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If Southwest Asia is a *Heartland of Metallurgy*, where are the mines?

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Abstract: This paper examines early mining and metallurgy in Southwest Asia, a region often regarded as a heartland of metal production, yet lacking comprehensive archaeological documentation of its vast numbers of ancient mines. Focusing on copper and tin, the key components of tin-bronze, the study highlights the sparse, published evidence from some of the region's well documented mining sites, including Derekutugun (native copper) and Kestel/Göltepe (tin) in Anatolia, Vashnaveh (copper) and Deh Hosein (copper-tin) in Iran, and the Arabah Valley mining districts (copper) in the southern Levant. Here, we review the geological and technological contexts of these sites, detailing early mining techniques, ore extraction processes, and the role of metallurgy in regional economies from the Neolithic through the Iron Age of these two consequential metals. A brief discussion on future research directions is also included, focusing particularly on the isotopic analysis of metal sources and the trade networks that distributed these materials across the ancient Near East. Overall, the paper contributes a synthesis of available evidence and addresses the limitations and strides made in the study of early mining and its impact on the many forms of metallurgy in the ancient past.

Keywords: Mining, Metallurgy, Near East, Southwest Asia, Levant, Copper, Tin-bronze.

Résumé : Cet article examine les débuts de l'exploitation minière et de la métallurgie en Asie du sud-ouest, une région souvent considérée comme le cœur de la production métallurgique, mais qui manque de documentation archéologique complète sur ses nombreuses mines anciennes. En se concentrant sur le cuivre et l'étain, les composants clés du bronze à l'étain, l'étude met en évidence les rares preuves publiées provenant de certains des sites miniers bien documentés de la région, notamment Derekutugun (cuivre natif) et Kestel/Göltepe (étain) en Anatolie, Vashnaveh (cuivre) et Deh Hosein (cuivre-étain) en Iran, et les districts miniers de la vallée d'Arabah (cuivre) dans le sud du Levant. Nous passons ici en revue le contexte géologique et technologique de ces sites, en détaillant les techniques minières anciennes, les processus d'extraction du minerai et le rôle de la métallurgie dans les économies régionales, du Néolithique à l'âge du Fer, pour ces deux métaux importants. Une brève discussion sur les orientations futures de la recherche est également incluse, axée en particulier sur l'analyse isotopique des sources de métaux et les réseaux commerciaux qui distribuaient ces matériaux à travers le Proche-Orient ancien. Dans l'ensemble, cet article présente une synthèse des preuves disponibles et aborde les limites et les progrès réalisés dans l'étude de l'exploitation minière primitive et son impact sur les nombreuses formes de métallurgie dans l'Antiquité.

Mots clés : mines, métallurgie, Proche-Orient, Asie du sud-ouest, Levant, cuivre, étain-bronze

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Broadly speaking, the advent of settled village life in Southwest Asia ensued in the period circa 12,000–10,000 BCE. Importantly, within the following millennia two critical technological transitions, among many, were emerging, namely the advent of mining and metallurgy. It is the act of mining, a kind of landscape exploitation, that underpins many of the papers presented in this publication. Our paper has two main goals, first, to discuss succinctly what evidence does exist for the few, major, excavated and well documented Southwest Asian copper and tin mines and second, to succinctly overview the research problems that are most relevant to these mines.

REGIONAL TECTONICS AND ORE GEOLOGY OF SOUTHWEST ASIA

Early mining and metallurgy ensued in the extremely tectonically active, geologically tortured if you will, ore-rich regions of Southwest Asia, essentially the Fertile Crescent which for our purposes here includes the Anatolian and Iranian Plateau, then arcing across northern Mesopotamia and south into the Levant (figs. 1 and 2). The plate tectonics responsible for the complex geology of these regions generated significant metallogeny via plate contact and

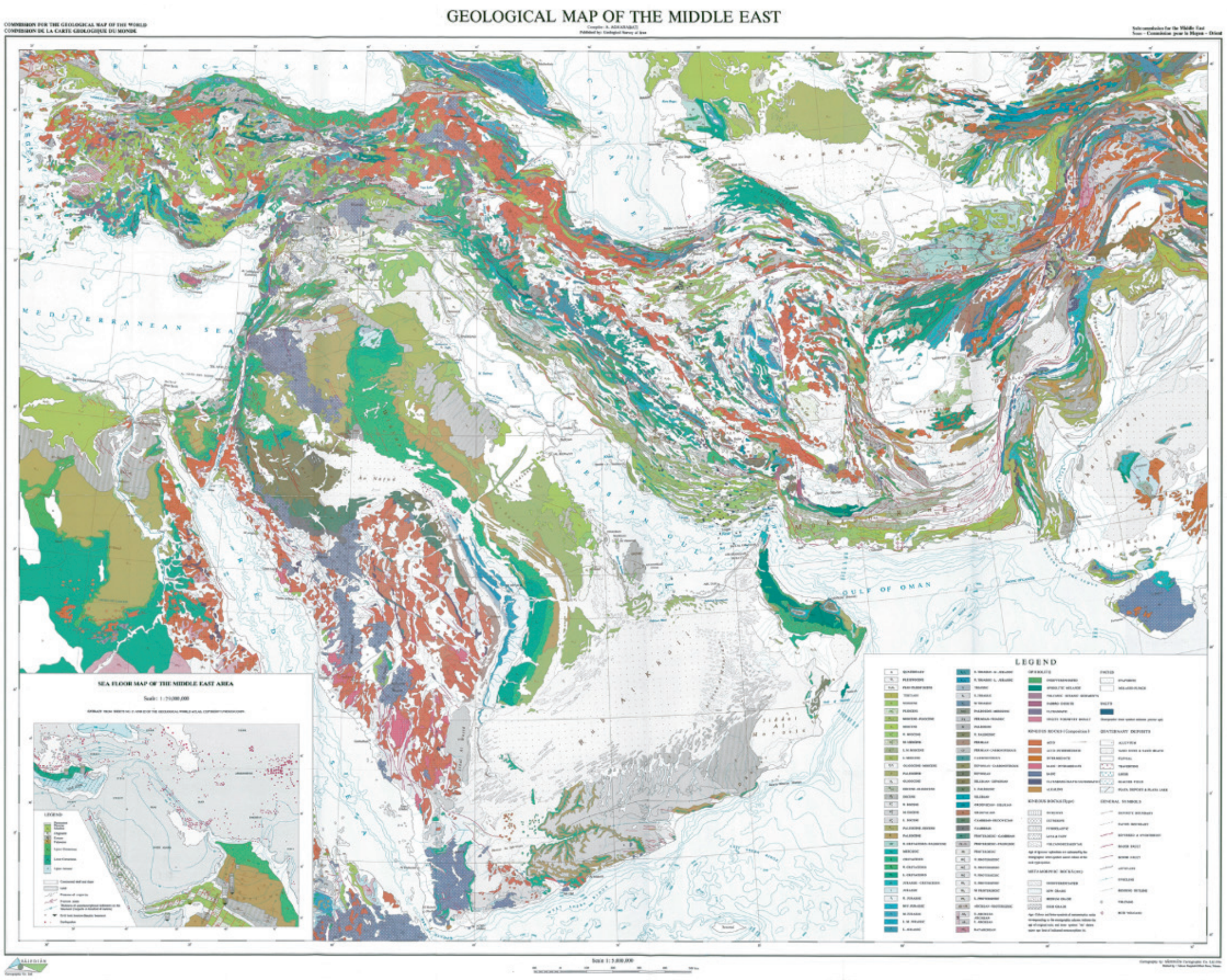

Fig. 1 – Geological map of the Middle East demonstrating its complex tectonic structure – (Map courtesy of the Geological Survey of Iran, 1986; Compiler Dr. Aghanabati).

subduction, vulcanism and metamorphism as well as myriad other powerful geological forces at play over the epochs. Over time, the ores exploited for the metals of antiquity were emplaced and weathered surficially often providing colorful, topographic clues to the presence of pigments/ochres, native copper and ultimately ores resting beneath. Here, we focus the following discussion on copper and tin, two metals that comprise the alloy tin-bronze and whose ancient mining played impactful roles in evolving societies and their economies in the greater region for millennia. The coming of tin-bronze in the late 4th/early 3rd millennium BCE is rivaled in terms of technological impact only by the later 2nd millennium BCE innovation of iron (e.g., Pigott, 2021; Erb-Satullo, 2019).

Figure 2, moving west from Afghanistan to Iran to Anatolia and southward to the Levant, presents some sense of the remarkable abundance of documented ore deposits, some with ancient mining, spread across Southwest Asia. Yet from this extraordinary multitude of known deposits, documented primarily by economic geologists, the number of archaeologically documented, i.e., those which have been excavated, chronometrically dated and subsequently published, currently remains strikingly small. Thus, we are significantly underinformed about the extractive processes that have allowed for the production of thousands upon thousands of artifacts in copper and its various alloys, used over millennia in Southwest Asia at many of the sites seen in Figure 2. The excavated mines our discussion will focus on are 3rd millennium BCE Derekutugun (native copper) and Kestel/Göltepe (tin) in Anatolia, ca. late 3rd/late 2nd millennium BCE Veshnaveh (copper) and 2nd millennium BCE Deh Hosein (copper-tin) in Iran, and the late 4th–1st millennium BCE mines of the Arabah, Timna (copper) in Israel and Faynan (copper) in Jordan.

LOCAL TECHNOLOGICAL DEVELOPMENTS: EXTRACTION FROM SEMI-PRECIOUS STONE TO METALLURGY

The Southwest Asian zone encompassing Anatolia, Iran, northern Mesopotamia, and the Levant, essen-

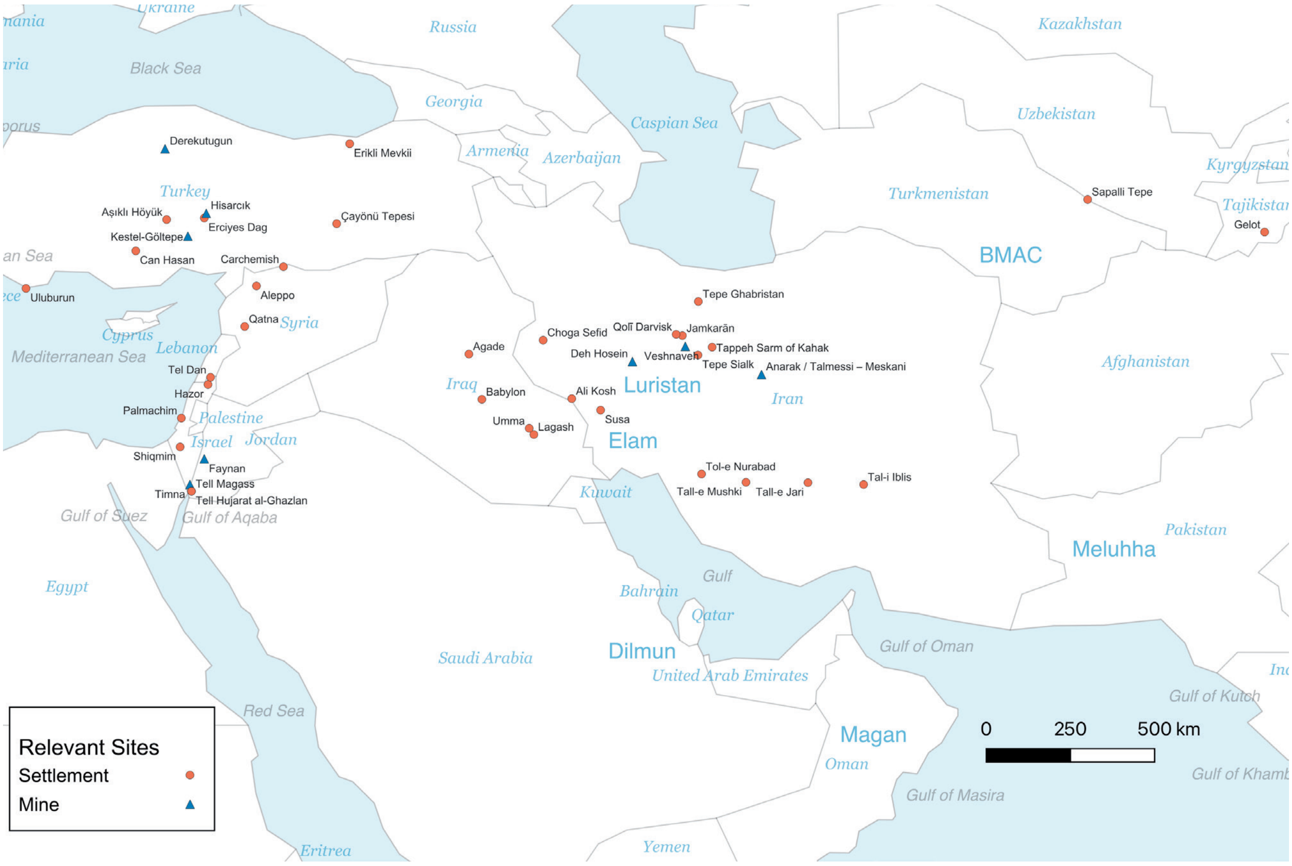

Fig. 2 – Mines and relevant sites in Southwest, Central and South Asia mentioned in the text (credit: J.B. Lowe)

