ANTHROPOLOGY

Tin from Uluburun shipwreck shows small-scale commodity exchange fueled continental tin supply across Late Bronze Age Eurasia

Wayne Powell[1,2]*, Michael Frachetti[3,4]*, Cemal Pulak[5], H. Arthur Bankoff[6], Gojko Barjamovic[7], Michael Johnson[8], Ryan Mathur[9], Vincent C. Pigott[10], Michael Price[11], K. Aslihan Yener[12]

This paper provides the first comprehensive sourcing analysis of the tin ingots carried by the well-known Late Bronze Age shipwreck found off the Turkish coast at Uluburun (ca. 1320 BCE). Using lead isotope, trace element, and tin isotope analyses, this study demonstrates that ores from Central Asia (Uzbekistan and Tajikistan) were used to produce one-third of the Uluburun tin ingots. The remaining two-thirds were derived from the Taurus Mountains of Turkey, namely, from stream tin and residual low-grade mineralization remaining after extensive exploitation in the Early Bronze Age. The results of our metallurgical analysis, along with archaeological and textual data, illustrate that a culturally diverse, multiregional, and multivector system underpinned Eurasian tin exchange during the Late Bronze Age. The demonstrable scale of this connectivity reveals a vast and disparate network that relied as much on the participation of small regional communities as on supposedly hegemonic institutions of large, centralized states.

INTRODUCTION

By 1500 BCE, bronze was the "high technology" of Eurasia. Iconic ancient states, such as the Shang (China), Mycenean (Greece), and Assyrian (Iraq), used bronze for military power and social prestige, as well as for common tools and utensils. During this period, small- and large-scale communities sought access to its main components: copper and tin. Copper was relatively abundant throughout Eurasia, with porphyry copper ores occurring throughout the Pontic-Caucasus-Zagros mountains, sedimentary copper deposits in eastern Egypt and the Levant, and volcanogenic deposits in Cyprus. Given this wide distribution, copper deposits lay within reach for all major states of the Eastern Mediterranean and Near East. Tin, however, is more than 30 times less abundant than copper in the Earth's crust (*1*), and conditions under which tin deposits form are geologically limited. Furthermore, unlike copper, most deposits of tin lay far from major urban centers of the ancient world. Throughout the second millennium BCE, the acquisition of tin was thus a strategic military and economic endeavor, comparable to crude oil today. As a result, scholars have long speculated about the ore sources and exchange trajectories that funneled tin across Eurasia toward major markets of consumption during the Late Bronze Age (LBA; ca. 1650 to 1200 BCE) (*2*).

[1]Department of Earth and Environmental Sciences, Brooklyn College, Brooklyn, NY 11210, USA. [2]Earth and Environmental Sciences Program, The Graduate Center, New York, NY 10016, USA. [3]Department of Anthropology, Washington University in St. Louis, St. Louis, MO 63130, USA. [4]School of Cultural Heritage, Northwest University, No. 229 Taibai Road, Xi'an, Shaanxi Province, China. [5]Institute of Nautical Archaeology at Texas A&M University, College Station, TX 77843, USA. [6]Department of Anthropology, Brooklyn College, Brooklyn, NY 11210, USA. [7]Department of Near Eastern Languages and Civilizations, Harvard University, Cambridge, MA 01238, USA. [8]Stell Environmental Enterprises, Exton, PA 19341, USA. [9]Geology Department, Juniata College, Huntingdon, PA 16652, USA. [10]Asian Section, University of Pennsylvania Museum, Philadelphia, PA 19104, USA. [11]Michael Price, Santa Fe Institute, Santa Fe, MN 87506, USA. [12]Institute for the Study of the Ancient World at New York University (ISAW), New York, NY 10028, USA.
*Corresponding author. Email: wpowell@brooklyn.cuny.edu (W.P.); frachetti@wustl.edu (M.F.)

Here, we document the confluence of distant tin ore sources among the cargo of the Uluburun shipwreck. Excavations of the LBA shipwreck [1320 cal. BCE ± 15 2σ (*3*)], found off the coast of Turkey (Fig. 1), yielded the world's largest Bronze Age assemblage of raw metals ever found (*4*). The ship's primary cargo consisted of 10 metric tons (MT) of Cypriot copper ingots (*5*) and a staggering 1 MT of tin ingots, easily the largest and most securely dated collection of ancient tin metal known worldwide (*6*). Archaeologists and historians have long sought to trace the sources of tin needed by rival Mediterranean empires, whose expansive imperial goals demanded powerful war machines by the LBA. These empires, embroiled in extensive political conflict and warfare, were important metal consumers with demand likely exceeding hundreds of metric tons per year. Using the common LBA ratio of 9 parts copper to 1 part tin, the Uluburun tin cargo could have produced 11 MT of bronze of the highest quality, enough to outfit a force of almost 5000 Bronze Age soldiers with swords.

While tin was arguably the most critical hard commodity in Eurasia for over 2000 years, the exact sources of tin and its distribution networks across Eurasia have remained largely speculative, with few exceptions. Here, we provide the first comprehensive analysis of 105 tin ingots from the Uluburun shipwreck (91% of the total tin cargo) using a combined methodology of Pb isotope, trace element, and Sn isotope analyses. This systematic approach permits reexamination of the possible sources of Uluburun tin and demonstrates that the composition of two-thirds of the ingots is consistent with a source in the nearby Taurus Mountains of Turkey. In addition, we document the chemical fingerprints of the remaining one-third ($n = 35$) of the tin ingots, tracing them to ore deposits in Tajikistan and Uzbekistan, over 3000 km east of their final resting place.

