the strengths of various Fraunhofer lines from the mid-photosphere and chromosphere and have concluded that the source of the solar cycle variation in S_c is the facular brightening associated with magnetic fields that penetrate the upper layers of the solar atmosphere (*9, 22*). The correspondence between changes in S_c and in the Lyman α radiation, which is formed in the upper chromosphere, supports this idea. Other studies, however, have suggested that only part of the physical origin of the S_c variation is facular, the remainder being attributed to either global pulsations (*5*) or photospheric temperature variations (*23*). It remains to be seen whether mechanisms for S_c variations, other than a solar cycle variation in facular emission, can also account for coupling between S_c and the Lyman α emission.

It will be of interest, in the future, to determine how changes in the entire solar spectrum, not just the UV portion, correspond to variations in total irradiance. In particular, measurements of irradiance variations at wavelengths from 300 to 400 nm, which may account for some 13% of the total irradiance variability, have yet to be made with sufficient precision to permit a reliable evaluation of the contribution of this spectral region to total irradiance variability or to establish the relative roles of sunspots and faculae for understanding either the day-to-day variations or the solar cycle trends. Simultaneous observations by ACRIM II and SUSIM, both to be launched on the Upper Atmosphere Research Satellite, should allow an improved understanding of both the total and the UV solar irradiance variations.

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21 October 1988; accepted 21 February 1989

Kestel: An Early Bronze Age Source of Tin Ore in the Taurus Mountains, Turkey

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An ancient mine located at Kestel on the outskirts of Niğde, in the Taurus Mountains of south central Turkey, has been dated by radiocarbon and pottery type to the third millennium B.C. Archeological soundings in the mine located cassiterite (tin oxide) in the detritus of ancient mining activity. Cassiterite is also present in veins and, as placer deposits, in streams nearby. Since tin is used with copper in order to form bronze but is thinly distributed in the earth's crust, the presence of tin ore at Kestel offers a source for the much sought after tin of the Bronze Age. The discovery of an ancient mine containing cassiterite sheds light on this question, but also greatly complicates the accepted picture of regional economic patterns in the highland resource areas of Anatolia and of interregional metal exchange in the formative periods of urbanization and metal use in the eastern Mediterranean.

The Bronze Age began in southwestern Asia in the fourth millennium B.C. with the introduction of metal objects in which copper had been alloyed primarily with arsenic or tin. Metal assemblages excavated from major urban centers of ancient Anatolia, Syria, and Mesopotamia reveal the development of an alloy of copper with 5 to 10% tin (*1*). This development from arsenical copper to tin bronze occurred largely during the third millennium B.C. By the mid–second millen-

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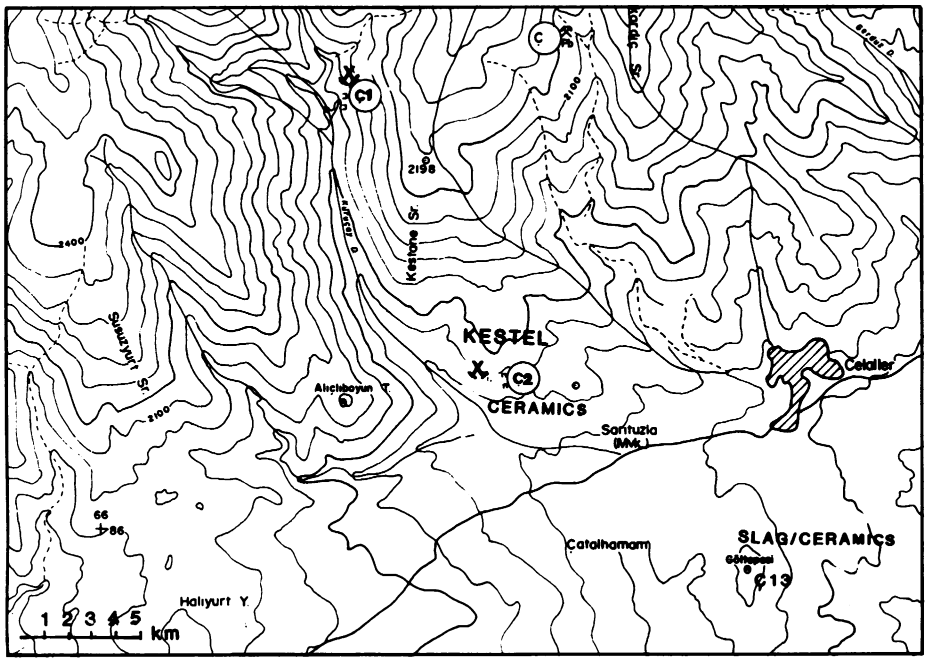