tially the Fertile Crescent, can be considered the location of this region's metallurgical "heartland" in which the earliest known exploitation of copper-base ore minerals for pigments and beads began around the 11th millennium BCE (Roberts et al., 2009; Pernicka and Anthony, 2010, p. 164; see also Pigott, 2021, p. 828, fig. 29.1; Pigott: in press, fig. 1). Such mineral exploitation was followed by the use of native copper for beads and small implements from about the 8th millennium BCE. Well known examples of early (i.e., Neolithic) native copper use are: the folded bead from Ali Kosh in Iran (Smith, 1968; 1969); the multiple occurrences of beads at Aşıklı Höyük (Yalçin and Pernicka, 1999) and Çayönü Tepesi in Anatolia (e.g., Muhly, 1986, p. 5–7; Stech 1990). Less well known, but comparably early finds in this metal come from sites elsewhere, notably in Iran: Choga Sefid in Deh Luran, Tol-e Nurabad, Tall-e Mushki, Tall-e Jari in Fars, Tepe Sialk on the Iranian Plateau (Weeks, 2013, p. 278). The hammered, native copper mace head from Can Hasan can be considered anomalous based on its size, weight and that it was most probably used as a weapon (Yalçin, 1998). At 4th millennium BCE Tepe Yahya in Kerman in Iran, native copper use persisted here even as smelting emerged on the scene (Weeks, 2013, p. 278). Many of these finds comprise important examples of the initial (Neolithic) utilization of native metal for mostly decorative/aesthetic effect. Did these examples of experimenting with materials for such an effect pave the way for future metals-related innovations? Some would agree, others would not.

Millennia passed before the smelting of copper-base ores from ca. 5000 BCE and later can be documented (e.g., Roberts et al., 2009). The earliest dates for smelting and tin-bronze occurrences, ca. 5000 BCE are known currently from the Balkans/Serbia (Radivojević et al., 2021). Further east in the heartland, smelting is documented during the 5th/4th millennium BCE at sites including Tal-i Iblis (e.g., Pigott and Lechtman, 2003; Frame, 2012) and Tepe Ghabristan in Iran (e.g., Majidzadeh, 1979; Fazeli et al. 2005).

In the southern Levant, by the late 4th–early 3rd millennium BCE (Levantine Chalcolithic to Early Bronze Age), copper mining and smelting were active. This is concurrent with a broader appearance of copper-base objects, found in hoards and in settlement sites. The archeometallurgical record includes evidence for the exploitation of local ore sources in the Arabah Valley and small-scale production of copper artifacts at Chalcolithic period sites (Conrad and Rothenberg, 1990; Hauptmann, 2007; Levy et al., 2002). Simultaneously, the importation of a non-local copper metal—an arsenic-antimony-copper alloy—is evidenced by the analytical results from Chalcolithic metal finds at sites such as Nahal Mishmar, Shiqmim, and Palmachim (Tadmor et al., 1995; Shalev and Northover, 1993).

With regard to the exploitation of ores, when actual shaft and gallery mining began is a matter of some debate, but early on people were pitting into the surfaces of ore deposits in search of pigments. A progression from pits to shaft and gallery exploitation strategies is generally accepted along with alluvial and eluvial deposit mining occurring consistently across time (see fig. 3 for the mining chaîne opératoire). A significant number of the copper ore deposits noted in the maps above, with the exception of most of those in the Levant, are of the surface exposed, weathered copper sulfide type which means they have a reasonable likelihood of having ochreous pigments like hematite and also native copper accessible at or near their surfaces, often in the gossans that cap them (fig. 4). These gossans, the 'chapeaux du fer' or the 'Eisenhütten' are said to signal what lies beneath, but, until recently, it was very difficult to document the act of 'mining' native copper anywhere in the greater region. Well-known massive copper deposits, such as at Ergani Maden in central eastern Anatolia, and those in the Anarak (Talmessi/Meskani) mining district of central Iran, are native copper-bearing and are suggested to be among the important sources of this metal in early prehistory (e.g., Pernicka et al., 2011, p. 635–637, 643). Regrettably, modern mining has destroyed most indications of early exploitation at these and other mined ore deposits. It is also the case that native copper occurs in the upper zones, if not right at the surface of sulfidic orebodies, and therefore could have been easily collected and/or grubbed for by shallow surface pitting. An excellent and, in fact, the only exca-

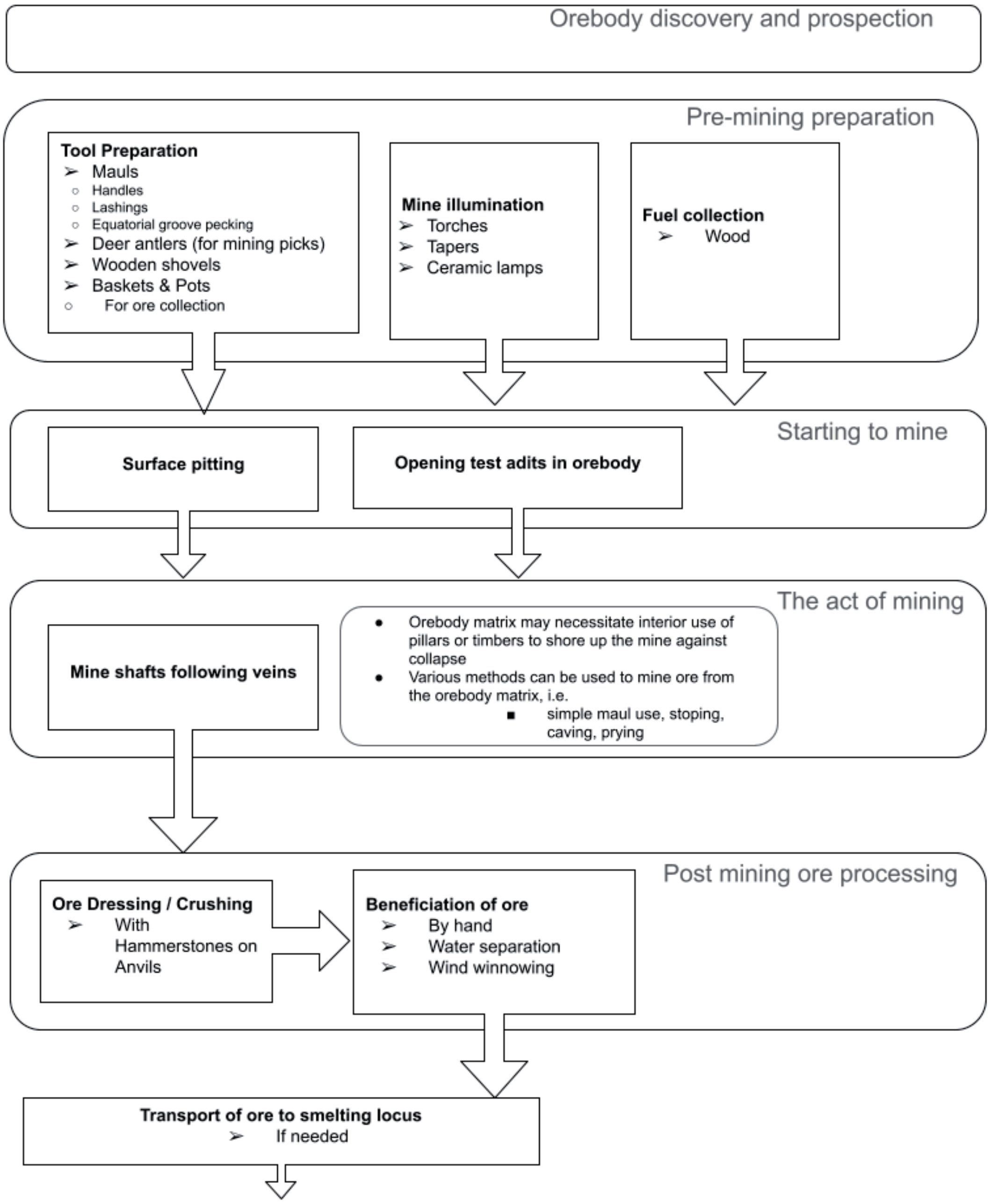

Fig. 3 – The *chaîne opératoire* for mining, from the discovery of a viable ore body to the transportation for reduction/smelting.

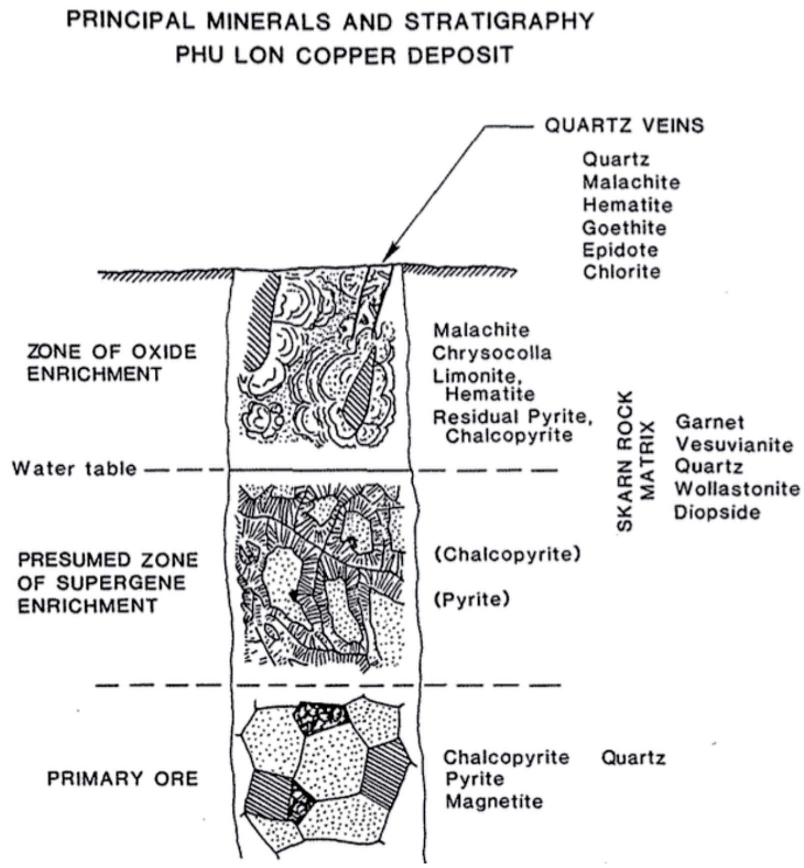

Fig. 4 – Schematic diagram of a weathered copper sulfide deposit capped by a gossan. Note the mineral changes from the primary ore layer to the oxide zone. Native copper is found in the surface gossan and in the Zone of Oxide Enrichment (diagram by W. W. Vernon in Rostoker et al., 1989, p. 71).

