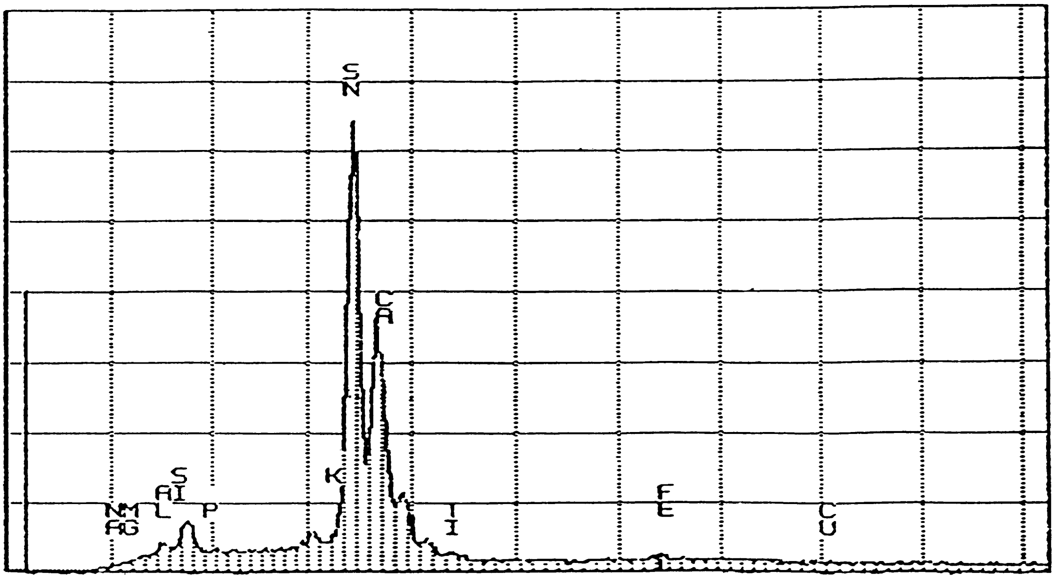

Fig. 15. Energy dispersive x-ray pattern of figure 14 (vertical axis = relative intensities; horizontal axis = energy in KeV from 0 to 10.24). The counting time was 60 seconds. The elements in order of peak height are Sn, Ca, Si, K, Al, Ti, and Fe.

Composition and Firing Temperature Range of the Crucibles

The compositions of three of the crucibles (nos. 1, 8, and 12), given in table 3, show them to be poor as conventional high-temperature refractories because the silica content is low for a refractory and the sodium and potassium oxides are very high. In fact, 63% SiO_2 and 11% Na_2O and K_2O are the appropriate values for a glass, melted between 800 and 1000° C. However, the aluminum oxide content is high and calcium oxide low for a glass. The presence of 20% alumina raises the melting point, the point at which the composition would be completely molten although still quite viscous, to close to 1150° C, as our refiring tests have shown. The equilibrium temperature at which the first liquid starts to melt is 732° C.[68] These compositions lie in the least stable, flux-rich corner of a plot of ancient refractory compositions measured by Freestone.[69]

The composition lies in the compatibility triangle of albite, nepheline, and sodium-silicate.[70] The first two are difficult to precipitate, and the third is not stable in a moist atmosphere. The phases found with x-ray diffraction (Phillips 34 Diffractometer with quartz plate) of the crucibles are albite, quartz, and glass. The albite and quartz are present as precursors or raw materials in the clay body, and the glass has formed during firing. Analysis by x-ray diffraction of one of the lowest fired regions of one of the crucibles shows that illite is the probable clay phase present. The size of the clay particles, 0.1–6 μ, is typical of illites, and the presence of considerable potassium in the regions of microstructure rich in clay also corroborates illitic clay as the likely clay type.

The firing temperature of the crucibles was estimated empirically by refiring five crucible fragments to 700, 800, 900, 1000, and 1100° C, followed by microscopic comparison of the variation in the unfired "originals" to the refired "standards" according to methods developed by Kingery and Tite.[71] Magnifications of 1000× and 5000× were required to reveal the significant and very fine microstructural details. At 1050° C the fragments changed color to a glassy, reddish-brown unlike that found in any of the

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[68] E.M. Levin, C.R. Robbins, and H.F. McMurdie, *Phase Diagrams for Ceramists* 1 (Westerville, Ohio 1964) 181 fig. 501.

[69] I.C. Freestone, "Refractories in the Ancient and Preindustrial World," in W.D. Kingery ed., *High-Technology Ceramics: Past, Present and Future: The Nature of Innovation and Change in Ceramic Technology* (*Ceramics and Civilization* 3, Westerville, Ohio 1986) 35–64; and Freestone, "Refractory Materials and Their Procurement," in R. Maddin ed., *Old World Archaeometallurgy* (Cambridge, Mass. 1991) 151–62.

[70] Levin et al. (supra n. 68) 181.

[71] See W.D. Kingery and J.D. Frierman, "The Firing Temperature of a Karanovo Sherd and Inferences about South-east European Chalcolithic Refractory Technology," *PPS* 40 (1974) 204–205; and M.S. Tite et al., "Technological Studies of Ancient Ceramics," in T.A. Wertime and S.F. Wertime eds., *Early Pyrotechnology: The Evolution of the First Fire-using Industries* (Washington, D.C. 1982) 61–72.

Table 3. Compositional Analyses of Four Ceramic Crucibles by Wavelength Dispersive Microprobe (Standard Deviations in Parentheses) and Phases Present in the Crucibles Identified by X-Ray Diffraction

SiO_2	Al_2O_3	FeO	MgO	CaO	K_2O	Na_2O	TiO_2	MnO	Total
Crucible 12									
Red (number of analyses, n = 11)									
63.03	20.81	1.27	0.67	0.56	4.52	6.64	0.04	0.06	97.59
(4.8)	(1.7)	(0.9)	(0.7)	(0.3)	(3.3)	(3.2)	(0.06)	(0.08)	
Crucible 8									
Red (n = 10)									
64.03	19.72	0.54	0.19	0.34	3.71	7.64	0.01	0.03	96.21
(4.1)	(1.4)	(0.4)	(0.17)	(0.21)	(2.9)	(4.1)	(0.01)	(0.01)	
Crucible 1									
Gray (n = 18)									
61.8	20.13	2.29	1.23	0.82	4.43	5.74	0.24	0.08	96.28
(10.9)	(3.6)	(2.0)	(3.1)	(0.54)	(2.2)	(3.2)	(0.71)	(0.12)	
Phases present: albite, quartz, illite, glass									
*Crucible 24 (somewhat weathered, arsenic-rich)**									
Brown (n = 20)									
57.6	2.3	20.4	0.2	0.5	1.1	0.04	0.02	0.09	79.9**
Phases present: quartz, hematite, illite, and 32 lines that show a probable mixture of As_2O_3 and As_3O_5***									

*As_2O_3 was estimated by energy dispersive x-ray analysis against a working standard of pure As_2O_3 to be 2–5% in the bulk at 2 and 5 mm from surface, and 5–10 times this concentration or 10–50% at the surface. An area 200 × 300 μ was counted for 5 minutes and corrected using a Tracor-Northern Semi-Quant ZAF correction program. The results were then normalized to the As_2O_3 working standard.

**The low total is due to the friable, porous nature of this sample, some of which undoubtedly was lost during grinding and polishing even though the sample was impregnated with a low viscosity epoxy resin. This composition demonstrates that this crucible fabric is different from the others, because even if the remaining 20% of a clay mineral or albite were added, the Fe_2O_3 content would far exceed that of the other crucibles and the sodium content would be far less.