The geochemical analysis of the Uluburun tin ingots reveals that the ores were not only sourced from vastly distant locations but that these regional ores converged to supply the bronze trade in the Mediterranean. Coupled with tin's geological rarity, geographic distance from major ancient population centers, and logistical complexity to procure, the tin ingots from Uluburun thereby index a

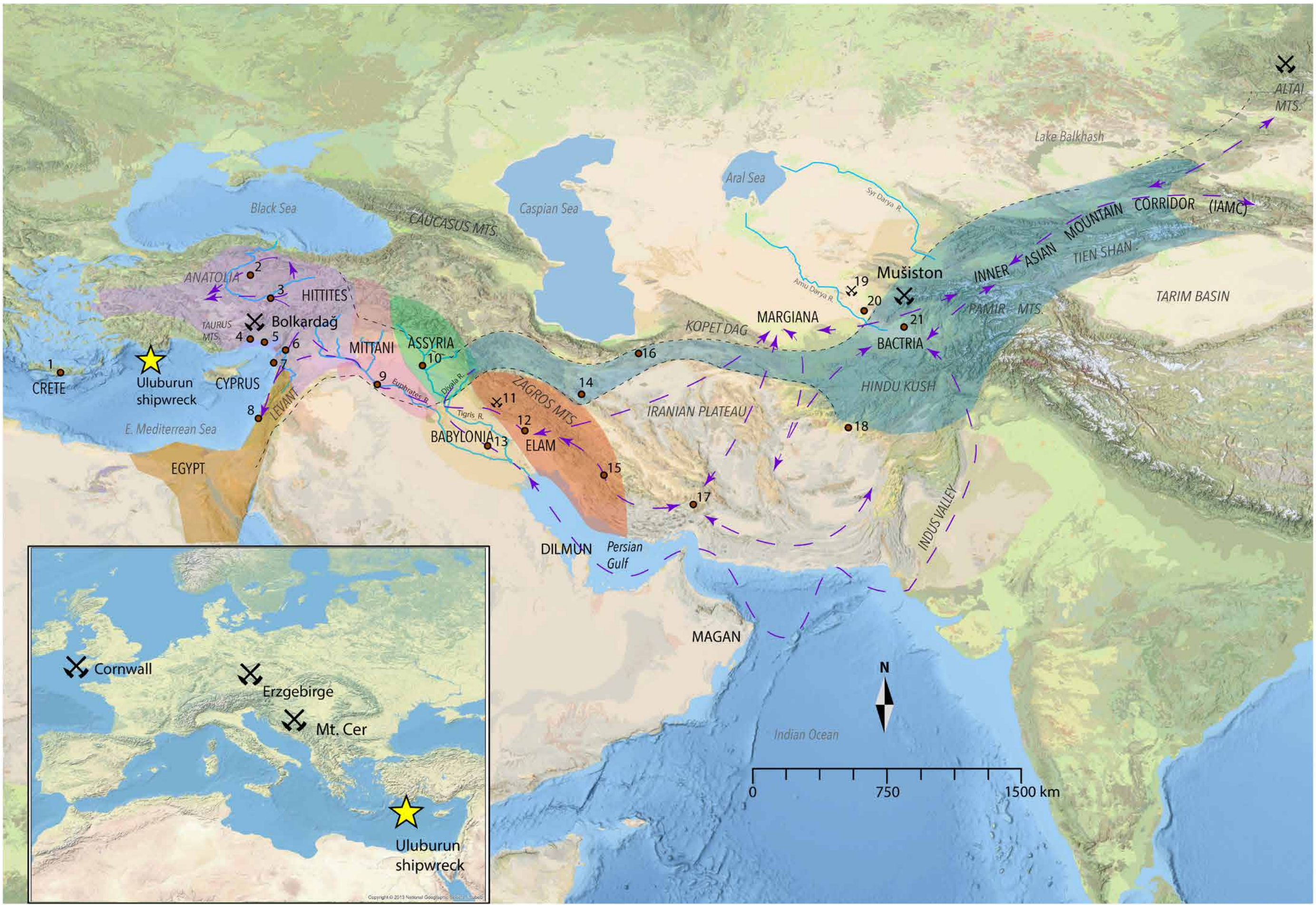

Fig. 1. Regional geography and main sites. 1, Hagia Triada; 2, Hattusa; 3, Hisarcık; 4, Mersin; 5, Tarsus; 6, Alalakh; 7, Ugarit; 8, Haifa; 9, Mari; 10, Assur; 11, Deh Hosein; 12, Susa; 13, Ur; 14, Arisman; 15, Tal-e Malyan; 16, Tepe Hissar; 17, Tepe Yahya; 18, Mundigak; 19, Karnab/Sichkonchi; 20, Sapalli; 21, Shortugai. Purple dashed arrows depict documented trade networks ca. 2200 to 1700 BCE. Blue shaded region reflects the corridor connecting the Anatolian and Central Asian/Middle Eastern tin trade (in blue), ca. 1600 to 1000 BCE. Other shaded areas represent key LBA polities. Inset map illustrates the location of ancient tin sources in Europe.

vast interconnected landscape of regional operatives and socially diverse participants who produced and traded essential hard-earth commodities throughout the LBA political economy from Central Asia to the Mediterranean in the late second millennium BCE. Ultimately, our findings suggest that LBA tin exchange required participation of communities ranging from small-scale highland populations to urbanized states to meet the abundant demand for bronze, which stimulated long-distance connectivity between Near Eastern urban centers and mining communities from Anatolia to Central Asia.