vated example, comes from the site of Derekutugun in north central Anatolia, where researchers collected pieces of native copper in stream beds close to the mine (e.g., Yalçin and Ipek, 2016, p. 19, Abb. 7)

COPPER AND TIN MINES OF SOUTHWEST ASIA

Derekutugun native copper mine (north central Anatolia)

The Derekutugun mine is located near a village of the same name in the Bayat district of Corum Province of north central Anatolia (Yalçin et al., 2019, p. 122, fig. 3) (fig. 5) It is the only well documented locus of prehistoric native copper mining in Southwest Asia. It was excavated by Dr. Ünsal Yalçin and team from the Deutsches Bergbau-Museum in Bochum, Germany between 2009–2011 and 2015–2017. Particular archaeological attention was paid by this project to the area known as the Maziönü locality. This mining locus has been dated to the first half of the 3rd millennium BCE, but there is every indication this native copper deposits was exploited much earlier according to its excavator. The basic geology of the deposit is described as follows:

> "a red bed deposit type that was formed in an arid basin margin. The native copper could have been enriched in the groundwater by leaching of surrounding copper-bearing rocks and impregnated into the loose sediments in a reducing environment. This process was probably promoted by the high sulfate content, or the high sulfate content of the groundwater was the prerequisite for the leaching and enrichment of the copper (Aral, 1990). The gray-green conglomerate series contain partially charred plant remains, which confirm a reducing environment (Yalçin and Maass, 2013, p. 4)."

Thus, the native copper was formed over epochs in "cracks and cavities of Miocene sediments" and as mentioned, by leaching by sulfate-rich groundwater. The metal often co-occurs with the oxidic ores of malachite and cuprite and the deposit has pockets of rock salt and combustible lignite. All of these minerals could have drawn local peoples to seek them for various purposes. We see in Figures 6a and b, the steep cliff faces into which numerous mine shafts were dug and the location of a small settlement, found by geophysical prospecting, where crucibles, slag, potsherds and mining tools were found. The mining sequence is reconstructed as follows (see mine plan, fig. 6):

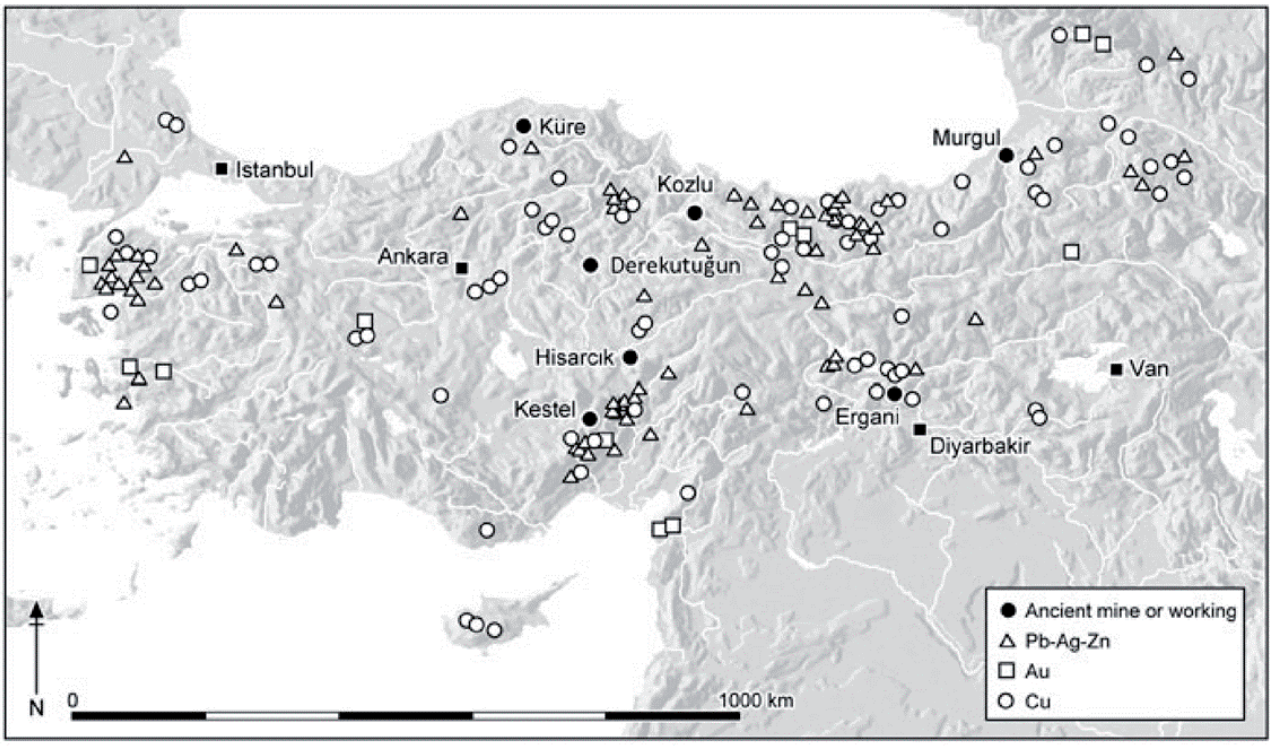

Fig. 5 – Known major ore deposits in Anatolia with important excavated pre-modern mines noted: Derekutugun: native copper; Kestel and Hisarcik: tin (after Lehner and Yener 2014, p. 532, fig. 20.1).

> "Following the copper-bearing cracks and layers, the Early Bronze Age miners entered the hill of Maziönü through a vertical shaft and then mined the metal in an east-west direction. So far, up to three floors have been identified in each of the four pits examined. Accordingly, the top floors would represent the older phases, and the bottom floors would represent the youngest phases. (Yalçin and Maass, 2013, p. 192, translated)."

The mine is best depicted through the maps and figures to follow. Figure 7a offers a wide view of the cliff face in which a multitude of mine shafts were dug in Prehistory in search of native copper. Given the steepness of the cliff-face one must wonder how the miners were able to negotiate the precipitous conglomerate cliff faces. The mining locus (Bergbaurevier) and the down slope mining settlement are indicated. Figure 7b shows the Maziönü

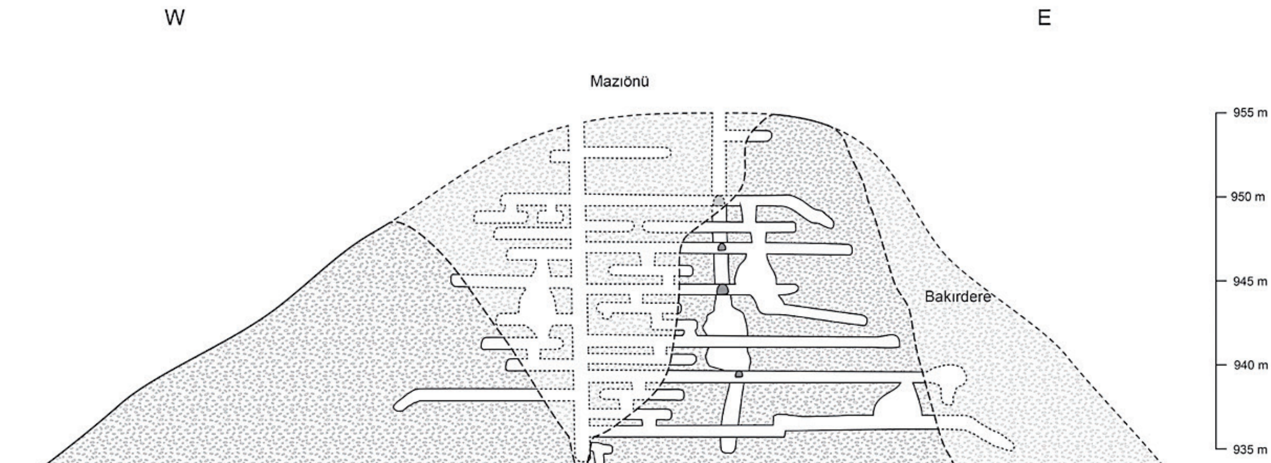

Fig. 6 – Derekutugun mine: diagram shows prehistoric mining works and their present morphology due to erosion (after Yalçin, and Ipek, 2016, p. 77, Abb. 92).

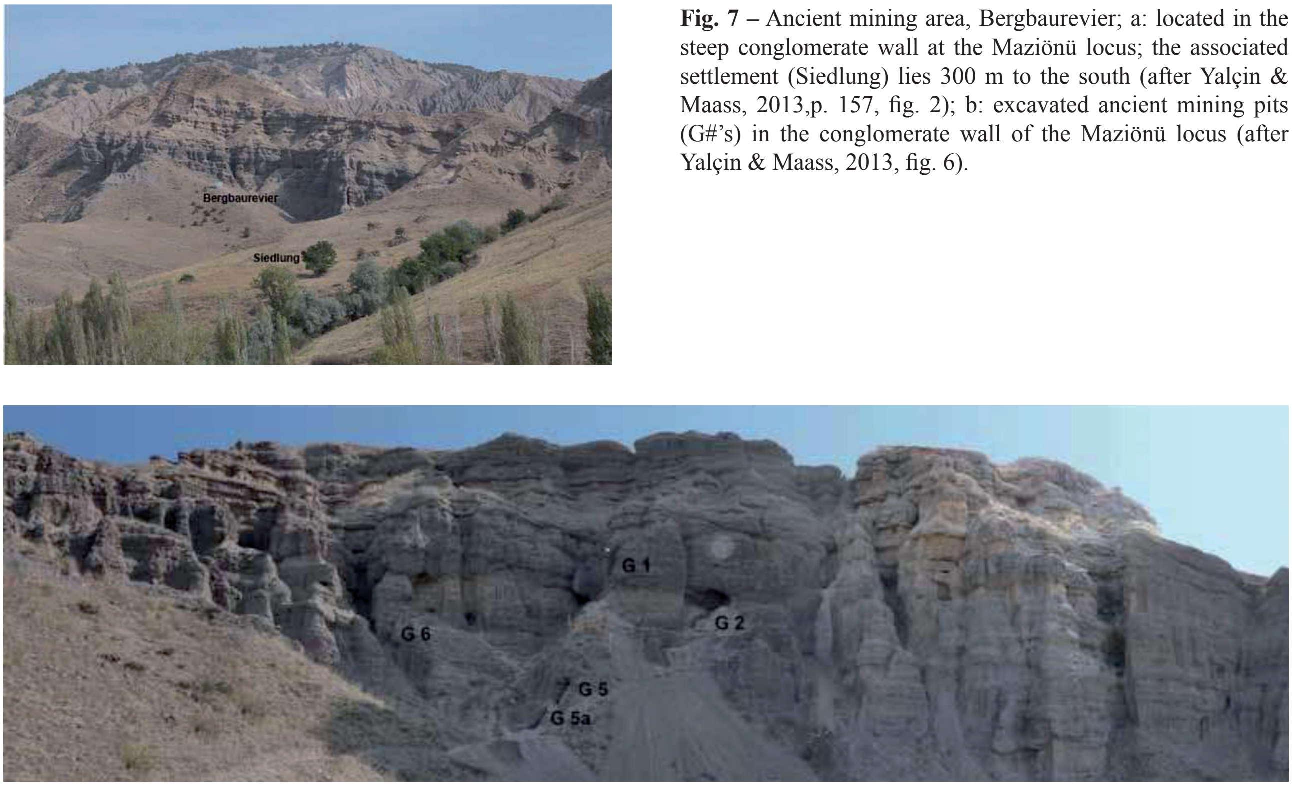

Fig. 7 – Ancient mining area, Bergbaurevier; a: located in the steep conglomerate wall at the Maziönü locus; the associated settlement (Siedlung) lies 300 m to the south (after Yalçin & Maass, 2013,p. 157, fig. 2); b: excavated ancient mining pits (G#'s) in the conglomerate wall of the Maziönü locus (after Yalçin & Maass, 2013, fig. 6).