***X-ray diffraction was carried out using a ground powder sample placed on a quartz plate in a diffractometer operated at 50KV, 40 mA and 10°/min. from 3° to 90° of 2θ.

crucibles, and at 1100° C bloating occurred, producing pores much larger than any of those found in the crucibles; thus 1000° C is estimated as an upper limit for the original firing. The refirings were carried out in an oxidizing atmosphere because the original firings were conducted in a mixed atmosphere as indicated by the colors of the crucibles, and because the iron oxide concentration (0.5–2.3%) is low and would have had a negligible effect in lowering the melting compared with the high sodium and potassium oxide concentrations. The degree of rounding of the particles and pores on the crucible exteriors showed the most similarity to firing temperatures of 700–800° C. The highest fired interiors relate to original firing temperatures of 950–1000° C.

There is an envelope of processing in a plot of time versus temperature for a firing in which the microstructure produced may be the result of a longer time at a lower temperature or of a shorter time at a higher temperature. Because these crucibles contain such thin inner layers of high-fired ceramic (0.6 mm being the thickest) and because the presence of so many colors indicates variation in atmosphere, or oxidation state, they probably did not reach equilibrium. They may have been used for only a short period of time, such that the heat and atmosphere did not have time to equalize from one side of the crucible to the other. We conjecture that the crucibles were set in the ground during the smelting operation in order to maintain the lower temperature and oxidized surfaces generally found on the exteriors and that a smelting process of relatively short duration occurred.

The redox colors indicate that reduction occurred on the inner surfaces, but also on the interior in the middle of the crucible cross section. This commonly occurs during a short-duration firing of a vessel with abundant organic temper, and some of the Göltepe crucibles have as much as 20–35% by volume pores. Local reduction was also concentrated at porous joints, which with time would have equilibrated with the surfaces. In several instances the black core or the reduction at a joint is separated from the inner black surface by a less reduced layer, indicating disequilibrium, short-duration firing, and two possible sources of reduction: one from the interior surface, and another from the original vegetal temper inside the crucible walls. We suggest furthermore that the crucibles were not prefired as ceramics and then used for tin smelting, but rather that they were fired for the first time with the tin ore charge in place.

Table 4. Elemental Identification of Crucible Surfaces by Nondestructive X-Ray Fluorescence

Crucible Number, Area Sampled	Interior Surface		Exterior Surface	
	Major Elements	Minor Elements	Major Elements	Minor Elements
Thick-walled crucibles containing tin				
1, ceramic	Fe, Ca	Sr, K, Ti, Mn	Fe	K, Ca, Ti, Sr
1, slag drip	Sn, Fe, Ca	Ti, Mn, Sr, Rb	—	—
1, slag drop	Fe, Sn	Ca, Ti, Mn, Sr	—	—
1, brown powder residue	Sn, Fe, Ca	Sr, Ti	Fe, Ca	K, Ti, Mn, S, Rb
2, ceramic	Fe, Ca	K, Ti, Mn	Fe, Ca	K, Ti, Mn, Sr, Rb
2, slag drop	Fe, Ca, Sn	Ti, Mn, Sr, Rb	—	—
3, bloated ceramic	Fe, Sn, Ca	Ti, Mn, Sr, Rb	Ca, Fe	K, Rb, Sr
4, scoria	Fe, Ca	Sn, K, Ti, Sr, Rb	Ca, Fe	K, Ti, Mn, Sr
6, scoria	Fe, Sn	Ca, K, Mn, Sr, Rb	Fe	Ca, K, Ti, Mn, Sr
8, scoria	Fe, Sn	Ca, Sr	Fe	Ca, K, Sr
9, slag drip	Fe, Sn	Ca, Sr	Fe	Ca, K, Ti, Sr, Rb
10, scoria	Fe, Sn, Ca	Sr, Rb	Fe	K, Ca, Ti, Sr, Rb
14, scoria	Fe, Sn	Ca, Rb, Sr	Fe, Ca	Sr, Rb, K, Ti
15, scoria	Fe, Ca, Sn	Sr	Fe, Ca	Sr
16, ceramic	Fe, Ca	K, Mn, Ti, Sr, Rb	Fe	Ca, K, Ti, Mn, Sr
16, slag	Fe, Sn	Sr	—	—
17, scoria	Fe	Sn, Ca, K, Sr, Ti	Fe	Ca, K, Ti, Sr
Thick-walled crucibles containing tin and arsenic				
5, scoria	Fe, Sn	Ca, Sr, Mn, Ti	Fe	Ca, K, Ti, As, Sr
7, scoria	Fe, Sn	Ca, Sr, As, Rb	Fe	Ca, K, Ti, Mn, Sr, Rb
11, ceramic	Fe, Ca	Sr, As, Sn, Ti, K, Mn	Fe	Ca, Sr, K, As
11, residue	Fe, Ca, As	Sr, Sn, Ti, K	Fe, Ca, As	Sr, Sn, K, Ti, Mn
12, scoria	Fe, Ca, Sn	Sr, Ti, Mn, As	Fe	Ca, K, Ti, Mn, As, Sr
13, slag drop	Fe, Sn	Ca, K, Ti, Mn, Sr, Rb	Fe	Ca, K, Ti, Sr, As
18, scoria	Fe, Ca	Ti, As, Sn, Sr	Fe, Ca	Ti, As, Sr
19, ceramic	Fe, Ca, As	Fe, Sn, Ti, K	Fe, Ca, As	Sr, Sn, K, Ti, Mn
Thick-walled crucibles containing arsenic				
20, ceramic	Fe, Ca	As, Sr, K, Ti, Mn	—	—
21, residue	Fe	Ca, Ti, K, As, Mn, Sr	—	—
Thin-walled crucibles containing arsenic				
22, residue	Fe, Ca	As, K, Ti, Sr	—	—
Thin-walled crucibles containing tin and arsenic				
23, slag drip	Fe, Sn	Ca, Sr	Ca, Fe	Sr, As
24, residue	Fe, As	K, Ca, Sn, Sr, Sb, Cu	Fe, As	Ca, K
24, ceramic	Fe, As	K	—	—

No gold, lead, or silver was found. Peaks are listed in order of decreasing intensities. Minor peaks are 10% or less of the height of the highest major peak.

Contents of the Crucibles

The interior and exterior of each crucible fragment and those interiors with large areas of slag or brown concreted powder were analyzed using nondestructive x-ray fluorescence (United Scientific Dubois Object Analyzer with Tracor-Northern TN5502 Analysis System) (table 4).[72] Elemental tin was detected on the interior surfaces of 21 of the crucibles but not on any of the exterior surfaces. No tin was found on one thin-walled crucible (no. 22) and two thick-walled crucibles (nos. 20–21). A typical x-ray fluorescence spectrum (crucible 1) is shown in figure 16. Iron and

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[72] The major and minor elements from phosphorus upward in atomic number were identified over an area of 1 cm^2 × 200–300 μ in depth. In our system, the values are not corrected and cannot be quantified. The minor peak intensities in table 4 are 10% of the major peaks after background was subtracted.