RESULTS

All 105 Uluburun tin ingots analyzed yield $^{208}Pb/^{204}Pb$ values that are consistent with Late Paleozoic to Cenozoic ores, except for KW 0516, which was derived from an older source. Tin isotope ($\delta^{124}Sn$) values span ~2 per mil (‰) from −0.88 to 1.24‰ with a median of 0.70‰ (table S1). Organizing the data according to their isotopic signature and their geological age allows for the identification of eight ingot groupings (Fig. 2B): three derived from Late Paleozoic ores (P1, P2A, and P2B) and five from a Late Mesozoic to Cenozoic source (MC1A, MC1B, MC1C, MC2A, and MC2B). Blind clustering of samples using *t*-distributed stochastic neighbor embedding (*t*-SNE) analysis statistically verified these groups (Fig. 3), where the four variables input to the *t*-SNE algorithm reflect independent aspects of the metal: $^{208}Pb/^{204}Pb$, $\delta^{124}Sn$, $^{206}Pb/^{204}Pb$ Pb inputs, and Pb concentration.

DISCUSSION

Mesozoic-Cenozoic ore groups

The Uluburun tin cargo includes a morphologically diverse (oxhide, slab, bun, and stone anchor shaped; Fig. 4) group of Pb-enriched ingots (MC1) that were produced from ores collected in the Taurus region and subsequently pooled and smelted at the nearby Pb-Ag mining center of Bolkardağ where extraneous Pb was added (*7*). Comparison of median $\delta^{124}Sn$ from tin ingots and tin ores from across Europe and Central Asia (*8*) further supports this conclusion, with 49 Pb-enriched ingots being comparable to the Taurus tin ores of Kestel and Hisarcık (Fig. 5). This is also true for 11 oxhide and slab ingots (MC2) with $^{208}Pb/^{204}Pb$ consistent with slightly older mineralization in the Taurus Mountains, likely Aladağ. Note that

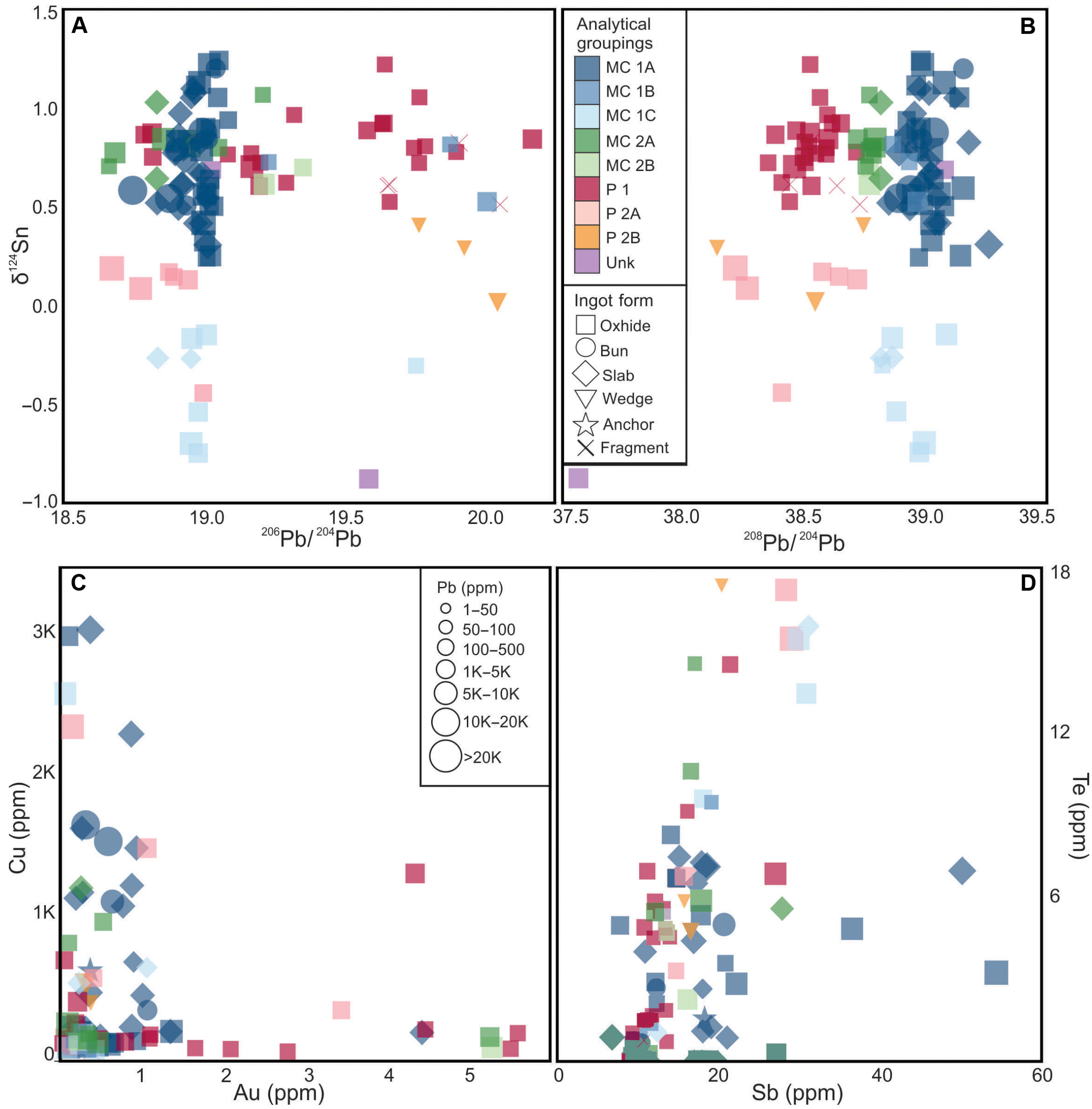

Fig. 2. Cross-plots of Uluburun tin ingot compositions. (**A**) δ^{124}Sn versus ^{206}Pb/^{204}Pb; (**B**) δ^{124}Sn versus ^{208}Pb/^{204}Pb; (**C**) Cu versus Au; (**D**) Sb versus Te. Analytical groupings correspond to isotopic and chemical composition correlated with age: MC, Mesozoic-Cenozoic; P, Paleozoic; Unk, unknown; icon shape corresponds to ingot form; icon size reflects Pb concentration. Note that axes in (D) are limited to 60 parts per million (ppm) of Sb for readability, thereby omitting three bun ingots with Sb > 100 ppm (KW 199, KW 847, and KW 1326). Similarly, samples KW 198, KW 199, and KW 2874 with Cu > 5800 ppm were omitted.