Fig. 8 – Views of mine interiors at Derekutugun (after Yalçin & Maass, 2013, p. 162, Abb. 8, 172, Abb. 22).

area of the mine with its specific mining loci (G1, 2, 5, 5a, & 6). The mining complexes sit densely in this area, which emphasizes how intensive the mining activity was at Derekutugun. The sinuous profiles of the mine shafts are suggestive of the use of stone mining mauls to crush the orebody matrix containing the native copper in the slow, arduous process of hand mining (fig. 8). Numerous mining mauls and ore crushing tools did occur in the shafts and in vicinity of the pits, as well as near the mines (fig. 9a).[1] One so-called "pit" (Pit 1) had a length of ca. 20 m and an average height of 0.60m suggesting, in turn, prone miners working their way through the deposit. The shafts were probably initiated with the use of hand-held mauls which was in turn followed by, for example, the technique of prying off with wooden branch pry bars (see

1. Stone mining implements are discussed in greater detail in Yalçin and Ipek, 2016, p. 50–51, 53–54, 93–110).

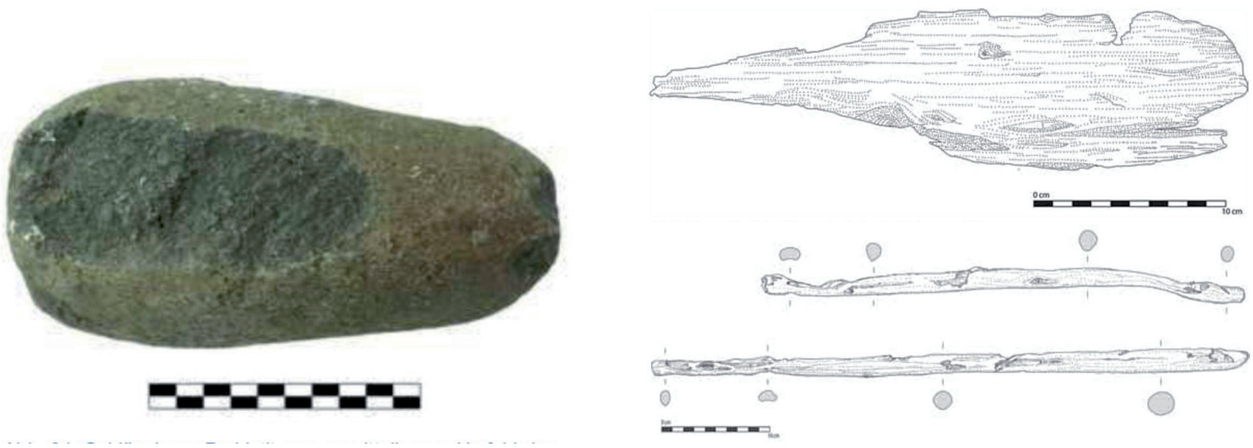

Fig. 9 – Mining tools of Derekutugun; a: peridotite mining maul from the immediate vicinity of the mining area; b: wooden (oak) mining shovel from mining locus 5a; c: two wooden (hazelnut) pry bars from mining locus 5a (Yalçin & Maass, 2013, p. 178, figs. 28, 29, 31).

fig. 9b) loose slabs of copper bearing wall rock. Some sort of 'picking' (holes 5 cm in size) with hardwood or horn (antler?) seems to be a common mining technique given the multitudinous marks seen in the mine walls. Also, apparently, some ore crushing with small stone hammers, did take place to some extent within the mine pits perhaps to make the mined material easier to remove.

Mined material was shoveled for removal using wooden shovels found in the mine into containers (ceramic?) (fig. 9b). Actual ore processing appears to have been carried out at the small, mining settlement about 300m down slope, where quite large hammerstones were found, one up to ca. 4 kg. Some, but not all, had been notched for hafting to a wooden handle. They were used to crush the host rock so the copper could be isolated for a final crushing using small hand-held, cylindrical to spherical hammers stones (ca. 600-700 g) against flat surfaced anvil stones (10–30 cm). Repetitive crushing produced round depressions in the anvil faces (4–10 cm in diameter and 0.5 cm in depth). The hand-held stone mining tools were mostly locally acquired peridotite, a hard coarse grained igneous rock ideally suited to ore crushing (fig. 9a). Other mostly hard stone cobbles in basalt, limestone, sandstone and andesite were also made modest use of. Some grinding stones were found, perhaps for fine crushing of ores, but not sure why this would be necessary for sorting the sizeable native copper fragments. They may have been used for food processing.

Figure 10 shows native copper from the mines, seen as nodules (10a) collected from stream beds near the mining area and native copper specimens (10b) from the mine which occurred in up to remarkably large 5 kg specimens. Specimens of this size presumably could have been cold worked into artefacts of some size or melted down for casting and perhaps even alloying with tin to make bronze. This alloy is known to appear initially during the

Fig. 10 – Native copper lumps from Derekutugun, found in a stream near the mines (left) and (right) in situ inside the mine [after Yalçin, and Ipek, 2016, p. 19, Abb. 7 (left) & 71, Abb. 87 (right)].

same period in which this deposit is being mined. The copper occurred in the conglomerates within the fissures as copper sheets or nodules (Yalçin and Ipek, 2016, p. 71, fig. 87). Most probably it was the process of the native copper eroding out of the conglomerate matrix and being re-deposited in the stream bed that led to the discovery of the deposit and its subsequent mining.

The copper itself bore noticeable traces of silver, gold and iron with silver characterizing Derekutugun copper. Various other elements were present as impurities at very low trace element levels (see fig. 41 and table 1 in Yalçin and Maass, 2013, p. 187–188). It should be noted that vanadium content can be 'quite high', but it appears to be associated with a higher gangue presence. A high vanadium presence was also noted in some slag from a looter's excavation at the Erikli Mevkii settlement locus and in the magnetite sands washed from the Bakredere stream near the mine.

Yalçin and colleagues' overall assessment of the lead isotope potential of Derekutugun is that it constitutes a 'closed isotope field' specific to the mine area such that it can be distinguished from various other ore-bearing loci in proximity to this mine and well beyond.[(2)] This has significant potential for linking copper from the mine to artifacts made from it and distributed throughout the greater region.

Potsherds and some complete vessels were also found in the mine shafts and pits with associations to other Anatolian sites (Yalçin and Maass, 2013, p. 14). Uniquely, wood (pine) 'kindling", a kind of long, thin taper it seems, for illumination were found on floors of some mine shafts II (Yalçin and Ipek, 2016, p. 52, Abb. 66, 67). There is no indication that fire-setting was used in this mine. Pits 5 and 5a yielded some 1650 traces of these thin tapers, ca. 4–18 cm long and often 4–6 cm in length and up to 10 cm long.

Initial ceramic finds in the vicinity of the mine indicated a prehistoric date and then with organic finds from within the mine itself, radiocarbon dating at the laboratory at ETH Zurich was performed on pieces of wood kindling, on 2 wood implements, a grain of grain and additional plant remains. The earliest dates for the Maziönü locus indicated a calibrated age of ca. 2900–2550 BCE, centered between ca. 2850–2700 BCE with a suggested periodization in the Anatolian Early Bronze Age II (Yalçin and Ipek, 2016, p. 185–186, Abb. 39). Suggested dating for mine ceramics supports an EBA date for the central and northern Anatolia region (Yalçin and Ipek, 2016, p. 17).[(3)] Mining in other loci at the mine dates as late as ca. 2000 BCE so it was exploited, perhaps intermittently, over the centuries.

Finally, this one-of-a-kind, all-important mining site must have yielded significant amounts of native copper over the centuries of the Anatolian EBA (see Aral, 1990, p. 67–71). The mined native copper in turn went into melting crucibles yielding substantial raw copper ingots(?) for local use as well as long distance trade for purposes of tin-bronze production early in the Bronze Age.

2. Lead isotope analysis of Derekutugun copper is discussed in greater detail in Yalçin and Maass, 2013, p. 188–191; Yalçin and Ipek, 2016, p. 74–76.
3. Mine ceramics are discussed in detail in Yalçin and Ipek 2016, p. 55–68, 111–194.

Kestel/Göltepe (south central Anatolia)

We turn now from the mining of native copper to tin mining at the highland Kestel/Göltepe tin mining complex in the ore-rich Bolkardağ district of Taurus Mountains of south-central Anatolia (fig. 11). The site was excavated in the 1980s and 1990s by Prof. K. Aslihan Yener of the Oriental Institute of the University Chicago and her team (Yener, 2000; 2021). The Kestel mining area is home to significant evidence of early tin mining and comprises the earliest known such mining in Eurasia ranging in date from late 4th well into the 3rd millennium BCE, but tin continued to be mined in the Bolkardağ at least until 2000 BCE (if not later). Calibrated ^{14}C dates range from ca. 3240–3100 BCE to 2870–2200 BCE (Yener, 2008, p. 58). EBA I-III ceramics were also found within the mine confirming its early mining activity.

In the ca. 2 km^2 area around the Kestel mines 1 and 2, substantial open pitting and ore processing is in evidence and probably represents early mining activity ca. 3000 BCE (Powell et al., 2021; Yener, 1996-7). Some evidence of crucible smelting of tin-bearing ore in this area was encountered and Yener suggests it may represent efforts to assay the ore "in order to make strategic decisions during mining" (Yener, 1996-7, p. 60). Estimates of ore extraction in the open-pitting zones around the mine entrances could range upwards of thousands of tons and that perhaps ten times as much ore was extracted in this manner than in the substantial underground workings. The mine's 4 km of tunnels produced ca. 4,600 m^3 of tin ore and it is possible, that even with working of a low-grade tin ore (1% Sn), ca. 115 tons of tin metal could have been produced from the Kestel mining locus over the span of a millennium (Yener, 2008, p. 58). This is certainly one of the largest ancient shaft and gallery mines known in Southwest Asia.

In the Kestel mine itself, there are two main episodes of mineralization, the first with a primary focus on cassiterite in the surface deposit. A second episode deposited a hematitic ore which was, within the mine, extracted for its albeit low tin content (fig. 12). This latter ore necessitated crushing and grinding by hand to a powder which was then smelted in ceramic crucibles. This was the main activity undertaken at the ore processing site of Göltepe some 2 km distant from the Kestel (Yener, 2021).