Fig. 1. Map of the mining district of Kestel in the central Taurus Mountains in Turkey (Ergun Kaptan).

nium, bronzes containing substantial amounts of tin are found at most sites in the eastern Mediterranean. The integration of the new alloy into the metallurgical repertoire, replacing arsenical coppers, progressed at variable rates throughout southwestern Asia. Although iron artifacts in small numbers have been excavated in these early stratigraphic contexts, the use of iron as a widespread substitute for bronze did not occur until the first millennium B.C. (*2*).

The highland regions of Turkey and Iran have often been referred to as the source of metals and minerals missing in the undifferentiated environments of Mesopotamia and Syria. Although sources of copper for this period have been more easily identifiable in part because of continued exploitation (*3*), sources of tin have remained an archeological enigma. Tin ore is thinly distributed in the earth's crust and has been exploited in only a few places in the world. The failure of archeological and geological surveys to locate tin ores for the Bronze Age in Turkey or Iran led to the examination of remoter sources such as Cornwall in the British Isles, Malaysia, the mountains of the Hindu Kush in northern Afghanistan, Bohemia, and Nigeria (*4*). Additional evidence supporting distant geographic sources of tin arose from interpretations of early second millennium B.C. texts, such as the Assyrian Trading Colony tablets from Kültepe (ancient Kanesh). There thousands of cuneiform tablets were found which documented a complex commercial network tying together Anatolian market centers with sites in Syria and Mesopotamia. The strategy of this interregional trade focused on textiles and metals, primarily silver and gold originating in Anatolia, and *anaku* (Akkadian, translated as "tin"), transshipped through Assur in northern Mesopotamia from an unspecified location (*5*). The accepted conclusion of this search for ancient tin was one of sourcing the metal for the entire extent of the Bronze Age outside the eastern Mediterranean.

In 1984, as part of a project in which lead-isotope ratios and trace compositions of ores and objects were being used to determine exchange patterns of silver, traces of the tin-containing mineral stannite (Cu_2FeSnS_4) were discovered at Sulucadere, in the Taurus mining district of Bolkardağ (*6*). Since cassiterite (tinstone, SnO_2), which is the sole economic ore of tin, can be found as a weathering product of stannite (*7*), cassiterite was searched for in the general area and subsequently identified in placer deposits in streams in the Taurus foothills near Niğde (*8*). In addition to cassiterite, the minerals observed in samples panned from these streams included hematite, magnetite, garnet, tourmaline, apatite, scheelite, cinnabar, pyrite, pyrrotite, rutile, titanite, monazite, and gold. The streams are located near the Ecemiş corridor, a natural fault zone providing access through the mountains from the central Anatolian plains to Cilicia and the Mediterranean Sea. The area is characterized by paleozoic marble, amphibolite, quartzite, and gneiss cut by granite intrusions.

A preliminary survey of this area in 1987 identified several streams which yielded cassiterite. Among the placer deposits of cassiterite sampled by the Turkish Geological Research and Survey Directorate, the highest concentration was found at a stream called Kuruçay, situated between survey locations Ç1 and Ç2 (Fig. 1). Slag from several deposits in the vicinity of Eskigümüşler and Çamardı yielded high trace levels of tin (2500 ppm), suggesting a source nearby. These survey locations are 35 km southeast of the city of Niğde and about 2 km from the village of Celaller near Çamardı. Open pit mines and mine entrances, mostly collapsed, were found in an area, 2 km^2, on one of the south-facing slopes of a huge crystalline dome formation, the Niğde massif. Mining tools made of gabbro and quartz-tourmaline were found on the slope in vast profusion, suggesting that they may have been used in the construction of the shaft and gallery systems. The gabbro source was most probably an outcrop located 1 km to the southwest. Twelve hitherto unknown archeological sites were mapped in proximity to Çamardı. Ceramics on this slope dated from the late Chalcolithic through the Byzantine and suggest a continual exploitation of this natural resource.