while Serbian tin ores are similar in composition to the MC2 group, the extent of exchange of tin from this small deposit is archaeologically conscribed within west-central Serbia (*9*).

Group MC1C is defined as a subset of seven Bolkardağ-derived ingots (oxhide and slab) with negative δ^{124}Sn values (Fig. 5). The polymetallic ores of Bolkardağ include stannite (Cu_2FeSnS_4) (*10*), a mineral typically associated with negative Sn isotopic values (*11*), and the analysis of one sample of stannite form Bolkardağ ore yielded a δ^{124}Sn value of −1.94‰, although further work is required to document the true range of values associated with these ores. Hydrostannates such as mushistonite {[Cu, Zn, Fe]Sn$(OH)_6$} and cassiterite (SnO_2) are the ultimate weathering products of stannite (*12*, *13*) and may have accumulated in nearby river sediments (*14*). Furthermore, given the greater bond strength of Sn in the oxidized product, the Sn isotopic composition of the oxides would shift somewhat to higher values. Accordingly, the most likely known source for group MC1C is the Maden stream, which flows below the polymetallic mineralization of Bolkardağ. Thus, 68 Uluburun tin ingots (65%) are interpreted to have been produced in the Taurus Mountains of Turkey.

Paleozoic ores groups

Lead isotope analysis (LIA) indicates that 35 of the remaining ingots were derived from Late Paleozoic ores. Twenty-six of these samples (group P1) are characterized by moderate to high δ^{124}Sn (median, 0.79‰) and variable enrichment in ^{206}Pb and were cast in the oxhide

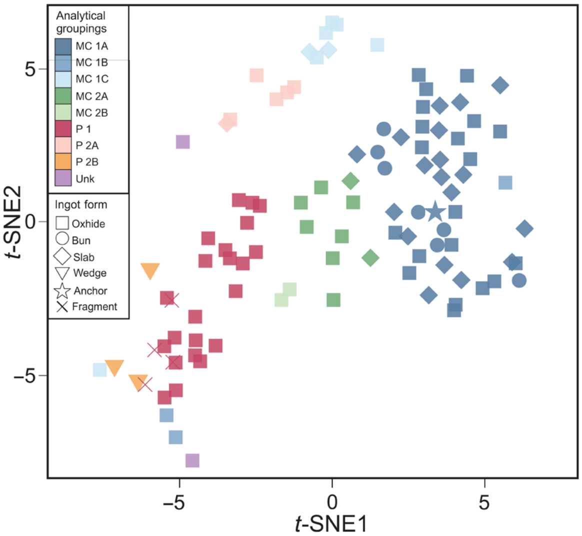

Fig. 3. Two-dimensional *t*-SNE plot showing visual clusters of proximal points (samples). The input variables to the *t*-SNE algorithm were three isotopic ratio measurements for lead and one for tin (position), corresponding to defined analytical groupings (color) and ingot form (shape). Analytical groupings correspond to isotopic and chemical composition correlated with age: MC, Mesozoic-Cenozoic; P, Paleozoic; Unk, unknown; icon shape corresponds to ingot form.

form. High Au, low Cu, Ag, and Pb and incorporation of radiogenic ^{206}Pb suggest a placer origin.

Nine samples (group P2) have low δ^{124}Sn (median, 0.14‰): Three wedge-shaped ingots (P2B) are enriched in ^{206}Pb but not the six oxhide ingots (P2A). As with P1, the chemical signature suggests that P2B was derived from stream tin. The only documented Late Paleozoic tin sources with comparably low δ^{124}Sn are the stannite and secondary cassiterite-bearing Mušiston deposit in Tajikistan and deposits in the eastern Altai region of Kazakhstan (Fig. 5).

The provenance of the two remaining tin ingots is uncertain. The ^{208}Pb/^{204}Pb value of KW 0516 indicates a non-European Late Precambrian source. Sample KW 0403 exhibits unusually high ^{207}Pb/^{204}Pb decoupled from ^{206}Pb/^{204}Pb and does not align with currently documented Eurasia sites.

Tin and lead compositional ranges for P1 ingots overlap with tin ores from Cornwall, Sardinia, Erzgebirge, and the Tien Shan Mountains. However, additional constraints narrow the list of potential candidates. Erzgebirge tin trade did not extend to the Mediterranean or Black Sea (*8*, *14*), making it an unlikely contributor to the Uluburun shipwreck tin ingot assemblage. Many of the Uluburun tin ingots, including stannite-associated samples (Mušiston and Bolkardağ) and a subset of P1 ingots, exhibit elevated concentrations of Te compared to the average crustal abundance of 0.03 parts per million (ppm) (*15*). Tellurium enrichment is associated with epithermal mineralization systems (<1-km depth) (*16*), consistent with the 0.5- to 3-km depth of Central Tajikistan's polymetallic tin deposits (*17*). The lode and greisen ores of Cornwall formed at greater depths (2.5 to 6 km) (*18*); the single Te analysis from the English tin ingots has <1.3 ppm of Te; and the P1 group lacks the correlation between Pb, Bi, Sb, and In observed in the Salcombe tin ingot assemblage (*19*). Thus, Central Asia is a more likely origin than Britain for the ingots in question.