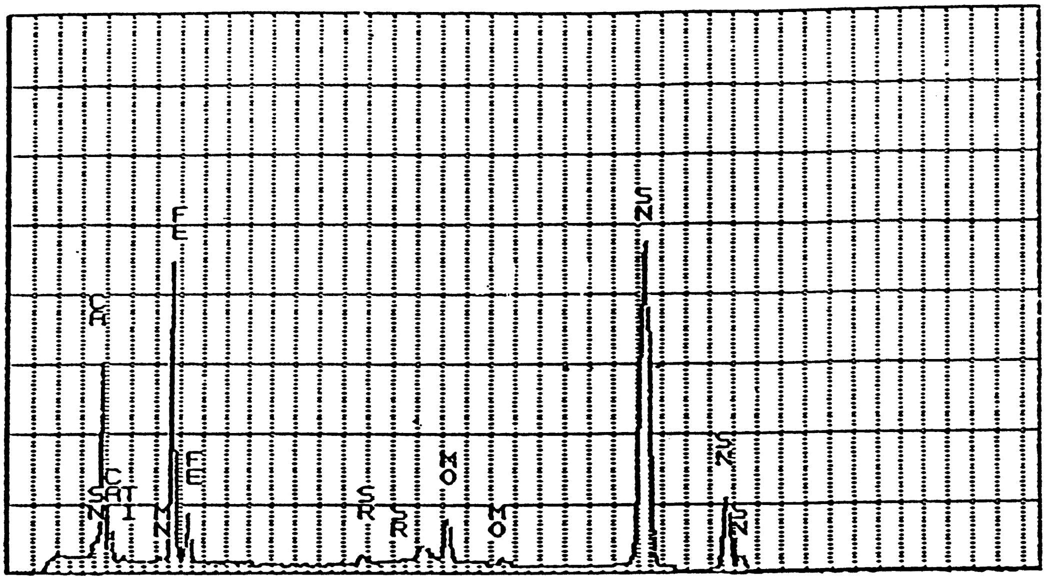

Fig. 16. X-ray fluorescence spectrum of the inner surface of crucible 1 (vertical axis = relative intensities, horizontal axis = energy in KeV from 0 to 40.96). The counting time was 120 seconds. The elements in order of peak height are Sn, Fe, and Ca, with minor amounts estimated in hundredths of a percent of Sr, Ti, and Mn.

calcium were other major elements present, and potassium, titanium, manganese, strontium, and rubidium usually were present, with arsenic often present in minor amounts of approximately hundredths of a percent. Copper was found only in the analysis of crucible 24, a crucible with an atypical texture and composition. Tin was smelted on the interiors of the crucibles and was processed separately from copper in this third-millennium Göltepe technology.

Arsenic oxide was found on half of the crucibles; in one case—that of the atypical crucible 24—a relatively high concentration of about 2–5% was found in certain areas. The other samples only yielded parts per hundred arsenic. On three examples arsenic was found on the outside but not on the inside of the crucibles; on one, it was found both on the outside and inside. On four it was found on the interiors only. In short, arsenic was sometimes present in variable amounts and sometimes absent. Such variability can be explained if arsenic was deposited from the vapor phase. We suggest that arsenic was an intentional addition because it is not present in the ore from Kestel, although it is available in the region.[73]

Analyses of Slags

Surprisingly few analyses of tin slags have been published. Compositional data for historic and modern tin slags derived from studies by Tylecote and Wright are plotted in three ternary diagrams showing the variation of tin oxide with iron oxide, calcium plus magnesium oxides, silica, and alumina (fig. 17).[74] They tend to be higher in iron, alumina, and silica than the slags analyzed by electron beam microprobe analyses from Göltepe (Smithsonian Institution, Department of Mineral Sciences, ARL 9-spectrometer wavelength dispersive microprobe) (fig. 18). The Göltepe analyses show a pattern of "line blends" between tin in the center and a limited ratio of the components represented on the other sides of the triangles. If the tin in the center is 100% pure, then each 10% increment in distance from the center represents a 10% drop in tin concentration until one reaches the outer lines; one may then derive a ratio of the components in the two outer corners by taking the ratio of the outer line lengths. Likewise, the closer one gets to one of the outer corners of the triangle, the closer to 100% of that component is found. The points on this plot

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[73] Arsenic may have been an intentional addition in the smelting process. Only one sample taken from the soil detritus of mining inside the Kestel mine showed trace levels of arsenic (0.23%). The analysis was done by atomic absorption spectrometer by H. Özbal of Boğaziçi University, Istanbul. Arsenopyrites, however, are readily available in the upper altitudes of the Niğde Massif (C. Göncüoğlu, personal communication).

[74] *Early History* 107–109, and P.A. Wright, *The Extractive Metallurgy of Tin* (New York 1966) 87–89.

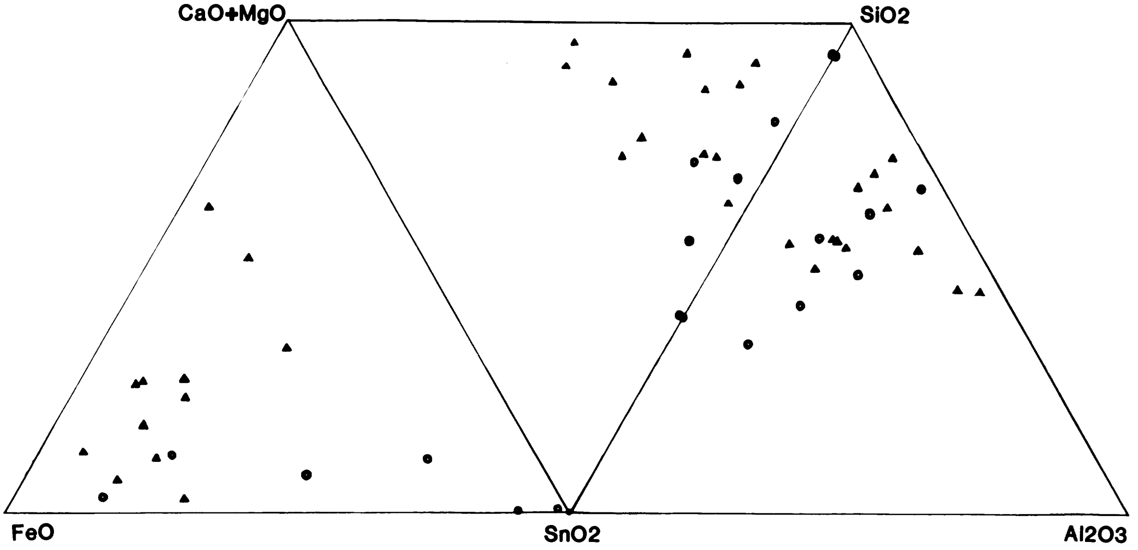

Fig. 17. Summary of current data on the composition of tin slags from the historic period (triangles) and modern tin slags (dots). (After *Early History* 107–109, and P.A. Wright, *The Extractive Metallurgy of Tin* [New York 1966] 87–89)

define the compositions of the phases present in the slags. The Göltepe slags have a narrow range of alumina-silica ratio as well as silica to alkaline earths (calcium oxide plus magnesium oxide) and alkaline earths to iron oxide. These narrow ranges of composition indicate that precursors of specified composition were utilized in a limited range of proportions in batching of raw materials into the crucibles.

Representative examples of slag compositions determined by microprobe analysis are shown in tables 5 and 6 and in figure 19. One example from crucible 13 shows a homogeneous slag composition (fig. 19a) in which poor segregation of the tin phase occurred, and in another example, a heterogeneous slag composition (figs. 19b–c) is represented in which segregation of the tin phase from the silicate is much more complete. The limited homogeneity found in the glass compositional data indicates a nonequilibrium, kinetically controlled pyrotechnology and reinforces the ceramic evidence that a heating process of relatively short duration was performed. This range of compositional variability also suggests that liberation of prills of tin from the slag would have required a multiple-step processing consisting of grinding the