The tin-bearing, hematitic ore lumps from Kestel were hauled to this site to be beneficiated in pit workshops seen here (fig. 13). Surface survey yielded some 55,000 stone tools, 5,000 of which were excavated from the pit workshops. The tools were used to grind the ore to a powder rather than only crush it. The resulting powder (ca. 2% tin) was smelted in ceramic crucibles and

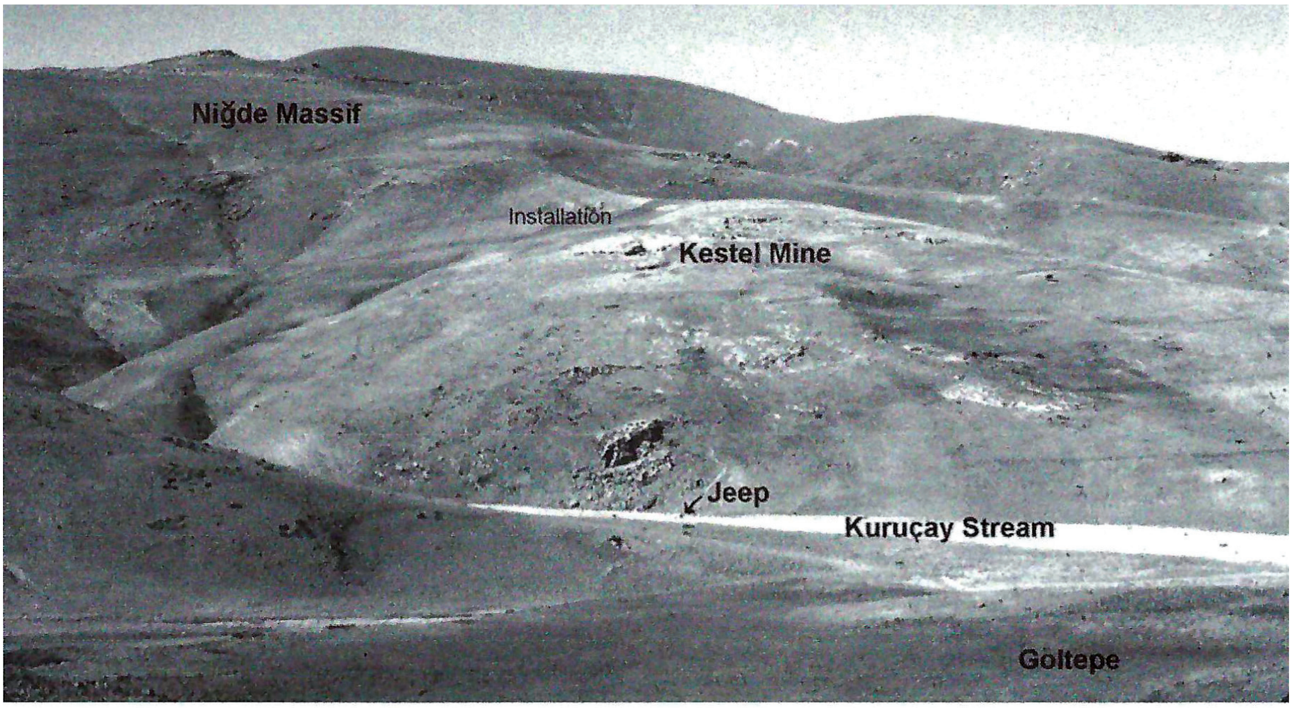

Fig. 11 – The 3rd millennium BCE Tin Mine at Kestel, Anatolia (Yener, 2021, plate 1A).

Fig. 12 – Dr. Mike Johnson sampling a quartz-hematite vein above the main entrance to the Kestel mine (Courtesy of Prof. Wayne Powell.)

probable bowl furnaces—1 ton of vitrified earthenware bowl furnace or crucible fragments were excavated at Göltepe. The tin-rich glassy slag layer in these fragments showed 30–90 wt % tin content and attest to the industrial-scale, high temperature processing of tin-bearing ores practiced at this remarkable site (Yener, 2021).

Lead isotope analysis (LIA) has linked tin-bronze artifacts from Bronze Age sites in Anatolia and Syria to the Bolkardağ mining district in the Taurus mountains where the Kestel-Göltepe complex is located (Yener et al., 1991; Sayre et al., 1992; 2001). By all indications the massive amount of tin produced at this complex was traded far and wide across the greater region. Subsequently, and despite recent arguments to the contrary (Berger et al., 2023a; 2023b) in the later 2nd millennium BCE, tin from the Bolkardağ mining district, it has been argued using LIA, was cast into some of the ingots found among a ton of tin ingots excavated from the Uluburun shipwreck—

Fig. 13 – Plan for Göltepe Building 1 (Area A) depicting ore processing, workshop stalls, thermal installations, ore grinders, and crucibles. This building dates to EBIII, Period 2. Some 5000 ore crushing tools were excavated from the workshops along with crucibles, powdered tin ore and ca. 1 ton of vitrified tin-rich material (Courtesy of Prof. K. A. Yener. Yener 2021).

about 1320 BCE—off the southern Turkish coast (Pulak, 2000; Powell et al., 2022; cf. Berger et al., 2022; cf. Williams et al., 2023; cf. Powell et al., 2024).

Interestingly, thus far in Southwest Asia, the Kestel mines are joined by only two other documented tin sources with mining evidence from later Prehistory. A second small Anatolian source is now known within the Erciyes Dag volcanic zone, at Hisarcik, Kayseri Province, central Anatolia. Here tin ores were emplaced via volcanic fumaroles (Yener et al., 2015).

Deh Hosein (western central Iran)

The third Southwest Asian source, one of particular importance, is located on the Iranian Plateau in the western central Zagros mountains in the mining district located at Deh Hosein (see fig. 2; Nezafati et al., 2011). Here sizable polymetallic deposits of copper, tin and mixed copper-tin ores, including stannite (Cu_2FeSnS_4), are found on the eastern border of Luristan Province in western Iran, renowned for its unique tradition of bronze casting. Additionally, Deh Hosein lies in relative proximity to sites in the Anatolian-Mesopotamian arc wherein some of the earliest tin-bronzes dated to the early 3rd millennium BCE have been documented (Rahmstorf, 2017, p. 188, fig. 16.3).

At Deh Hosein clusters of more than 75 open pit workings of deposits close to the surface with huge spoil heaps are spread across an expanse of 4.5×6 km^2 of this impressive mining landscape (fig. 14b). The presence of underground mine workings as well have been confirmed. The site was initially published by M. Momenzadeh (2004) and then by Nezafati and colleagues in 2011 following a season of research at the site. A single ^{14}C date inside an open pit mine yielded a calibrated date of ca. 1775–1552 BCE (Nezafati et al., 2011). No indications of smelting have been found at the site. If smelted, the stannite from Deh Hosein could have been used to produce, in a single stage process, tin-bronze of uncontrolled tin content.

Elemental analyses of bronzes held in Iranian Museums plus excavated bronzes from the Belgian Mission in Luristan all showed bronzes of uncontrolled tin content which could have been smelted from Deh Hosein ores (see also Haerinck and Overlaet, 2004; Fleming et al., 2005). In addition, Nezafati and colleagues conducted LIA on 18 Deh Hosein ore samples and 25 museum bronzes (Nezafati et al., 2011). These Luristan Bronzes dated stylistically to the 3rd millennium BCE and the Deh Hosein ores all shared LI signature compatibility as did a portion of the Luristan Bronzes dated to the 2nd and 1st millennium BCE. Significantly, ancient Near Eastern copper-base artifacts from the 3rd millennium BCE and later spread from western Anatolia to the southern Gulf also shared signature compatibility with the analyzed Deh Hosein ores—therefore, the research team suggested that Deh Hosein could well have served the greater Near East and beyond as important source of copper, tin and mixed copper-tin ores used to make EBA and later tin and tin-bronze artifacts (Nezafati et al., 2011).

In 2023 LIA published by Daniel Berger and colleagues in Frontiers in Earth Science suggests possible

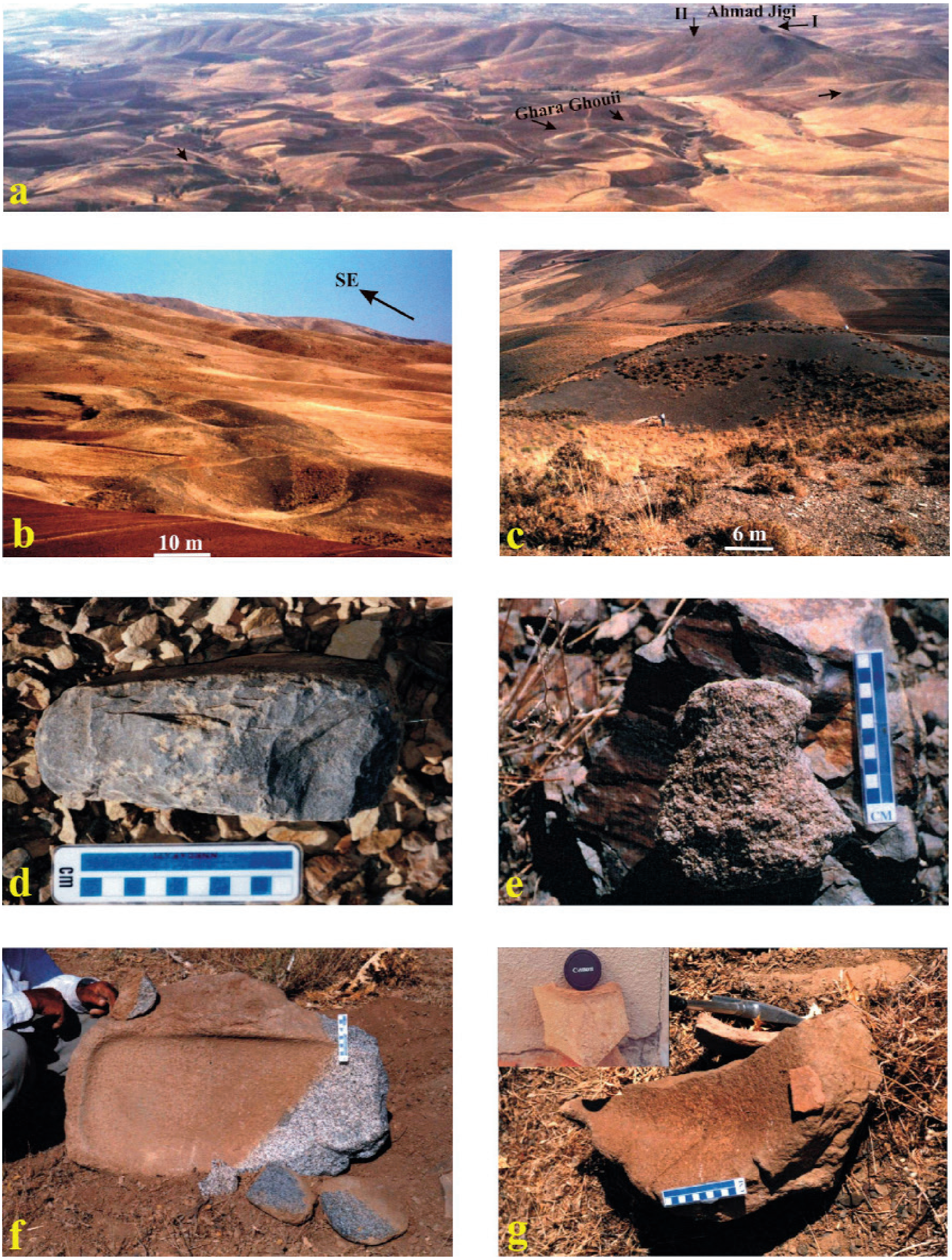

Fig. 14 – Deh Hosein mining landscape, open-pits, spoil heaps and mining and ore processing tools (after Nezafati et al. 2011).

signature compatibility between artifacts from three Central Asian sites, namely (Gelot, Gonur and Sapalli Tepe) and Deh Hosein ores. These sites date several centuries earlier than the single ^{14}C date for Deh Hosein. Thus, in sum, Deh Hosein can be seen as a prime example of an ore-rich, polymetallic deposit from which early on tin-bronze could have been chanced upon experimentally without the previous knowledge of, or conscious effort required to isolate copper and tin ores in order to smelt them to the two metals necessary to produce tin-bronze. Thus, Deh Hosein ranks as one of the most important copper, tin and copper-tin bearing deposits in Southwest Asia that, based on current indications, may well have been supplying tin metal across a sizeable expanse of the ancient Near East, if not across greater Southwest Asia.