One mine (Ç2 in Fig. 1) called Kestel-Sarıtuzla is located at 1800 m above sea level and 200 m above the cassiterite-bearing Kuruçay stream. The underground system (Fig. 2) measures approximately 40 m in its greatest surveyed extent. Originally a natural cavern, several tunnel-shaped shafts branch off, having been made by following and mining out natural veins, which also filled alcove-like cavities in the limestone. These galleries were no wider than necessary to allow access, in some sections no more than 60 cm in diameter. Several collapsed shafts suggest a larger, interconnecting system.

Several 1 by 2 m soundings (S.1 through S.4 in Fig. 2) were initiated inside the mine. One sounding (S.2) was made at the meeting point of three more or less vertical tubular shafts in the deepest accessible section of the mine, at a spot where a mortar-like object of gabbro, marked with circular grooves, was found in situ. Excavation proceeded in 5-cm increments. The accumulated deposit yielded late Chalcolithic and Early Bronze Age (late fourth through the third millennium B.C.) sherds. Late Chalcolithic ceramics include dark-faced burnished, plain simple, and painted wares. The shapes are mostly flaring neck jars and deep bowls. Pottery indicative of the Early Bronze Age include red and black burnished wares (Karaz-Pulur–Khirbet Kerak), shaped mostly into carinated bowls. The ceramics from this and the other soundings will, once dated, allow a reconstruction of the time span for the mineral exploitation. Aside from the ceramics found throughout the deposit, charcoal, animal bones, a gabbro hammerstone, a seed tentatively identified as mallow (*Malva*), and a metal artifact, not yet analyzed, completed the finds. The original floor was reached at a depth of 93 cm.

Charcoal was found at one level in sounding S.2, at a depth of 68 cm in the floor deposit, associated with bones and sherds. The identification of the bones (*9*) yielded important information about the diet and environment of the miners. The bones are of various animal species: domestic goat (*Capra hircus linneaus*), an ungulate (*Bovidae sp.* probably *Bos*), dog or other canine (*Canis sp.*), and rodent (*Rodentia sp.*). The charcoal sample was examined for wood microstructure (*10*) and indicated the presence of oak (*Quercus sp.*), coniferous wood probably either fir (*Abies sp.*) or juniper (*Juniperus sp.*), and possibly almond (*Prunus sp.*). Four charcoal samples gave radiocarbon determinations from 4020 ± 80 to 3830 ± 65 years before present, calibrated to 2874 to 2133 B.C. (*11*), dating the use of Kestel mine at this level firmly in the Early Bronze Age.

What was being mined here in antiquity? The location of the mines above the cassiterite-bearing stream suggested that these mines may also have contained tin. To determine the nature of the original ore, several samples from the floor deposit, which represents the detritus of mining, were taken from a depth of 68 cm for identification of the minerals present. The deposit was coarsely particulate, and when the sample was separated by heavy liquid separation and magnetic sorting, the heavy fraction contained particles chiefly of the iron minerals hematite and magnetite. A number of visually identifiable particles from this level gave energy-dispersive spectra of tin with minor amounts of silicon and iron, suggesting that these particles were of nearly pure cassiterite, which was confirmed by the x-ray diffraction of several samples, one of a single, well-formed tetragonal crystal (Fig. 3).

The cassiterite in the mine is concentrated mainly within the granite intrusion, near quartz-hematite veins and minor occurrences in pegmatites and tourmaline-bearing quartz veins. It is important to point out that veins of cassiterite-bearing hematite as well as tin-bearing quartz were found exposed due to collapse of the roof of a mine shaft immediately upslope, and large amounts of hematite were also found discarded outside the mines. The Kuruçay stream produced the highest concentration of cassiterite among all the tin-bearing streams in the Niğde Massif. The presence of cassiterite in the streams, in the collapsed veins and within Kestel mine at a level in the deposit of mining detritus which was radiocarbon dated to the Early Bronze Age demonstrates that tin ore was available in the Taurus Mountains at the inception of bronze use in the eastern Mediterranean (*12*). The possibility remains that other minerals also were present in the mine, but our investigation thus far indicated that tin was the important component.