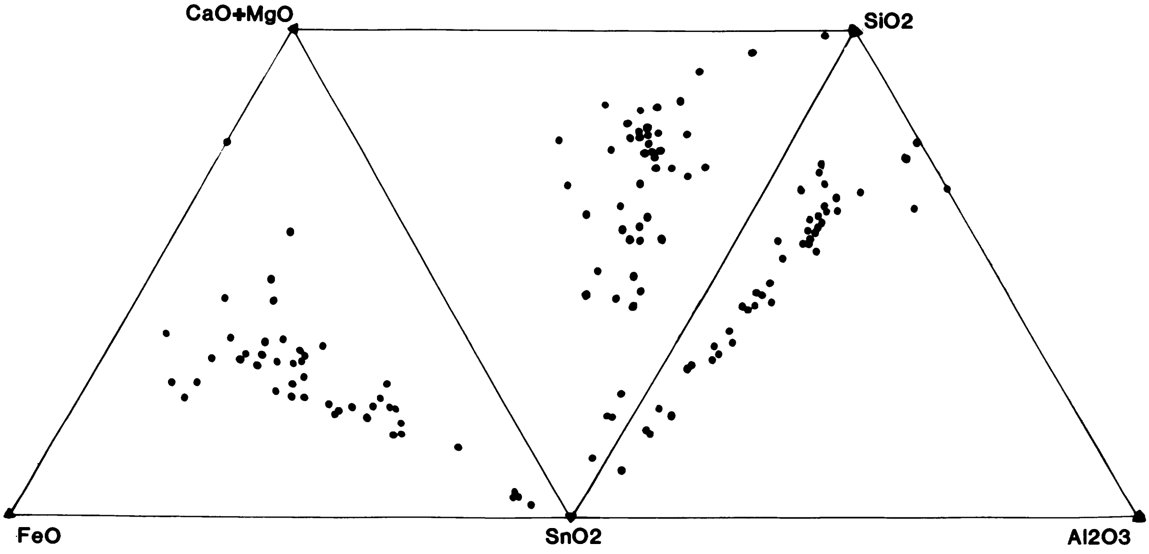

Fig. 18. Quantitative analysis of Göltepe tin slags (electron microprobe). Results of 47 analyses are shown, each repeated 15 times, corrected for absorption, fluorescence, and atomic number effects, and for variations in beam current; also monitored for any instrumental drift by repeatedly analyzing working standards.

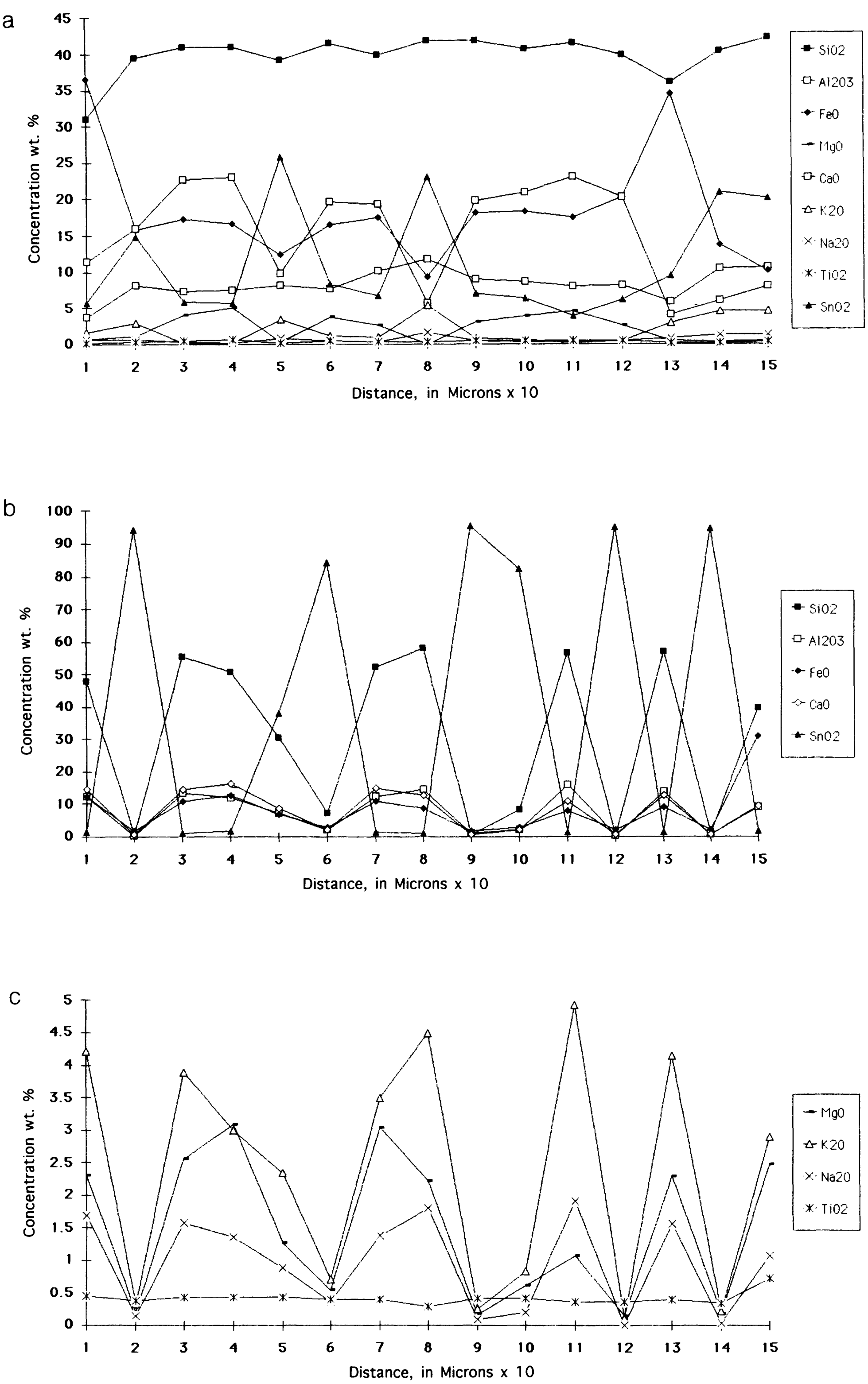

Fig. 19. Compositional variation among tin slags, plotted as concentration versus distance in 10-μ increments (maximum analysis volume is 7 μ for each point): a) a homogeneous slag, showing poor precipitation of tin; b) a heterogeneous slag, showing far superior separation of the tin-rich and silica-rich phases; and c) a heterogeneous slag, with minor and trace constituents

Table 5. Compositional Analysis of Heterogeneous Slag from Crucible 11 by Wavelength Dispersive Microprobe

Slag	Increments in Microns														
Composition	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
SiO_2	47.96	0.50	55.38	50.80	30.45	7.17	58.18	58.03	0.73	8.17	56.53	0.25	57.02	0.99	39.38
Al_2O_3	12.19	0.37	13.49	11.79	7.18	2.13	12.29	14.53	0.85	2.22	15.81	0.17	13.84	0.55	8.92
FeO	12.31	1.66	10.83	12.71	6.95	2.85	10.83	8.52	1.74	2.87	8.02	2.12	9.00	1.96	30.84
MgO	2.30	0.19	2.55	3.09	1.27	0.55	3.02	2.21	0.16	0.62	1.07	0.15	2.28	0.18	2.46
CaO	14.29	0.61	14.38	16.31	8.78	2.22	14.95	12.57	0.69	2.24	10.65	0.49	12.56	0.69	9.36
K_2O	4.21	0.32	3.88	3.00	2.33	0.71	3.49	4.48	0.25	0.83	4.92	0.10	4.13	0.22	2.88
Na_2O	1.68	0.14	1.58	1.35	0.89	0.36	1.37	1.79	0.08	0.19	1.91	0	1.55	0.03	1.07
TiO_2	0.45	0.38	0.44	0.44	0.43	0.40	0.39	0.28	0.42	0.41	0.36	0.36	0.40	0.35	0.72
SnO_2	1.42	94.23	1.04	1.58	38.07	84.10	1.49	1.05	95.42	82.19	1.32	94.92	1.33	94.59	1.59

Average 99.10.
856 analyses on five crucible slags were made using an ARL 9-spectrometer wavelength dispersive microprobe operated at 15KV and monitored for beam current drift. Geological standards of known composition were employed for ZAF corrections, including kakanui hornblende for SiO_2, Al_2O_3, K_2O, Na_2O, TiO_2, and MgO, and pseudowollastonite for CaO, cassiterite for SnO_2, and magnetite for FeO. The beam was defocused to 7 μ, and each element was counted for 10 seconds.