The predominantly oxhide form of the P1 tin ingots may provide an additional clue to their provenance. Copper ingots of this form have been documented over a vast area from southern France and Central Germany to central Iraq but are absent from the British Isles (*20*). By the 14th century BCE, copper oxhide ingots had become a Cypriot "commodity brand" (*20*), but the origin of the form predates its adoption in Cyprus. The oldest securely dated full-size copper oxhide ingots have been found on Crete and date to ca. 1500 to 1450 BCE (*20*). LIA indicates that some of these were derived from non-European copper, possibly from Anatolia, Afghanistan, Iran, Southern Russian, or Central Asia (*21*). This raises the possibility that the oxhide form was not indigenous to the Mediterranean but originated farther east (*21*). The presence of Te-enriched examples and oxhide form of the P1 Uluburun tin ingots, along with the presence of Mušiston-derived tin (P2) within the Uluburun cargo, points to a Central Asian origin for the 26 P1 ingots.

LBA tin and the tin trade

What is known about the tin trade in the ancient Near East is based mainly on commercial records from the 19th century BCE found at the central Anatolian site of Kültepe. Written on clay tablets in the cuneiform script five centuries before the Uluburun ship, these texts document an extensive trade in tin ingots and textiles between Mesopotamia and Anatolia but provide only ambiguous references to tin arriving in Mesopotamian from the east (*1*). There are a handful of Assyrian records contemporaneous with the Uluburun ship that refer to trade in tin from Anatolia to Iraq (*22*), but no textual evidence definitively identifies localities from which tin was mined.

Numerous tin deposits have been identified in areas east of the great Bronze Age population centers in Iraq. Those in Afghanistan lack evidence of ancient exploitation (*23*), but copper ore containing cassiterite was mined at Deh Hosein in Iran during the second millennium BCE (*24*). In addition, numerous tin mines and smelting sites dating to the 18th to 11th centuries BCE have been excavated in Kazakhstan (*25*) and, from ca. 2600 to 1250 BCE, in Uzbekistan and Tajikistan (*26*) including the unique stannite-rich mine at Mušiston. Looking westward, tin production sites dating from ca. 3000 to 2000 BCE have been found at Kestel and Hisarcık in south-central Anatolia (Fig. 6) (*9*, *27*, *28*), and placer ores were worked across LBA Europe, including Bohemia-Saxony (*29*), Serbia (*30*), and Cornwall (*19*). With the exception of Anatolia, where tin ores lay within the provincial territory of Hatti, the identified tin ores lie within regions with no identified Bronze Age state formation.

Both ancient texts and archaeology of Central and Western Asia provide insight concerning the apparatuses that supported a vast, interregional network of metallurgical production and transport across this region. Excavations in the mining site of Mušiston (Tajikistan) show that the populations that worked the tin mines were probably seasonal inhabitants supported by a combination of seasonal herding and connectivity with lowland agricultural communities (*26*, *31*). Cities in the adjacent lowlands reached their apogee in the Middle Bronze Age (ca. 2000 to 1500 BCE) and subsequently entered a period of decline in the LBA (*32*). However, during the LBA, this region saw the fluorescence of less aggregated, small-scale settlements, suggesting a shift toward more diversified economic strategies ranging from mobile pastoralism to more integrated forms of agricultural production (*33*). Ecologically situated pastoralist systems coupled with context-specific farming hamlets shaped a complex network of interacting communities concentrated in the piedmont regions of the Inner Asian Mountain Corridor (IAMC). This interaction entangled local communities from the northern edges of the

Fig. 4. Representative forms of tin ingots from the cargo of the Uluburun shipwreck.

Iranian Plateau through the Pamir and Tien Shan foothills eastward toward China and northward to the Altai mountains in shared networks of resource exchange (*34–36*).

After ca. 1500 BCE, the archaeological data suggest a period of considerable and renewed connectivity in terms of commodities and technologies throughout the IAMC (*37*). The northeastward transmission of a range of regionally sourced materials, including ceramics (*38*), textiles (*39*), and newly introduced domesticated crops (*40*), all demonstrate that large networks of contact existed among communities living north-south throughout the piedmont regions of Inner Asia in the late second millennium BCE (*41*). Human genomic data identify increased regional admixtures among Central Eurasian populations throughout the second millennium BCE, establishing clines of admixed central steppe ancestry that spanned throughout the IAMC as far south as the Indus region by 1000 BCE (*42*, *43*).

Research concerning the metallurgical networks that fueled tin-bronze production throughout the IAMC fits documented transmissions in other materials and ideas. The archaeological remains recovered from Mušiston and nearby tin mines at Karnab (Uzbekistan) consist of small-scale occupations and incised coarse-ware ceramics that are typologically similar to those documented among