Veshnaveh (north central Iran)

This large mining complex is situated in north central Iran as seen in fig. 2. The ore bodies are emplaced in middle-upper Eocene volcanics and sedimentary rocks in the larger Ormieh-Dokhtar volcanic belt spanning the length of western Iran (Nezafati and Stöllner, 2017, p. 68, figs. 1a and b). It was first documented by economic geologists in 1969 (Holzer and Momenzadeh, 1971, p. 2). Interestingly, this discovery is sandwiched between the American Theodore A. Wertime and his international team's pioneering "A Metallurgical Expedition through the Persian Desert" (Wertime, 1968), which did not visit Veshnaveh, and the fieldwork at Veshnaveh by the eminent German mining archaeologist Gerd Weisgerber from Bochum's Deutsches Bergbau-Museum in 1976 and 1978, and that of the French mission led by Thierry Berthoud and colleagues (Berthoud et al., 1976), whose teams did sample the Veshnaveh mines. This period can be seen as comprising the early beginnings of archaeometallurgy in Iran and in Southwest Asia generally. Subsequently, it was in the period 2000–2005 that Thomas Stöllner with Iranian-German teams undertook field work at the Veshnaveh mines (Chegini et al., 2001; Stöllner et al., 2004; Stöllner et al., 2011; Nezafati and Stöllner, 2017).

The Veshnaveh mines are comprised of three main loci, namely Mazrayeh, Lāghe Morād and Chāle Ghār, all within several kilometers of one another (see Nezafati and Stöllner, 2017, p. 70, fig. 3). Interestingly, these 3 mining loci share identical mineralizations (fig. 15). Some 60-plus mine workings of various sizes were recognized by the teams that have studied them, which are ^{14}C dated from the late 3rd to the mid-late 2nd millennium BCE. However, there are dates suggesting that copper mining may well have persisted into the early Iron Age in the late 2nd millennium BCE. The site's dating is supported by the presence of prehistoric, grooved mining mauls and the use of fire-setting as part of the mining process. The grooved mauls suggest they were hafted and, as Gerd Weisgerber once told me, the sinuous nature of prehistoric shaft mining, as seen in the Veshnaveh mines, reflects the use of such mauls (fig. 16c). It is suggested that the moderate copper ore yield during the period of exploitation is reflected in the unsophisticated mining techniques utilized in these mines (Nezafati and Stöllner, 2017, p. 68).

In terms of what ore was being mined, it appears to have been primarily chalcocite (Cu_2S; fig. 17). Other than chalcocite, the primary ore mineralization is described as comprised of bornite, hematite, digenite, chalcopyrite, native copper, and pyrite - hence deposits having a major sulfide component (Nezafati and Stöllner, 2017, p. 77). Copper in veinlets can range as high as 34.5% while hematite ranges as high as 17.5%. Veshnaveh copper is found only in the andesite-basalt unit occurring primarily in thin lenses, pockets, veins and veinlets, groundmass disseminations, amygdales and impregnations (Nezafati and Stöllner, 2017, p. 76). The veins and veinlets range from a few millimeters to several centimeters in width running several meters long and these were mostly mined out by Veshnaveh's ancient miners (Nezafati and Stöllner, 2017, see p. 77, fig. 6).

At the same time in the Veshnaveh deposits both malachite and atacamite, two oxidic minerals, are abundant in the secondary mineralization of copper that is present. The question arises here concerning the nature of the smelting activity used to reduce the deposits predominantly sulfidic ores to copper metal. Smelting copper sulfides generally requires that the ores be roasted prior to smelting to drive off the sulfur (Rostoker et al., 1989, p. 70, fig. 1; Koucky and Steinberg, 1982, p. 165, fig. 19). Regrettably neither evidence for roasting nor smelting Veshnaveh ores appears to have been identified. One possible solution to the difficulties that arise from smelting sulfides is the use of co-smelting in which a one-step direct reduction to copper is achieved by smelting a mixture of sulfidic and oxidic ores (Rostoker et al, 1989, p. 73, table 1). For example, Veshnaveh chalcocite and malachite may have co-occurred in the orebody, so that they were mined together without a conscious understanding that they were two distinct ores. Such an ore mixture was noted at the Lāghe Morād mine (Nezafati and Stöllner, 2017, p. 73, table 2). Co-smelting would have yielded copper metal in the smelting furnace in a single step. Or those smelting such ores could have intentionally mixed chalcocite with malachite to achieve one step smelting to copper metal. The reason that co-smelting as a solution to the presence of sulfur in the Veshnaveh mines is raised here is that the predominance of sulfides in these orebodies meant that those doing the smelting of these ores starting in the early 3rd millennium BCE had to have been able to deal with removing the sulfur and co-smelting would have been one solution to its presence.

In addition, no evidence was found of any sort of permanent settlement in the greater region surrounding the mines, nor was there evidence of the smelting of copper ore at these mines. It is possible that prehistoric pastoralist groups may have been exploiting the mines seasonally and were responsible for moving the ores to regional settlements conducting smelting to copper metal. It has been speculated that at the start of exploitation in the early 3rd millennium BCE Veshnaveh copper was being smelted

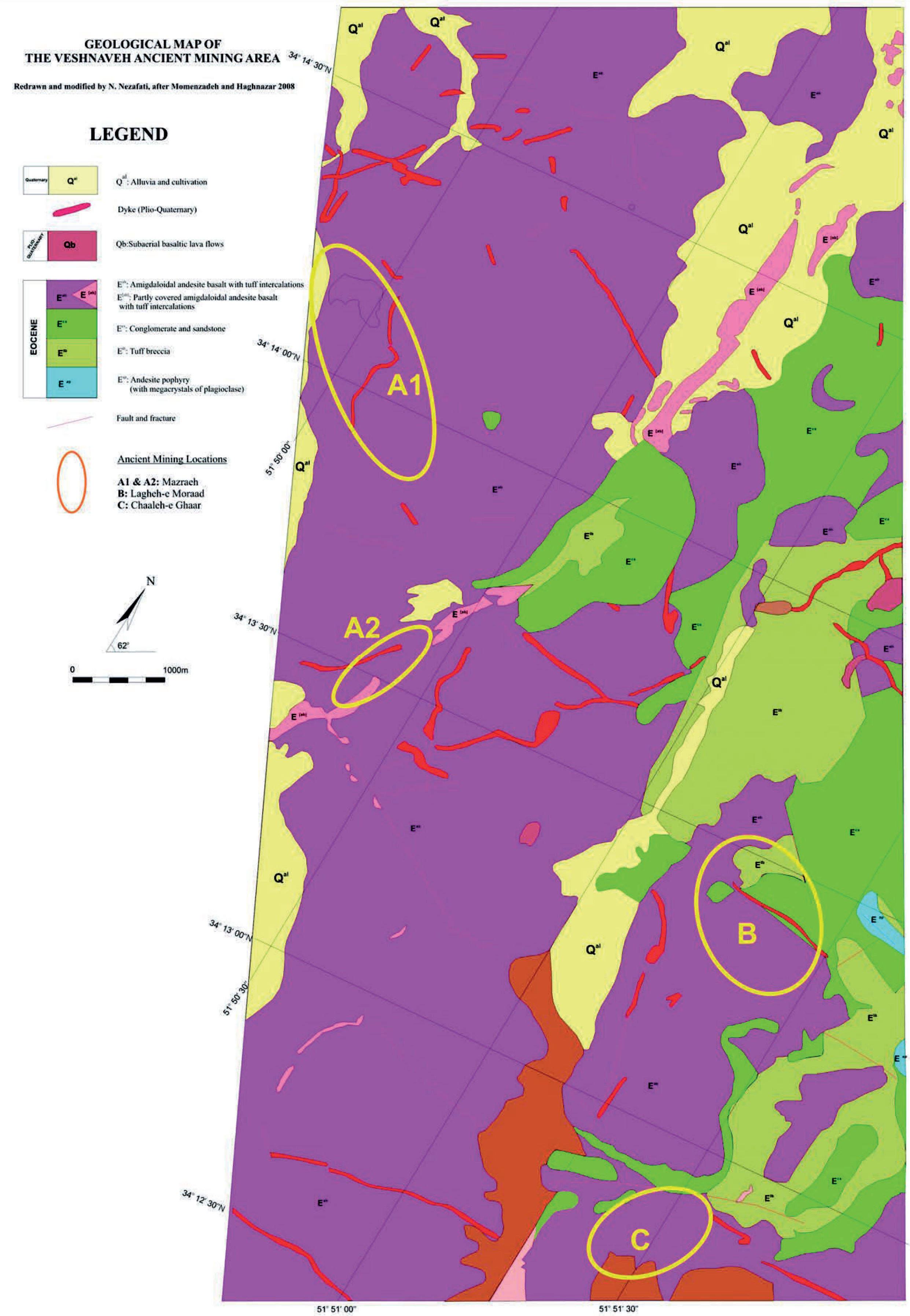

Fig. 15 – Geological map of the Veshnaveh Mining areas: A1 & A2: Mazrayeh, B: Lāghe Morād, C: Chāle Ghār (after Nezafati & Stöllner 2017, p. 70, fig. 3).

Fig. 16 – Veshnaveh copper mine, Iran (from Nezafati & Stöllner, 2017, p. 69, fig. 1 a-h).

at two major settlements in relative proximity to these mines, namely Tepe Sialk (e.g., Schreiner et al., 2003) and Arisman (Chegini et al., 2001; Vatandoost et al., 2011). Both of these sites yielded substantial evidence for copper smelting; however, lead isotope and trace element analyses of Veshnaveh ores eliminated these sites as possibilities (Nezafati and Stöllner, 2017, p. 71, 81).

At the same time, some level of isotopic signature compatibility was signaled at two other regional sites (near Qom), namely Tappeh Sarm of Kahak and Qolī Darvish, Jamkarān (Azarnoush and Helwing, 2005). Importantly, LIA of Veshnaveh ore and host rock provided an "indication of close genetic kinship" between the two. This in turn is of particular value in not only the analyses of samples from these two regional sites, but also it bodes quite well for the use of the isotopic signature of the Veshnaveh ores in future comparative studies of these ores and LIA results from other prehistoric sites on the Iranian Plateau. At Tappeh Sarm (Iron Age II/III) four artifacts shared similar isotopic ratio with the Veshnaveh samples, whereas only one sample from the workshop area at Qolī Darvish was isotopically compatible with the Veshnaveh samples (Nezafati and Stöllner, 2017, p. 79–84). The authors do suggest that chalcocite and bornite (both copper-sulfide ores) may have been transported from Veshnaveh to settlement workshops as at Qolī Darvish for smelting. This site dates from the Late Chalcolithic to the Early Bronze Age and has deposits dating to the 2nd millennium BCE as well.