Table 6. Compositional Analysis of Homogeneous Slag from Crucible 11 by Wavelength Dispersive Microprobe

Slag	Increments in Microns														
Composition	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
SiO_2	30.94	39.59	40.93	41.01	39.25	41.53	39.81	41.86	41.88	40.63	41.47	39.77	36.10	40.30	42.21
Al_2O_3	3.79	8.12	7.36	7.53	8.08	7.73	10.06	11.81	8.94	8.68	8.04	8.07	5.88	10.41	10.55
FeO	36.58	15.82	17.37	16.62	12.37	16.49	17.38	9.29	18.16	18.33	17.45	20.27	34.53	13.77	10.16
MgO	0.68	1.10	4.10	5.01	0.36	3.66	2.54	0.04	3.08	3.84	4.47	2.60	0.53	0.26	0.40
CaO	11.39	15.92	22.63	23.09	9.83	19.66	19.29	5.64	19.80	20.91	23.04	20.17	4.04	5.97	7.91
K_2O	1.65	2.86	0.07	0.11	3.38	1.05	1.00	5.44	0.85	0.64	0.10	0.52	2.83	4.47	4.48
Na_2O	0.58	0.66	0.26	0.16	0.79	0.40	0.33	1.52	0.40	0.34	0.25	0.45	0.85	1.22	1.35
TiO_2	0.11	0.24	0.38	0.54	0.20	0.51	0.36	0.30	0.47	0.52	0.42	0.49	0.15	0.19	0.24
SnO_2	5.67	14.92	5.77	5.61	25.80	8.38	6.65	23.08	7.00	6.41	3.85	6.10	9.48	20.82	20.04

Average 98.39.
856 analyses on five crucible slags were made using an ARL 9-spectrometer wavelength dispersive microprobe operated at 15KV and monitored for beam current drift. Geological standards of known composition were employed for ZAF corrections, including kakanui hornblende for SiO_2, Al_2O_3, K_2O, Na_2O, TiO_2, and MgO, and pseudowollastonite for CaO, cassiterite for SnO_2, and magnetite for FeO. The beam was defocused to 7 μ, and each element was counted for 10 seconds.

ore to very fine particle size, and a density separation step such as sedimentation, vanning, or winnowing, followed by smelting.

The microstructural evidence from a representative droplet of slag (fig. 20) shows a sintered structure consisting of well-joined grains of a calcium-containing phase (fig. 20a, upper left), porosity (fig. 20a, upper right), and a heterogeneous mixture of glass and various crystals. In some grains the glass contains more iron (fig. 20a, lower left), in others more tin (fig. 20a, lower center), and in others more glass. The tin phase (seen as white needles or when seen on end as equiaxed particles) tends to precipitate at pore and grain boundaries, although some is found in the bulk (fig. 20b). X-ray diffraction has identified the tin-rich phase as cassiterite, SnO_2. Compared with other slags of copper, for instance, the surprising aspect of these microstructures is the small size of the tin oxide precipitates, 20 μ in maximum length by about 0.7 μ in maximum diameter. Most dendrites are 5–8 μ long by 0.5 μ in diameter, which is below the limit of resolution of the naked eye (about 100 μ or 0.1 mm). Thus, this step of tin processing had to have occurred without direct visual observation of the tin prills in the slag. Bachmann[75] cites a study by Tylecote of barely visible spherical globules of tin measuring 150–200 μ in a slag from an eighth- to second-century B.C. fort in Portugal. A similar microstructure of

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[75] H.-G. Bachmann, *The Identification of Slags from Archaeological Sites* (London 1982) 26.

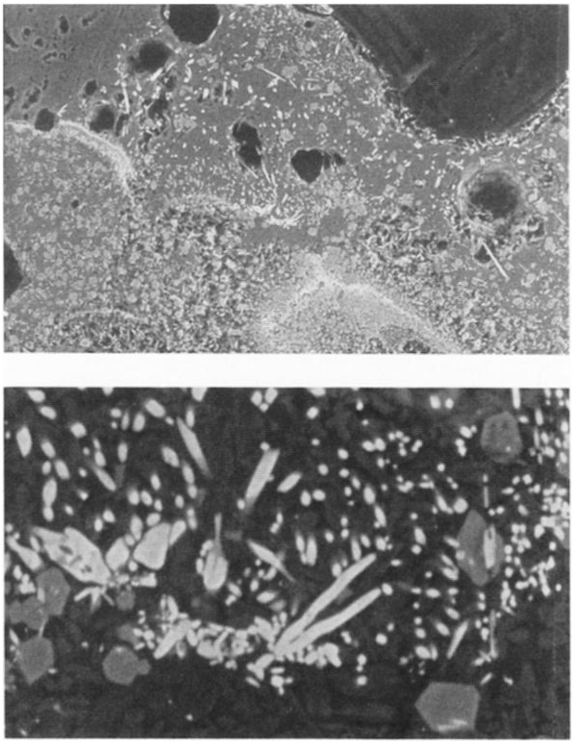

Fig. 20. Back-scattered SEM image of the microstructure of a droplet of tin slag in cross section at original magnifications of 500× (a) and 3,500× (b). Note in (a) the sintered structure of calcium-containing particles (upper left) and sintered grains of mixed phases. The whitest areas contain tin and occur at boundaries of particles that have been sintered or fused together. The dark gray rounded areas are pores. Note in (b), a magnification of the center of (a), the needlelike tin-containing particles and gray, angular, equiaxed particles rich in iron, believed to be fassaite in a darker field consisting of dark gray, lathlike precipitates and a darker, and thus lower, atomic number, glassy matrix.

oxidized tin inclusions in a glass melt of similar thermal history is shown by Clark-Monks and Parker.[76] In modern sheet glass, molten soda-lime-silica glass batches are floated onto molten metallic tin for support and to maintain surface smoothness, and cassiterite inclusions are the major defect.

The phase assemblage determined by x-ray diffraction, in order of decreasing intensities, consists of quartz, cassiterite, fassaite, calcite, and glass with very minor amounts of cristobalite and probably tin metal. Of the 128 diffraction peaks, no match was found for 31, and only one tin metal peak was found, with another possible. The equiaxed, angular, gray grains in the Göltepe slags are high in alumina, silica, calcium oxide, and iron oxide, and are probably the clinopyroxene, fassaite, identified by x-ray diffraction. The mineral fassaite is a ferro-augite, $(Fe, Ca, Mg, Al, Ti)_2 (Si, Al)_2O_6$ with an approximate composition of 38% SiO_2, 19% Al_2O_3, 10% FeO, 7% MgO, and 24% CaO, as present in the slag. In this mineral iron is present mostly in the reduced Fe^{2+} state. This mineral is not present in the mine and would have precipitated during the smelt.

Ore from the Kestel mine contains quartz, calcite, magnetite, and cassiterite of 1.5% SnO_2 content. Three of the ore phases are present in the slag, another indication of incomplete equilibration of the raw materials in the slag. Our data show that the cassiterite ore was enriched to an average of 20 wt%, but because we are analyzing debris, we are probably missing both the most tin-rich ore and the most tin-rich slag.