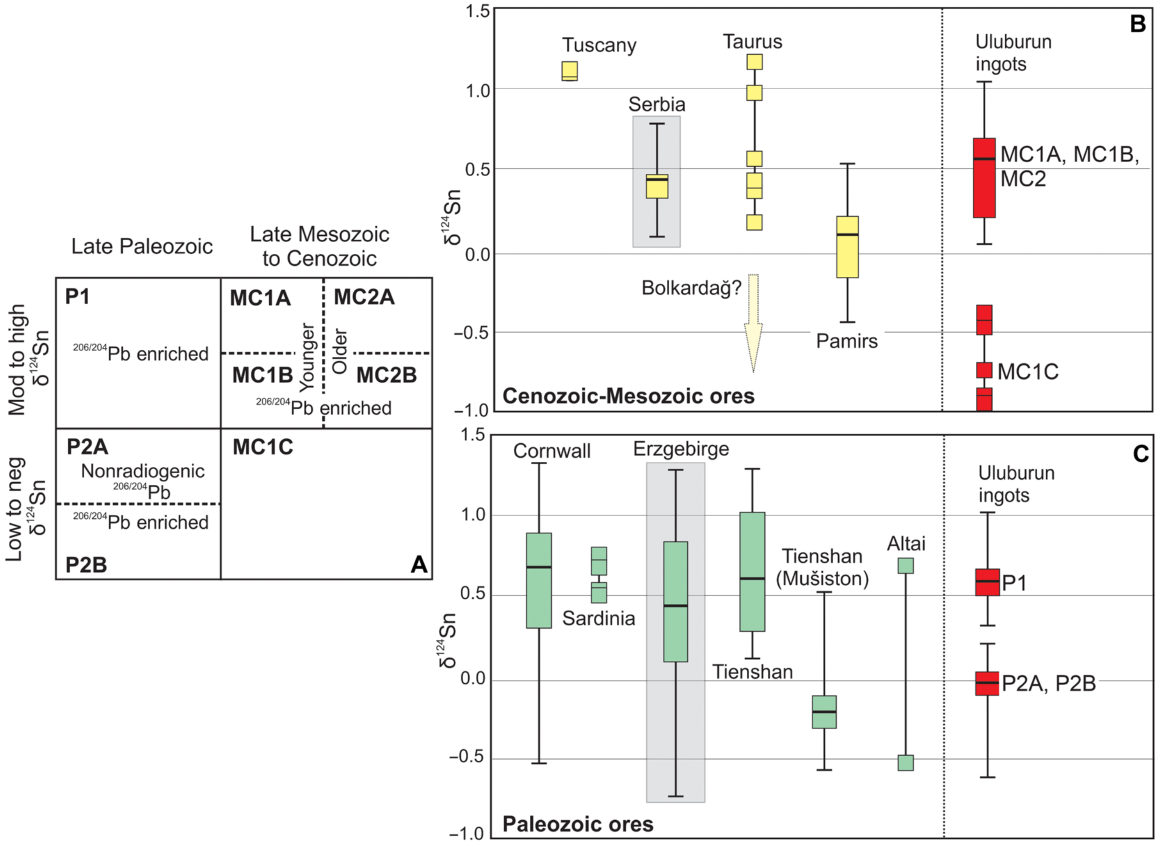

Fig. 5. Characteristics of ingots used to define groupings and comparison of δ^{124}Sn ranges of tin ores from Europe, Anatolia, and Central Asia. (**A**) Isotopic characteristics of ingot groupings; (**B**) Mesozoic-Cenozoic ores and corresponding ingots; (**C**) Paleozoic ores and corresponding ingots. Boxes illustrate the range of the second and third quartiles, and the median is marked with a horizontal line. δ^{124}Sn values of the ingots have been adjusted by −0.2‰ to compensate for fractionation during evaporative tin loss during the smelting process (*8*, *9*). Ores shown to have no presence in the LBA Mediterranean (*9*) are grayed out. Ore data compiled from the work of Berger *et al.* (*51*), Mason *et al.* (*9*), and this study. Note that the δ^{124}Sn values for ores have been reduced to account for the by +0.2‰ fractionation associated with smelting (*7*, *8*).

contemporary agropastoralists of the steppes/IAMC. Evidence for mining technology in the form of stone hammers and small-scale smelting operations is known from settlements along the IAMC from at least 1800 BCE (*44*). Analysis of bronze metals suggests that, by the LBA, bronze production relied on sourcing from a wide range of ores throughout the mountains of the IAMC (*25*). Similarly structured, small-scale communities may also have been engaged in tin trade from Muŝiston (and nearby sources) southward and westward across the Iranian Plateau (*45*). However, the connectivity between the mountainous regions of Inner Asia and Southwest Asia (Iran, Iraq, and the Levant) is less well documented in the LBA. Of notable importance, however, is the rise of communities sometimes described as "mountain tribes," living in the northern highlands of the Iranian Plateau, as well as along the westward piedmont of the Hindu Kush.

Textual evidence from the 19th century BCE for a commercial network moving tin from Central Asia to Mesopotamia is likewise robust (*1*), but the documentation dries up by the 16th century BCE, and chemical analyses of archaeological material from southern Iraq a few centuries later suggest that after 1500 BCE, the region relied mainly on the reuse and recycling of bronze (*46*). Therefore, the origin of the tin ingots from the Uluburun shipwreck demonstrates the continuation of large-scale commercial connections between Central Asia and the Mediterranean in the LBA, perhaps by way of transport routes that circumvented southern Mesopotamia for political reasons.

The potential vectors and transport routes from ancient Bactria (Fig. 1) across the Iranian Plateau have been considered by scholars for decades. The piedmont steppes of northern Iran provide a near-continuous and logical geography linking the mountain pastoralists of the Hindu Kush, Pamir, and Tien Shan to the Bactria-Margiana Archaeological Complex and westward across Iran [e.g., (*41*)]. Laursen and Steinkeller (*47*) describe the trade networks across Iran and the Persian Gulf in the Early and Middle Bronze Ages, suggesting that what has been termed the "Great Khorasan Road" was likely already in operation for the tin trade. The Uluburun cargo demonstrates that the land route continued through the LBA, connecting it to the documented evidence from the Middle Bronze Age (*1*) and suggesting that the Indian Ocean routes may have diminished.