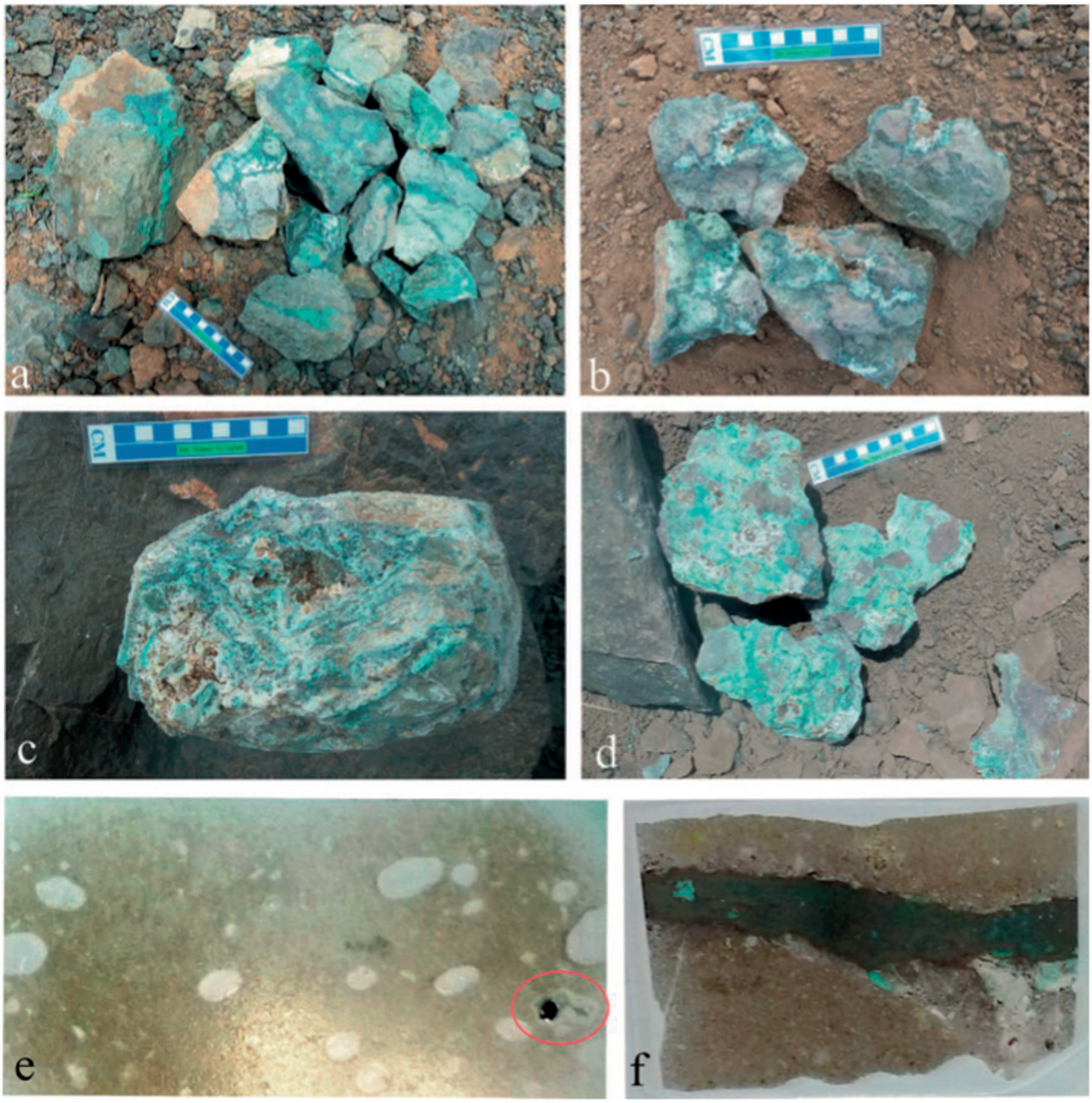

Fig. 17 – Examples of Chalcocite (Cu_2S) copper ores from Veshnaveh (Nezafati & Stöllner, 2017, p. 77, fig. 6).

The Arabah Valley (southern Levant)

Some of the best-preserved ancient mining landscapes in the broad region of Southwest Asia lie in the Arabah Valley. This metallogenic region is defined by the meeting of the African and Arabian tectonic plates creating a latitudinal (N-S) rift valley that runs from its convergence with the East Anatolian Fault in the north, through the Beqaa Valley in modern day Lebanon, and southward to the Red Sea. Activity along this fault system resulted in the formation and exposure of rich deposits of copper in the southern stretch along the Dead Sea Transform, known topographically as the Arabah Valley. Mining in the Arabah Valley contributed vast amounts of copper to the Levantine cultural and economic systems, with activity concentrated in the late Chalcolithic to Early Bronze Age and again in the Iron Age and Roman periods. The exploitation of these ore resources was distinct from those in central and northern Iran and across Anatolia, having principally served the metals markets immediate to their vicinity. In the Bronze and Iron Ages, the Arabah primarily supplied copper to Levantine settlements to the northwest and northeast of the mines (Genz, 2000; Hauptmann et al., 1992). From the late 4th to 1st millennium BCE, copper derived from the Arabah intermittently ventured into the greater eastern Mediterranean metals markets, interplaying with raw and scrap copper (among lead, silver, gold, and tin) supplies from Egypt, Cyprus, southern Anatolia, the Aegean, as well as points further east (Yahalom-Mack et al., 2014; Hauptmann et al., 2015; Kiderlen et al., 2016). There are periods of trade into Egypt; throughout time, the role of Egypt vacillated between that of consumer (Rademakers et al. 2017; see a recent summary in Ben-Dor Evian et al., 2021) and exploiter of the copper resource.

Relevant to the periods addressed in this volume, archaeological remains of ancient mining and copper processing can be found in two main areas of the Arabah. On the eastern side of the rift valley, approximately 70 km from the Dead Sea, sits the Faynan mining district and on the western side, 25 km north of the Red Sea, sits the Timna Valley (see fig. 2).

Geology of the Deposits

The metallogenetic districts of Faynan and Timna are host to the richest copper ore deposits in the Levant. Once forming the same mineralization, the two mining regions now lie approximately 105 km apart due to the continued lateral displacement of the African and Arabian tectonic plates occurring on a geological timescale (i.e., hundreds of millions of years). The deposits are categorized as sedimentary stratified deposits "formed by the erosion of Precambrian veins and subsequent deposition in a lagoonal milieu at the borderline of the Cambrian sediments to the Precambrian basement" (Hauptmann, 2020, p. 39). The mineralizations are rich and multi-metallic; the ore minerals found there are chemical precipitates in sedimentary host rocks, to which large quantities of metal have been added in solution (Hauptmann, 2020, p. 54).

Copper occurs in several geological units at Faynan and Timna. If and when these were exploited on either side of the rift valley depended on characteristic traits like surface exposure, depth of deposit, and host rock, which, at times, mired accessibility for the ancient miners (Hauptmann, 2007, p. 63–65). The earliest exploited deposits were the copper minerals of the Massif Brown Sandstone (MBS; fig. 18). Many outcrops of green malachite in a soft sandstone host rock likely contributed to ease of accessibility for miners in the 4th–3rd millennia BCE. The richest deposits occur in the Cambrian dolostones and sandstones of the Dolomite-Limestone-Shale Unit (DLS; fig. 18). The DLS mineralization consists of secondary copper intergrown with manganese oxides (Hauptmann, 2020,p. 55–56), which was of significance to the increased efficiency of smelting operations in the 1st millennium BCE. The DLS deposit sits at a far greater depth to the southwest, where it is known as the Timna Formation. Having no surface exposure there, it was minimally, if ever, exploited in antiquity. At Timna, the Cambrian deposits are overlain with Cretaceous sandstones. The Amir formation, lying just beneath the MBS was the only deposit exploited there between the 5th–1st millennium BCE (Hauptmann and Horowitz, 1980; fig. 18). The ore minerals found in both deposits are secondary copper ores such as malachite and various copper silicates like chrysocolla, plancheite, and dioptase (Hauptmann, 2007) (see fig. 18).

Faynan

Faynan is a massive mining region divided into districts or areas by hills and valleys. While the industrial scale smelting debris was noted by earlier travels into

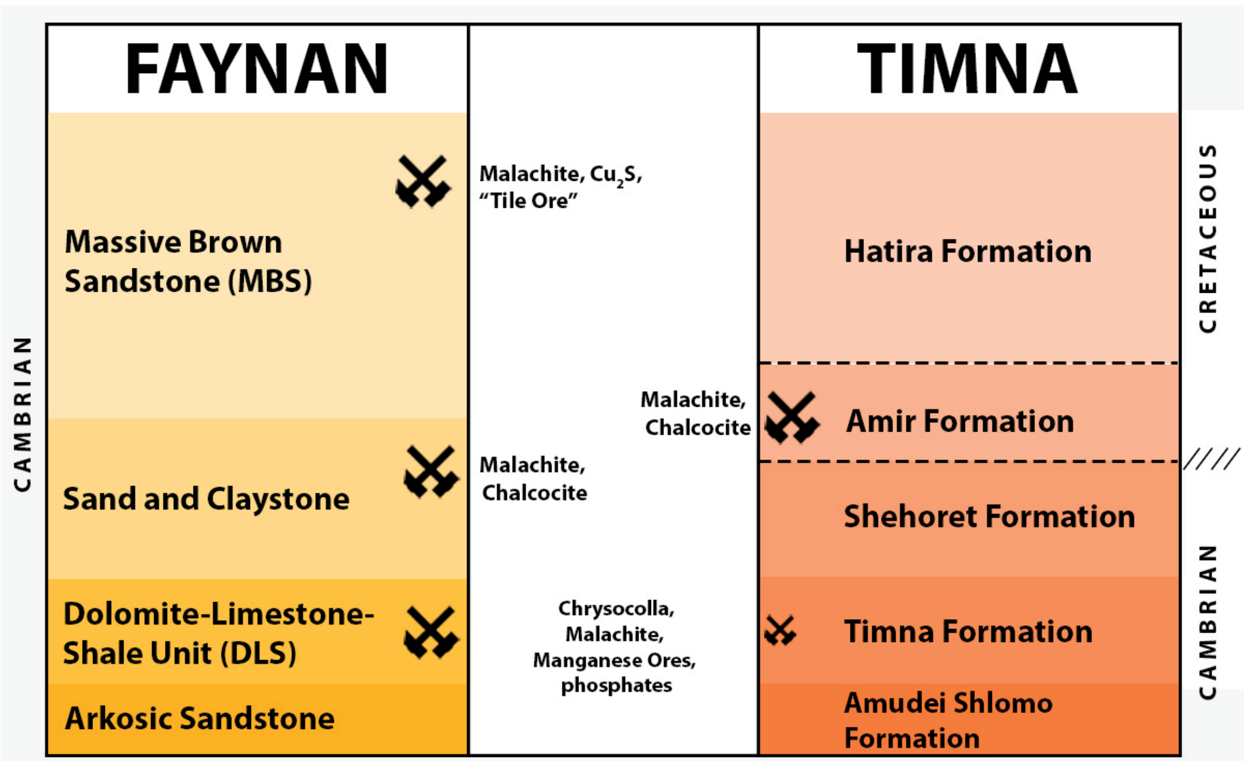

Fig. 18 – Lithostratigraphy of copper mineralization at Faynan and Timna (after Hauptmann, 2007, p. fig. 4.4).

the region, the first to recognize Faynan's historical significance was American archaeologist Nelson Glueck in the 1930s. Intensive research focused on past metallurgical activity in the Faynan Valley was initiated by Andreas Hauptmann and Gerd Weisgerber of the Bochum Mining Museum in the 1980s (Hauptmann, 2007). This was followed by successive research campaigns led by institutions in Jordan and worldwide. The latest of such endeavors began in 2002 with extensive surveys and excavations led by Thomas Levy and Mohammad Najjar of the University of California, San Diego (Levy et al., 2014). Throughout time, research has focused equally on Faynan's metallurgical and settlement history, with studies of landscape exploitation, and geological and environmental sciences.

Neolithic to Chalcolithic Periods

Earliest exploitation of copper mineral resources in the Arabah considerably pre-dates metallurgy. Prized green stones were collected from surface exposures in the area and traded or transported long distances to settlement sites in the Pre-Pottery Neolithic (11,500–10,500 years ago; Bar-Yosef et al., 2008). Hauptmann suspects that the utilization of copper ore from Faynan occurred on a modest scale with a likelihood that it was collected out of surface erosion rubble of the DLS (Hauptmann, 2007, p. 145). Working of malachite was discovered at Wadi Faynan 16, showing the use and value of the resource prior to the pyro-metallurgical revolution. Early indication for the use of Faynan ores for metals comes only in the late Chalcolithic. Adit mines at the mining areas Wadi al-Abiad, Wadi Ratiye, and Qalb Ratiye show efforts for ore removal that likely began prior to the 4th millennium BCE (Weisgerber, 2003, p. 79; Hauptmann, 2007).