The presence of cristobalite indicates a relatively low temperature process but one that was held for a considerable length of time, thus giving credence to the reprocessing of the slag. The transformation of some of the magnetite to glass and fassaite also indicates considerable time or else a very fine magnetite particle size that could only have been achieved by considerable grinding or the use of very fine alluvial sediments. The original composition of the charge must have approximated by weight about an equal part of calcite, magnetite, quartz, and probably a clay or other alumino-silicate containing considerable potassium oxide. Perhaps a small amount of potassia-rich ash could have been added to bring the final potassia totals up to 3–5%.

In order to determine how fluid the slag would have been at 950° C, a differential thermal analysis was conducted (Perkin-Elmer DTA-1700, 25–1100° C at 10°/min. in air). The median of the glass transition range, or Tg, which usually occurs over a 50° C temperature span, is 860° C for the slag, which is high compared to typical glasses and earthenware and stoneware glazes. This high Tg indicates that the slag would not have been fluid enough to pour at 950° C. Tylecote[77] mentions that early tin-rich slags from Caerloggas in Cornwall at about 1500 B.C. contained tin-silicates with melting points of about 900° C, thus representing a much more fluid composition. The

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[76] C. Clark-Monks and J.M. Parker, *Stones and Cord in Glass* (Sheffield 1980) 95, 185. A much more agglomerated structure, also identified as cassiterite, is shown in E.R. Begley, *Guide to Refractory and Glass Reactions* (Boston 1970) 101. For tin smelting, see F.H. Norton, *Refractories* (New York 1968) 369.

[77] *Early History*; Tylecote does not define a viscosity for the melting temperature.

high value for glass transition of Göltepe slag corroborates the observation of the nonwetting behavior of the slag droplets onto the crucibles and also supports the necessity of a multiple-step processing involving comminution and resmelting.

TECHNIQUES OF PROCESSING CRUCIBLE TIN

We would like to propose a model for the processing of tin metal based on the Göltepe crucibles. Eventually, replication experiments will be conducted to approximate the processing parameters established by these analyses. We know from physical chemistry some of the parameters of tin smelting, and we have established others by examination of the crucibles, their surface residues, and slags.

From Ellingham diagrams we know that to smelt cassiterite, SnO_2, to metallic tin involves a temperature of 950° C at a partial pressure of oxygen of 10^{-14} atmospheres.[78] To smelt SnO to tin metal involves a much higher temperature range of 1250–1540° C, but a lesser reduction of only 10^{-6} to 10^{-12} atm. A partial pressure of 10^{-4} can be maintained in a smoky bonfire or updraft kiln, and copper smelting requires 10^{-6} atm. Only the first process is possible, given the low temperature processing parameters reconstructed from the Göltepe remains. Using a low temperature for smelting, however, required special means of achieving a highly reducing atmosphere. Thus, the suggestions of partially covered crucibles packed with a reducing fuel and of crucibles containing vegetal fiber, which helped insulate and maintain the atmosphere and temperature, seem reasonable. The range of processing variables was established, and these included processing in reduction between 800 and 1000° C (interior temperatures, 700–800° C for exterior temperatures) for a relatively short duration of a few hours at most, during which time the raw materials sintered but did not entirely melt into a glass, nor did the temperature of the crucibles equilibrate through the crucible wall thickness. Sufficient time was allowed, however, for the precipitation of very small cassiterite and fassaite crystals, on the order of a few microns.

The smelting process we suggest involves several steps: grinding the ore, separating it by density differences probably in a washing stage, followed by partial melting in reduction of a glass of such high viscosity that it could not have flowed out of the crucible. The slag would have required chipping from the crucible, grinding, separating, and at least one more smelting step, if not several, in order to grow the tin prills. The smelting process was not efficient because of the high viscosity of the slag in which the nucleation and growth of tin grains occurred. The growth and agglomeration of these grains would probably have been the rate limiting process. The final step in the process would have been the agglomeration of the tin particles and their separation from the slag. This final firing would have required a low temperature of only 273–300° C at which point the tin metal would have been "sweated" out of the finely crushed slag.

The technique of utilizing a crucible to smelt or melt metal has often been discussed and replication experiments have been attempted by several researchers.[79] In the experiments the crucible is placed in a simple furnace, such as a hollow in the ground surrounded by charcoal, and blown with bellows. This process leaves little trace other than the crucible and fire-reddened or blackened earth.[80] The functional requirements of a crucible fabric are its refractory nature and strength. Often it is a mixture of clay with large amounts of coarse mineral and rock fragments, which reduce the possibility of cracking and shrink-

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[78] J.M. Floyd, "The Physical Chemistry of Tin Smelting," in J.M. Cigan, T.S. Mackay, and T.J. O'Keefe eds., *Lead–Zinc–Tin '80* (Washington, D.C. 1980) 508–31.

[79] It has often been assumed that crucible smelting is rarely possible; see, e.g., R.F. Tylecote, "Can Copper Be Smelted in a Crucible?" *Journal of the Historical Metallurgy Society* 8 (1974) 54. Nevertheless, Smith disagrees: see C.S. Smith, "Tal-i Iblis: Metallurgical Archaeology," *Iran* 5 (1967) 146–47; and Wertime (supra n. 17) 336. Crucible smelting technology has now gained more credence because of recent experimentation; see U. Zwicker, H. Greiner, K.-H. Hofmann, and M. Reitinger, "Smelting, Refining and Alloying of Copper and Copper Alloys in Crucible Furnaces during Prehistoric up to Roman Times," in P.T. Craddock and M.J. Hughes eds., *Furnaces and Smelting Technology in Antiquity* (London 1985) 103–15. Tylecote later changed his mind: "Extraction Metallurgy: Historical Development and Evolution of Thermal Processes," *Abstracts* of the International Colloquium on Archaeometallurgy, 18–21 October 1988 (Bologna 1988) 9. New analysis has strengthened the possibility of a technology based not on furnaces but on co-smelting copper sulfide and copper oxide using earthenware ceramic crucibles. See W. Rostoker, V.C. Pigott, and J.R. Dvorak, "Direct Reduction to Copper Metal by Oxide-Sulfide Mineral Interaction," *Archeomaterials* 3 (1989) 69–87; V.C. Pigott, S.M. Howard, and S.M. Epstein, "Pyrotechnology and Culture Change at Bronze Age Tepe Hissar (Iran)," in Wertime and Wertime eds. (supra n. 71) 215–36; V.C. Pigott and S. Natapintu, "Archaeological Investigations into Prehistoric Copper Production: The Thailand Archaeometallurgy Project 1984–1986," in Maddin ed. (supra n. 1) 156–62.

[80] *Early History* 107–109.

age.[81] Often straw, hair, or dung is added to increase open porosity for air to escape, but closed pores are also produced, which reduces the heat transfer through the walls. Crucibles are usually reduction-fired since metals must be melted under reducing conditions to prevent them from being oxidized and lost as a crucible slag.

The question of whether cassiterite or metallic tin was added as the mineral to the copper in a cementation procedure to produce bronze is debated and remains unsettled; both methods are possible. Both Charles[82] and Wertime[83] suggest the early use of the mineral cassiterite, but this is disputed by Maddin et al.[84] and Muhly.[85] Tylecote observed that the "close [compositional] control exercised in the Bronze Age suggests without doubt that the bulk of the original bronze was made by the addition of metallic tin and not by cementation with tin oxide under reducing conditions,"[86] which should have produced far more variable quantities.[87] Yet another alloying method for later periods was suggested by Cooke and Nielsen[88] from information derived from slags at Nichoria, Greece. Metalsmiths there were not using tin at all, but were reusing scrap bronze from elsewhere. Evidence from second-millennium B.C. Mesopotamian texts[89] and Middle Bronze Age Assyrian trading colony texts indicates that *annaku*[90] was transported in a variety of shapes, including metal bars. Late Bronze Age shipwrecks with tin ingots, such as those from Uluburun-Kaş and Cape Gelidonya off the coast of Turkey, demonstrate the utilization of tin metal in some centers.[91] Now, evidence of tin metal production comes from the site of Göltepe, pushing back its beginnings at least 1,000 years.