The original abundance of cassiterite in Kestel mine itself may be impossible to assay since it appears to have been mined out in antiquity. The trace element analysis of the remnant tin-bearing quartz and hematite veins inside the gallery yielded 700 ppm of tin. However, a visual assessment of a small sample of the floor deposit at the 68-cm depth suggests that cassiterite is about 5% by volume of the heavy-mineral fraction. High yields of tin (2480 ppm) were analyzed in the alluvial deposits from the Kuruçay stream immediately below the mine. Corroborative evidence comes from the results of semiquantitative optical spectral analyses of the panned stream sample. This sample yielded tin as the major element (*13*). Preliminary experiments heat-treating an unsorted sample of the exposed tin-bearing quartz vein a few meters from the Kestel

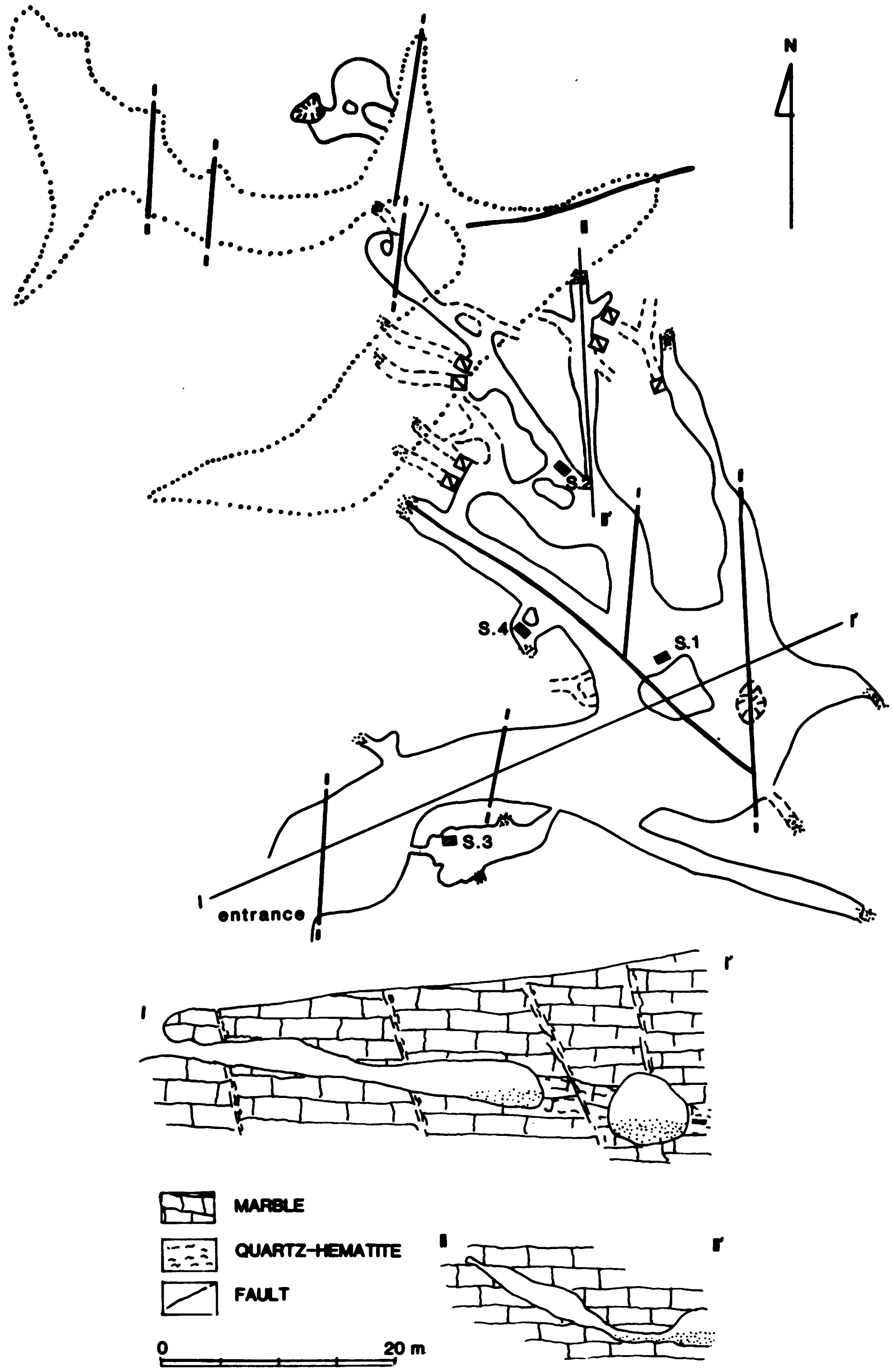

Fig. 2. Plan view and cross sections of Kestel mine (Ç2), with archeological soundings S.1 to S.4 indicated (Necip Pehlivan).

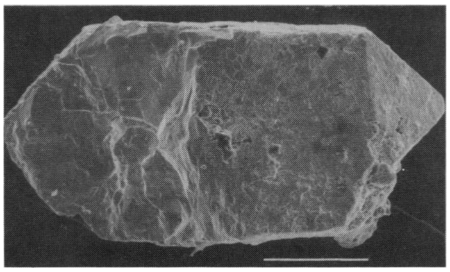

Fig. 3. Scanning electron micrograph of a crystal from a depth of 68 cm in Kestel mine; it was identified by x-ray diffraction as cassiterite. Scale bar, 100 μm.

mine entrance yielded globules of tin silicates containing up to 25% tin. This enrichment occurred at 400° and 800°C, which represent temperatures achievable in camp fires, but not at 1000° or at 1200°C, the minimum commercial smelting temperature for tin (*14*). The ore may have been ground in circular, mortar-like depressions in the country rock, which were found abundantly in a 1 km^2 area around the entrance of the mine. At a large specialized function site, Göltepe (Ç13) facing the mine, an estimated 25,000 groundstone tools suitable for ore processing were surveyed. The metallurgical processing and the reconstruction of smelting practices relevant to this mine are still under investigation and are complicated by the possibility that SnO_2 was used directly with copper to produce the alloy (*15*).

Lead isotope ratios were measured in several samples from the Kuruçay stream and from Kestel mines Ç1 and Ç2 (Fig. 1). Preliminary results indicate that these samples have the same isotopic signature, suggesting a similar source for the cassiterite in the Kestel mines and in the tin-bearing stream below. These lead isotope ratios represent part of the ores that we have characterized for the central Taurus range (*16*).