Tin from Turkey

Fundamentally different scales of organization existed between central Asian and Taurus tin production. The recognition of tin ingots from the Uluburun shipwreck with Bolkardağ signatures suggests the existence of a significantly larger and longer-lived tin industry in the south-central Taurus than previously assumed. The available data point to a model of decentralized mining at disparate locations

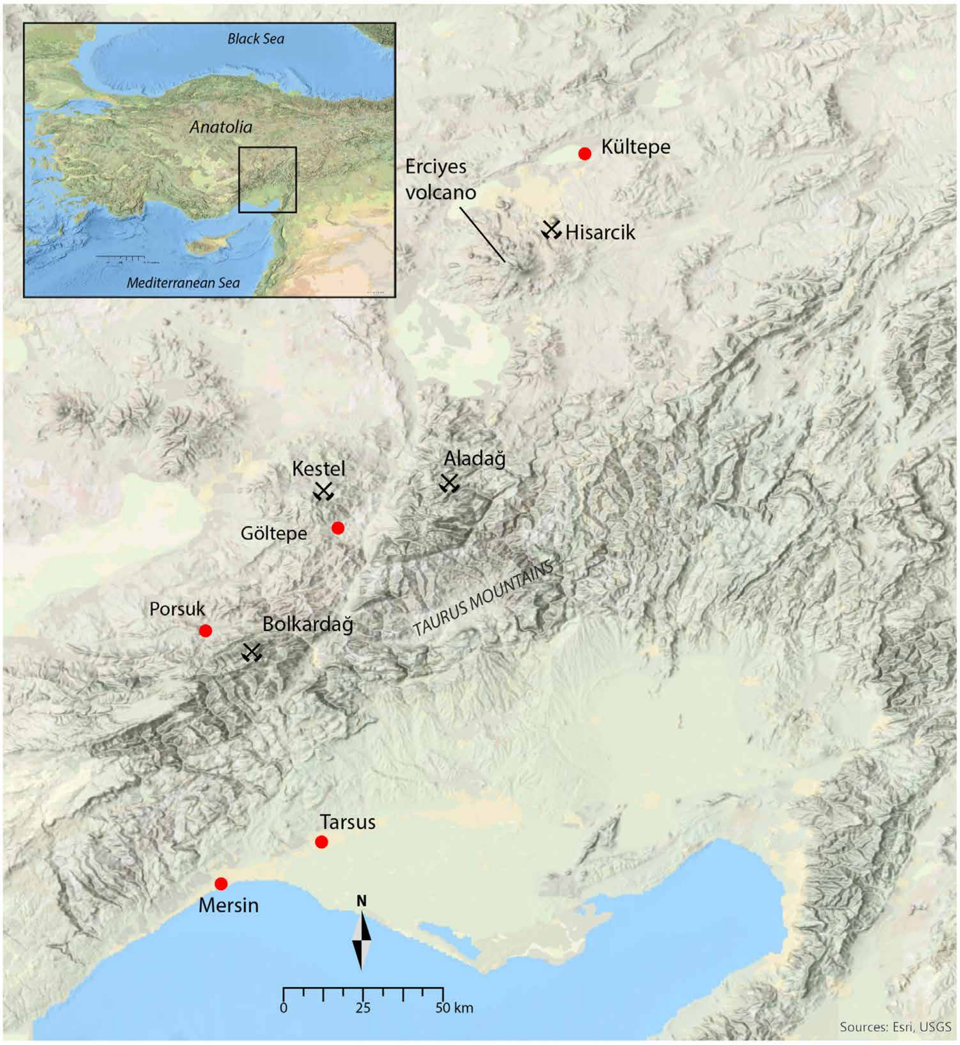

Fig. 6. Regional geography and main sites of south-central Anatolia.

that took advantage of atypical and smaller dispersed tin deposits. Tin ore or raw metal from multiple sources was agglomerated at strategically located hubs close to the tin sources such as the LBA Bolkardağ site of Porsuk at the head of the main Taurus passes (Fig. 6). From primary and secondary transshipment centers, ingots could be brought down to Mediterranean seaports located roughly 1 week away and loaded onto merchantmen such as the Uluburun ship.

Physical evidence of tin circulation within Anatolia is less visible. Sporadic evidence of an intra-Anatolian exchange comes from tax records found at the Hittite state capital (*48*) that are contemporary with the Uluburun shipwreck. These texts point to the accumulation of tin at the provincial capital of Kizzuwatna near the mining areas before the metal was shipped to the imperial capital of Hattusha, 2 weeks distant. International overland trade in Anatolian tin to Assyria and Babylonia (*22*) is documented in texts found at Assur in modern-day Iraq. Presumably, it converged with tin coming from the eastern network that also contributed tin to the Uluburun cargo. A greater degree of Hittite state oversight of Anatolian tin is suggested by these texts, differing from the dispersed nomadic model proposed for Mušiston.

Our analysis of the Uluburun tin ingots reliably documents multiple geographic sources of tin supplying the Mediterranean market for LBA bronze production. Roughly 30% of the Uluburun tin is sourced geologically to Central Asia, demanding a reassessment of the social and economic complexity reflected across diverse modes of political and social organization from the mines to the markets, and ultimately traded on seafaring vessels. The unexpectedly large percentage of tin from the Taurus Mountains (>65%) also requires a reconsideration of the importance of small-scale producers exploiting residual mineralization from previously exploited ores and placer deposits to fuel the major metallurgical industries that underpinned LBA Mediterranean societies and beyond.

While eastern sources of tin have been long speculated in archaeological debates, our data reveal a more socially diverse, multiregional, and multivector system underlying Eurasian tin trade. Anatolia, on whose southern shore the Uluburun ship had foundered, has rarely been suggested as a tin source. However, for Central Asia, a long-proposed source region, the exact provenience for traded tin had never before been documented. Our analysis exposes the complex geography, regional range, and social integrations that characterized

LBA tin trade, a necessary element for the effective production of bronze, a fundamental technology for millennia across Eurasia and beyond.