One of the more significant indications of the tin-slagged refractory materials from Göltepe is evidence for the utilization of the process of crucible smelting for tin. Smelting tin oxide is easily achieved in reducing tin oxide with charcoal with a suitable flux. This is the basis of one modern tin assay technique.[92] R.F. Tylecote has presented the range of tin content in crucible slags from a variety of sites, from 0% Sn, a medium range at 3–5%, and other slags that often show up to 13.5% metallic tin, mainly in the glassy phase.[93]

The recovery of tin metal from low-grade tin ore is demonstrated by Nigerian metalworkers.[94] Here the tin is said to be a by-product of iron smelting and was recovered as beads or wires after crushing the iron-rich slag of ore with a 0.1% tin content—with better results when enriched to 5%.[95] Another experimental smelt was attempted by Tylecote and Merkel,[96] this time in a furnace based on Nigerian examples of saucer-shaped hearth furnaces. Temperatures of 1000° C were needed and care was taken to burn away all charcoal so that it did not prevent tin prills from forming. The tin oxide was successfully reduced, but the gangue kept tin particles apart, resulting in a low tin content of 6.3%. A better grade was achieved with 30.88% tin content of ore with the formation of tin prills, and when remelted in a crucible, the content of tin was 98.8%.

OTHER CRUCIBLES FROM THE EASTERN MEDITERRANEAN

Crucibles have been found in eastern Mediterranean excavations dating back to the fifth millennium B.C. All are said to be part of the tool-kit of copper-

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[81] J. Bayley, "Non-metallic Evidence for Metalworking," in Y. Maniatis ed., *Archaeometry: Proceedings of the 25th International Symposium* (New York 1989) 219–303.

[82] J.A. Charles, "The Development of the Usage of Tin and Tin-Bronze: Some Problems," in *Search* 25–32.

[83] T.A. Wertime, "The Search for Ancient Tin: The Geographic and Historic Boundaries," in *Search* 1–6.

[84] R. Maddin, T.S. Wheeler, and J.D. Muhly, "Tin in the Ancient Near East: Old Questions and New Finds," *Expedition* 19 (1977) 41.

[85] Muhly 278–79.

[86] *Early History* 143.

[87] M.L. Wayman, M. Gualtieri, and R.A. Konzuk, "Bronze Metallurgy at Roccagloriosa," in R.M. Farquhar, R.G.V. Hancock, and L.A. Pavish eds., *Proceedings of the 26th International Archaeometry Symposium* (Toronto 1988) 128–32.

[88] S.R.B. Cooke and B.V. Nielsen, "Slags and Other Metallurgical Products," in G. Rapp, Jr., and S.E. Aschenbrenner eds., *Excavations at Nichoria in Southwest Greece* 1: *Site, Environs, and Techniques* (Minneapolis 1978) 182–224.

[89] P.R.S. Moorey, *Materials and Manufacture in Ancient Mesopotamia: The Evidence of Archaeology and Art: Metals and Metalwork, Glazed Materials and Glass* (Oxford 1985) 18–19; Muhly 25–67.

[90] Larsen (supra n. 13), identified as tin.

[91] See, e.g., G.F. Bass, C. Pulak, D. Collon, and J. Weinstein, "The Bronze Age Shipwreck at Ulu Burun: 1986 Campaign," *AJA* 93 (1989) 1–29.

[92] B.T.K. Barry and C.J. Thwaites, *Tin and Its Alloys and Compounds* (New York 1983) 28.

[93] *Early History*; Bachmann (supra n. 75).

[94] D.E.S. King, "The Provenance of Tin Metal in Workings for Alluvial Cassiterite in Nigeria," *Journal of the Historical Metallurgy Society* 23 (1989) 35–40. R.F. Tylecote, E. Photos, and B. Earl, "The Composition of Tin Slags from the South-west of England," *WorldArch* 20 (1989) 437.

[95] B. Earl, however, believes that the purpose of the operation was to win tin and not iron (personal communication, October 1990).

[96] R.F. Tylecote and J.F. Merkel, "Experimental Smelting Techniques: Achievements and Future," in Craddock and Hughes eds. (supra n. 7) 3–20.

based metallurgy. These are mentioned here because they represent a continuity of metal processing utilizing crucibles, rather than furnaces. The majority of those found in earlier contexts have hemispherical or boat shapes.[97] Some circular crucibles have flat bases, similar to those of Neolithic vessels, and would have stood on or in charcoal.[98] Some of the earliest crucibles known were found in a two-room workshop inside a dwelling unit at fifth-millennium Ghabristan II, in Iran.[99] Slightly later crucibles with copper deposits were excavated at Merhgarh III (4000–3500 B.C.) in Baluchistan, Pakistan.[100] Comparable evidence was found in late fifth-millennium B.C. contexts at Tal-i Iblis in Iran: 300 crucible fragments from Iblis II and 28 from Iblis I.[101] The Chalcolithic period in Israel has also yielded important evidence of crucible pyrotechnology. At Abu Matar crucibles were found in natural-draft melting furnaces.[102] The crucibles are small, hemispherical, straw-tempered, gray "metallic" ware bowls with rounded base and oval aperture with dimensions of 11 × 8 cm. The Late Chalcolithic phase G of the Amuq in southern Turkey yielded several crucible fragments with a slag accretion with 5% tin content.[103] The crucibles are described as miniature handmade vessels, one of which had slag of cupreous metal adhering to the fragments. Norşuntepe, an important multiperiod site in the Altınova valley near Elazığ, Turkey, yielded a furnace, crucibles, ore, and a ladle from Early Bronze I, and ore from the Chalcolithic levels, which was found to produce a copper-arsenic-antimony alloy easily when reduced with charcoal in a crucible either with or without liquid copper.[104]

From periods also represented at Göltepe, an EB IIIB workshop replete with metallurgical equipment was uncovered at ambiente 5 of period IVD Arslantepe, near Malatya, eastern Turkey.[105] Copper-encrusted crucibles with side knobs for lifting were found in association with multifaceted molds. Additional examples of crucibles were found at Tell es-Sweyhat in Syria in late third-millennium levels.[106] Troy has produced a number of crucibles from Early Bronze Age levels. The Troy III footed hemispherical examples have diameters of 10 cm and 12 cm.[107] Deep-sided and larger crucibles are more typical of the Middle and Late Bronze Age and later periods in both the Near East and Europe.[108] Larger crucibles

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[97] R.F. Tylecote, "Furnaces, Crucibles and Slag," in *Iron* 203.

[98] *Early History* 188.

[99] For crucibles from level 9, see Y. Majidzadeh, "An Early Prehistoric Coppersmith Workshop at Tepe Ghabristan," *AMIran* 6 (1976) 82–93. A complete crucible was found at the edge of a kiln measuring 25–30 cm in diameter.

[100] J.F. Jarrige, "Towns and Villages of Hill and Plain," in B.B. Lal and S.P. Gupta eds., *Frontiers of the Indus Civilization* (New Delhi 1984) 289–300.

[101] Caldwell (supra n. 17). One such crucible from Iblis II, area G, was excavated in situ in a firepit. Smith (supra n. 79) 147 commented on the copious residues of charcoal, the sparsity of slag, and lack of any furnace debris—all of which are paralleled at Göltepe.

[102] J. Perrot, "Excavations at Abu Matar," *IEJ* 2 (1955) 18, 19, pl. 1.6. The measurements of the furnace are 30–40 cm diameter, 3 cm thick with vertical walls 12–15 cm in height. See also S. Shalev and P.J. Northover, "Chalcolithic Metal and Metalworking from Shiqmim," in T.E.L. Levy ed., *Shiqmim* I: *Studies Concerning Chalcolithic Societies in the Northern Negev Desert, Israel (1982–1984)* (Oxford 1987); and M. Dothan, "Excavations at Meser 1957: Preliminary Report on the Second Season," *IEJ* 9 (1959) 28, fig. 9.