The wider implications of tin sources in the Taurus Mountain passes accessible to sites in southwestern Asia touch on the major archeological problem of the cultural fluorescence of late Chalcolithic and Bronze Age Anatolia (*17*). The development of Anatolian metallurgical technologies, indigenous resource management, and interregional metals trade can now be investigated within the context of this highland resource area. The exploitation of the Taurus polymetallic ores throughout the Bronze Age, which included copper, silver, and gold as well as tin, has enlarged our understanding of the formative processes of metal production. The early production and distribution of metal certainly had an economic effect on the producers of metals. Importantly, the access to critical metal resources located near a strategic crossroads could account for the countless intangible cultural connections in southwestern Asia, the eastern Mediterranean, and Mesopotamia so apparent in the archeological record but unexplained for so long.

These discoveries finally may resolve the origin of the elusive tin of antiquity and, in so doing, refocus the field of inquiry from a search for sources of tin ore to that of clarifying the scope and nature of the institutions that regulated metal technology and trade in the resource areas of Anatolia. Contrary to present archeological thought for the Middle Bronze Age, which has solely stressed the import of "eastern" tin into this region (*18*), our evidence suggests that some local tin sources were being exploited at that time—a social, political, and economic situation more complex than is reflected in the Assyrian trading colonies texts from Kültepe. Although Assyrian merchants may have been importing tin into the Anatolian colonies, an indigenous circulation of local resources akin to the Anatolian copper trade, may have existed as well. Viewed in this perspective local mining appeared to coexist with large-scale metal exchange. It may be conceivable that several sources of tin were exploited contemporaneously, which supports the validity of wider networks of interaction (*19*). The complexity of the distributional patterns of metals extracted during this intensely entreprenurial period remains to be elucidated.

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19 December 1988; accepted 13 March 1989