MATERIALS AND METHODS

A total of 105 Uluburun tin ingots (98% of the preserved metallic tin ingots) were analyzed. Metal shavings were extracted from the nonweathered cores of ingots using a 6-mm high-speed steel (HSS) twist drill bit. All granular and nonmetallic chips were discarded, and the metal shavings were retained in sealed polyethylene bags. Before dissolution, each sample was confirmed to be free of corrosion, inspected with a binocular microscope and scanning electron microscope (Hitachi TM3030Plus operating at 15 kV with an Oxford Instruments AZtec energy-dispersive spectrometer with the Oxford Instruments AZtecOne software platform). Approximately 100 mg of tin metal from each sample was digested in ultrapure concentrated HCl (12 M) heated at 100°C for 6 hours in enclosed Teflon containers.

A total of 17 cassiterite samples were analyzed: 11 single-crystal samples from the Pamirs of Pakistan and eastern Afghanistan and 6 samples from the Taurus region including 4 from Hisarcık and 2 from the Kestel mine. Cassiterite samples were digested following the procedure in (*49*): 0.25 g of −100-mesh cassiterite powder was mixed with 1 g of KCN and heated at 850°C for 1 hour in graphite crucibles contained within capped alumina crucibles. The resulting reduced tin metal beads were then dissolved in heated ultrapure 11 M HCl overnight.

Solutions were purified using the ion exchange chromatography described in (*50*). Samples were measured on the ThermoFinnigan Neptune multicollector inductively coupled plasma mass spectrometry (MC-ICPMS) at Peter Hooper GeoAnalytical Laboratory at the University of Washington, Pullman. The analytical procedure followed the methodology described in (*49*). Mass bias was corrected using Sb-doped solutions and an exponential mass bias correction defined in (*49*). The corrected values were bracketed with the National Institute of Standards and Technology (NIST) 3161A Sn standard (lot no. 07033) and data presented relative to this standard in per mil notation defined as

$$\delta^{124}\text{Sn‰} = \left(\frac{\left(\frac{^{124}\text{Sn}}{^{116}\text{Sn}}\right)\text{sample}}{\left(\frac{^{124}\text{Sn}}{^{116}\text{Sn}}\right)\text{NIST 3161}} - 1 \right) \times 1000$$

Instrumentation 2σ error for δ^{124}Sn based on blocks of 25 analyses is ±0.02‰, and full procedural 2σ error is ±0.08‰ based on 10 measurements of an internal tin metal standard.

The new cassiterite values were added to published Sn isotopic analyses of cassiterite ores compiled from (*8*, *51*), with data from the latter being converted to equivalent NIST 3161 standardized $\delta^{124/116}$Sn values using the following equation: δ^{124}SnNIST 3161a = [$\delta^{124/120}$SnPuratronic × 2] + 0.26‰. Experimental studies by Berger *et al.* (*8*) documented a fractionating effect during smelting due to the evaporation of tin favoring the lighter isotopes. They suggest a +0.2‰ correction for the 8 atomic mass unit of δ^{124}Sn used here. Empirically, it was noted that the application of this +0.2‰ resulted in the best match between artifacts and ores in the Balkans (*8*). Accordingly, for comparison of the isotopic composition of cassiterite ores with that of the tin ingots, the δ^{124}Sn values of ores were reduced by 0.2‰.

Trace element concentrations were measured with a Thermo Fisher Scientific iCAP-Q at Rutgers University using a Teflon introduction system with 2% nitric acid with a trace of hydrofluoric acid in the carrier acid. Dwell times were 10 ms on each of the three channels, which were at 0.1 mass unit spacing from the peak center, and 10 runs were acquired for each sample and standard. Concentrations were determined by a five-point calibration using synthetic standard mixtures (High Purity Standard 68A-A, 68A-B, and 68A-C) that were doped with Sn to match the matrix of the samples. Precision was better than 2%.

Lead isotope analysis results of four Uluburun tin ingots (lot 9269, KW 0206, KW 1326, and KW 2699) were added to the dataset of 104 samples reported in (*6*). Lead purification was accomplished following the procedure derived from (*52*). Samples were measured on the Nu MC-ICPMS at the University of Florida. Mass bias was corrected using Tl-spiked samples similar to that described in (*53*). Standard NBS 981 was used, and 2σ errors of the standard were <0.001 for all ratios reported. Blind clustering of samples was conducted using *t*-SNE (*54*), a statistical method for dimensionality reduction. It is a nonlinear algorithm, unlike principal components analysis (*55*). *t*-SNE builds two separate probability-density functions capturing the similarity of each point in the dataset to each other point in the dataset, one for the full dimensionality data and another for the reduced dimensionality data. The locations of the points in the reduced dimensionality data are chosen to minimize the Kullback-Leibler divergence (*56*) between the two probability distributions. We used the Rtsne package implementation of the *t*-SNE algorithm, a base random number seed to ensure reproducibility, and ran the algorithm 1000 separate times (restarts), choosing the run with the lowest cost. The four inputs to the *t*-SNE algorithm were the isotopic ratios ^{206}Pb/^{204}Pb, ^{208}Pb/^{204}Pb, δ^{124}Sn, and the concentration of Pb with a perplexity of 30. Before running the *t*-SNE algorithm, we normalized each variable by subtracting the mean and dividing by the SD.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at https://science.org/doi/10.1126/sciadv.abq3766

View/request a protocol for this paper from *Bio-protocol*.

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