[103] Braidwood and Braidwood (supra n. 9) 314, fig. 207.12, fig. 235.11; Braidwood, Burke, and Nachtrieb (supra n. 9).

[104] H. Hauptmann, "Die Grabungen auf dem Norşun-Tepe, 1974," in *Keban Project 1971 Activities* (Ankara 1982) 41–91, levels XXVI–XIX, pp. 21, 28–31, pl. 18.4. U. Zwicker, "Investigations on the Extractive Metallurgy of Cu/Sb/As Ore and Excavated Smelting Products from Norşuntepe (Keban) on the Upper Euphrates (3500–2800 B.C.)," in W.A. Oddy ed., *Aspects of Early Metallurgy* (Sheffield 1977) 13–26. H. Hauptmann, "Die Entwicklung der frühbronzezeitlichen Siedlung auf dem Norşuntepe in Östanatolien," *ArchKorrBl* 1 (1979) 9–20, pls. 3–12.

[105] A. Palmieri, "Scavi nell'area sud-occidentale di Arslantepe," *Origini* 7 (1973) 109–10, pls. 45–46. Also the third-millennium use of blowpipes and crucibles, and the technique of smelting, is well illustrated in a relief at Sakkara, Egypt, dating to the Fifth Dynasty (2450–2350 B.C.), contemporary with Göltepe.

[106] R.E.M. Hedges, "Analyses of Bronze and Other Metals from Tell es-Sweyhat," *Levant* 8 (1976) 66–67.

[107] Schliemann (supra n. 51) 409, 558; Blegen et al. (supra n. 51) 22, fig. 80.33.1263–65. Nearly 100 mold fragments give a sense of the magnitude of the metal production: J. Marechal, *Reflections upon Prehistoric Metallurgy* (London 1963). For the refractory nature of these artifacts, see M. Felts, "A Petrographic Examination of Potsherds from Ancient Troy," *AJA* 46 (1942) 239, 242.

[108] *Early History* 183–92. For a hemispherical crucible 18 cm in diameter from Ambelikou in Cyprus see U. Zwicker, "Bronze Age Metallurgy at Ambelikou-Aletri and Arsenical Copper in a Crucible from Episkopi-Phaneromeni," in Muhly et al. (supra n. 22) 63–69. For second-millennium crucibles from Mesopotamian sites see R.F.S. Starr, *Nuzi* (Cambridge 1939) pl. 57; E.A. Speiser, *Excavations at Tepe Gawra* I (Philadelphia 1935) 59; and C.J. Davey, "The Metalworker's Tools from Tell Edh Dhiba'i," *BIALond* 20 (1983) 169. On the basis of functional characteristics and stylistic similarities of the unusual crucibles from this site, Davey suggests a southern tradition that is idiosyncratic of Sumer, Egypt, and Babylon as opposed to the northern Anatolian/Syrian tradition; see C.J. Davey, "Tell edh-Dhiba'i and the Southern Near Eastern Metalworking Tradition," in Maddin ed. (supra n. 1) 63–68. Crucibles resembling these were also found in Cyprus (P. Dikaios, *Enkomi, Excavations 1948–*

for melting tin-bronze and possible crucible furnaces have been found in Cyprus at LBA Kition.[109] These examples have an inner thickness of 2.5 cm and an inner diameter of 25 cm, and are 30 cm high, with a hole in the center of the crucible wall.

Crucibles similar to the Göltepe examples in size and shape were found at Zok-Varhegy, Yugoslavia, dating to the third millennium B.C., as well as from Ambelikou, Tal-i Iblis, Kition, and Timna.[110] Earlier examples have diameters close to 10 cm.[111] Although these crucibles were for melting and smelting copper, they illustrate a parallel technique of winning metals utilized concurrently with the better-documented technique of smelting in a furnace.

CONCLUSIONS

To summarize, the evidence from Göltepe suggests that fired ceramic fragments may have functioned as crucibles with charcoal and a charge of stanniferous materials placed inside. The interiors of the crucibles were heavily reduced, and the inside surfaces were fired to a higher temperature than the exteriors. The tin-containing materials include both slag droplets and driplets, which scarcely wet the refractory, as well as a tin-oxide powdery interior surface layer that may indicate that a vapor phase reaction occurred at the surface. Bloating is limited to the interior surface, the replication of which provides an upper limit of 1000° C for the firing temperature; analysis of the microstructure indicates a maximum temperature of about 950° C. The bloating, adhering droplets of tin slag, and the tin-containing, powdery surface layer indicate that the surfaces were chemically and thermally altered in a process that involved the production of tin.

The nature of this process can be delineated, involving a reduction atmosphere, disequilibrium sintering, and a firing period of short duration. From the high viscosity of the slags, we suggest that probably two or more cycles of heating processes were carried out with a grinding, picking, and separation operation in between smelts. The Göltepe crucibles demonstrate a long continuity of such a process in the eastern Mediterranean area, and perhaps represent the end of a long tradition. By this time copper smelting had gone to tap slagging in furnaces in this region.

It is important to point out that Kestel and Bolkardağ are only two of probably many tin-bearing sources located in small but significant pockets in many areas of the Near East. The materials analyzed here provide clues about the emergence of tin production in a critical metalliferous zone. These investigations should next be coupled with a study of metal processing, considering which ores were used, and how much control was practiced over the production of tin metal during this formative period of metalworking specialization.

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1958 [Mainz 1969] 111, fig. 9; see also K. Branigan, *Aegean Metalwork of the Early and Middle Bronze Age* [Oxford 1974] pl. 44). In central Anatolia, Kültepe Ib yielded multifaceted stone molds and crucibles in a metal workshop dated to the later MBA: T. Özgüç, "Report on a Work-shop belonging to the Late Phase of the Colony Period Ib," *Belleten* 73 (1955) 77–80. For MB crucibles from Demircihöyük see M. Korfmann, *Demircihöyük* I: *Architektur, Stratigraphie und Befunde* (Mainz 1983) 160–61. LBA crucibles are also described from the Cape Gelidonya shipwreck: G.F. Bass, *Cape Gelidonya: A Bronze Age Shipwreck* (*TAPS* n.s. 57.8, Philadelphia 1967) 127 fig. 136: st 3–4. Crucibles were also found in Israel: for MB II examples at Hazor, see I. Yadin et al., *Hazor* I (Jerusalem 1958) pl. CXVIII.9–12; and B. Rothenberg, *The Egyptian Mining Temple at Timna* (London 1988) 196–97. Although not dated precisely, a large array of metallurgical remains were located in the western Sinai peninsula; see I. Beit-Arieh, "Serabit el-Khadim: New Metallurgical and Chronological Aspects," *Levant* 17 (1982) 111.

[109] V. Karageorghis, *Kition: Mycenaean and Phoenician Discoveries in Cyprus* (London 1976); R.F. Tylecote, "Observations on Cypriote Copper-Smelting," *RDAC* 1971, 53–58, discusses the technique using such a smithing hearth. The heat would come from above, thus making a large and shallow crucible most efficient in this case, contra H.H. Coghlan, *Notes on the Prehistoric Metallurgy of Copper and Bronze in the Old World* (Oxford 1975) 71–72, who considers the smaller crucibles to be more efficient.

[110] H.H. Ecsedy, "On the Early Development of Prehistoric Metallurgy in Southern Transdanuba," *Godisniak* 26 (1990) 225, fig. 8; also supra n. 98.

[111] Tylecote (supra n. 97) 183–227.