Owing to challenges in accurately dating mining landscapes (esp. those that have seen millennia of reuse), chemical and LIA studies have been instrumental in connecting metal production documented at settlement sites with Arabah ore sources. LIA was carried out on copper metals and metal working production debris excavated at Chalcolithic Period sites in the Beer Sheba Basin such as Tell Abu Matar, Bir Safadi, and Shiqmim. Results were compatible with the Faynan ore body signature, providing evidence that ore was transported distances of up to 100–150 km to workshop settings where smelting, refining, and casting occurred (Shalev and Northover, 1987; Hauptmann, 1989; Shugar, 2000). This organization of production paradigm, smelting and copperworking activities occurring a great distance away from the Faynan mines, is unique to this early phase of metallurgy in the southern Levant (Levy et al., 2002; Hauptmann, 2007, p. 148).[4] LIA studies in this vein also provided substantial evidence that workshops and settlements consumed copper from multiple sources already in the Chalcolithic period – introducing new alloys and complex metals to Levantine metalworking (Tadmor et al., 1995; Hauptmann et al., 2015).[5]

Early Bronze Age

Prior traditions appear to have continued into the Early Bronze Age I (EB I), as minimal remains of mining or smelting can be archaeologically or radiometrically dated to the period between 3600–3100 BCE (recently confirmed by archaeometric work in Ben-Yosef et al., 2016). Smelting activity at Wadi Fidan 4 is dated to the early EB I but represents the only attestation of reduction activity in the mining district (Adams and Genz, 1995; Genz and Hauptmann, 2002). Mines at Wadi Dana, Qalb Ratiye and Wadi Kalib exploiting the Massive Brown Sandstone (MBS) formation are dated to the EB phase of occupation in the region (though, possibly already active in the Chalcolithic; fig. 19). Pit mining is attested, dug into the gravel conglomerate that overlays the MBS mineralization (Hauptmann, 2007, p. 112). Pit mines are positioned in a linear fashion, one after the other, showing clear evidence for continued exploitation of a single vein from above. Mines there are generally shallow and were exposed from the surface or from hillside adits, rather than creating extensive underground workings. Debris and tools from stone hammer production were also among the finds at WF 4 (Hauptmann, 2007, p. 114).

The picture changes in the EB II-III, during which time an expansion of both the Faynan population and their part in metal production is evidenced (Fritz, 1994; Adams et al., 2010; Levy et al., 2002; Ben-Yosef et al., 2016). Further developments in mining techniques are apparent in the Early Bronze Age when shafts were dug in connection with galleries to more precisely and efficiently target and exploit copper ore veins. Stone hammers and 'pock mark' impressions on the walls of the mines reveal the primary tool used for rock breaking from the mid-4th millennium BCE. Similar tools and evidence were discovered at the sites of Faynan, Madsus, and al-Jariya in the Faynan region, which are dated to the EB II-III based on pottery in mining backfill and tailing refuse (Hauptmann, 2007).

Early Bronze Age pottery found in spoil heaps (mining waste) supports the dating of a cluster of mines in Wadi Khalid (Hauptmann, 2007, p. 116). Some adit mines are dug 15–20 meters into the hill side. The 'chamber-and-pillar' approach to bedrock removal and stabilization is first documented at EB II-III at Wadi Khalid, Wadi Dana, and possibly at Umm ez-Zuhur where the DLS mineralization was exploited at increasing depths (Hauptmann, 2007, p. 251, see here fig. 19). Evidence in Wadi Kalib for both mining and smelting shows the relocation of initial ore processing activities to the mines and out of distant settlement sites. Wadi Fidan and Khirbat Hamra Ifdan (Site 14) also became key settlement sites for copper producing communities in the valley (fig. 19). Researchers estimate over a

4. Archaeointensity data from smelting site Timna 39b reported in Ben-Yosef et al., 2008 suggests the possibility of smelting also taking place next to the ore source in the Chalcolithic, though results were inconclusive.

5. Based on LIA compatibility, scholars have proposed Anatolia as the probable source for imported Sb-As-Cu metals in the Chalcolithic.

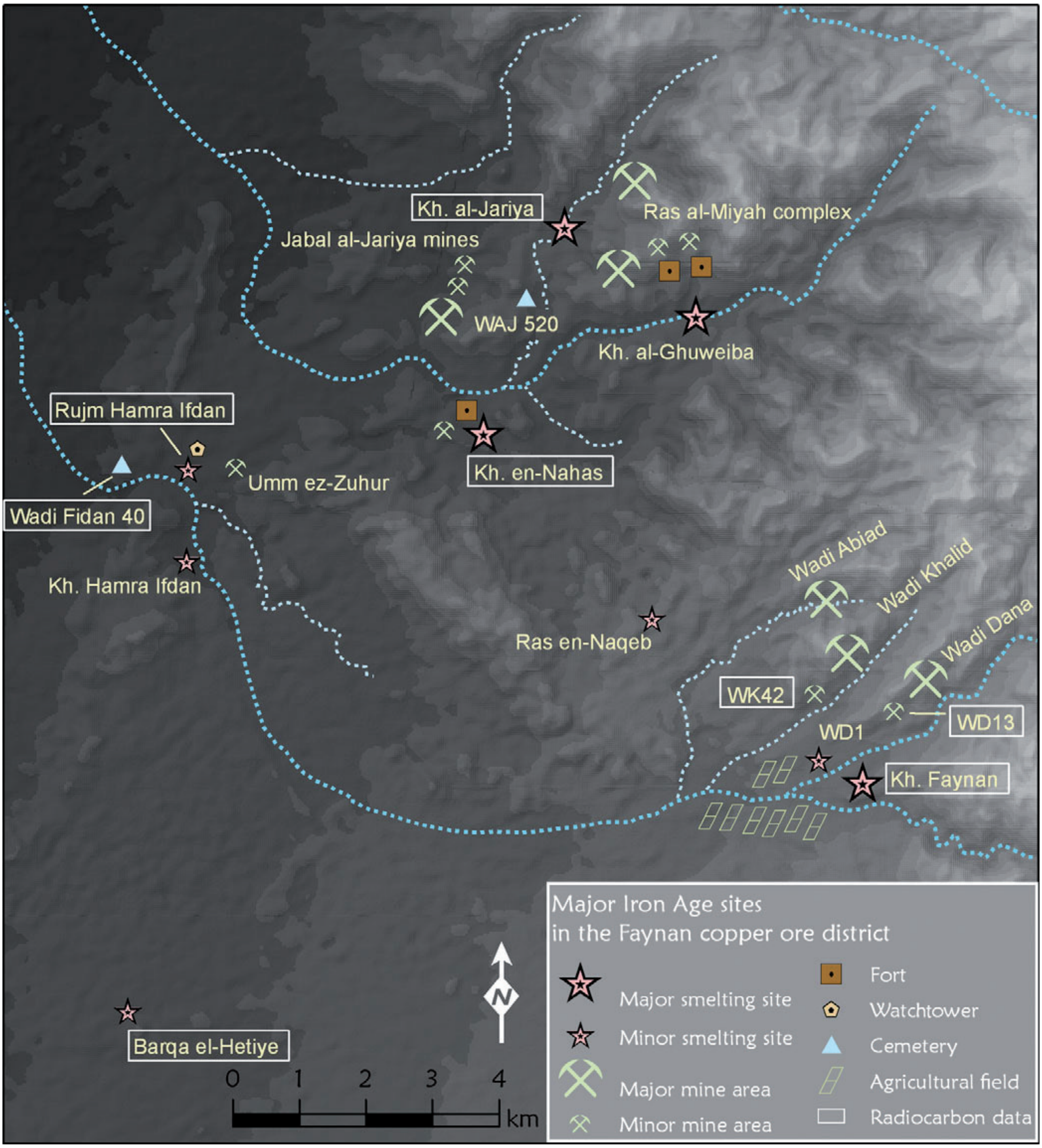

Fig. 19 – Mining and smelting sites in the Faynan copper ore district (from Ben-Yosef, Levy et al., 2010, fig. 1).

dozen smelting sites and several tons of slag at EB II-IV sites (Levy et al., 2002, p. 427; Hauptmann, 2007). This organizational revolution reduced the load of transport, allowing for an increase in efficiency and capacity for EB metal producers. Some consider this portion of the Bronze Age to be a golden age of Levantine copper production prior to the first millennium BCE. Isotopic compositions of small bar-shaped ingots found across the Cisjordan (west of the Jordan Valley) dated to the Intermediate Bronze Age are consistent with Faynan ores (Yahalom-Mack et al., 2014, p. 173). Despite noted decline in the urbanized systems of the EBA leading into the second half of the 3rd millennium, a sustained trade network of raw copper in Canaan is suggested (Yahalom-Mack et al., 2014).

Middle and Late Bronze Ages

Towards the end of the period, possibly already in the EB IV (note disagreements on periodization), decreased activity in Faynan was observed (Levy et al., 2002, p. 432). Far fewer mining and smelting sites were found containing MB pottery. Some scholars attribute diminished endeavors to the rise in circulation of Cypriot copper with the enactment of newly formed trade routes in the Eastern Mediterranean. Between the early to mid- 2nd millennium BCE, the isotopic signature of Cypriot copper can be found increasingly in copper alloys of the southern Levant (Galili et al., 2012; Yahalom-Mack et al., 2014). A diminished quantity of dateable remains for mining and smelting pursuits is noted from the Middle to the later part of the Late Bronze Age. Juniper splits found in the Wadi Khalid mines, interpreted as torches to light the subsurface galleries, returned radiocarbon dates in the Late Bronze Age (Hauptmann, 2007, p. 120). This led Hauptmann to propose continued, though reduced, exploitation. A correlation drawn between the Cypriot copper supply dominating the Late Bronze Age Levantine (and Mediterranean) metals market (Muhly and Gale, 1991) from ca. the 14th to 12th c. BCE and the absence of significant copper industries at either Faynan or Timna is unopposed by scholars. The picture again changes dramatically at the termination of the Late Bronze Age, when trade networks were severely crippled by widespread political collapse throughout the Mediterranean world. The position of Cyprus weakened, both in metal production and [to a greater extent] in trade, and the copper-rich island ceased to serve as the Levant's copper source for the better part of the next four centuries.

Iron Age

Production and population resurgence is evident in the last centuries of the 2nd millennium, first on a small scale, escalating to a peak in the early 1st millennium BCE. In the wake of the Late Bronze collapse and the rise of new geopolitical entities in the Levant, Faynan again rose to the status of prime copper supplier for the southern Levant. Upon reactivation of mining efforts in Faynan, evolution in technological practice is observed from the mining and ore processing perspectives. Exploitation of the DLS mineralization took place on a grand scale. Born out of the need to dig deeper to reach the vein deposits of the DLS, miners began to integrate new techniques. A system was developed to ease ore and rock removal as well as the movement of the miners. Foot- and handholds were created in the walls of the shafts to aid in the haul of workers and rock. Double shafts were mined at a distance of 50 cm from one another: one shaft served miners to reach the depth of the copper minerals and the other for raising ore and rock waste to the surface (Weisgerber, 2003, p. 85; see here fig. 20). The double shafts also, importantly, served to increase ventilation and light for the gallery mines below. It is postulated that iron mining tools were used in these periods and would have greatly increased the miners' rock breaking capacities (Weisgerber, 2006).

As in the Early Bronze Age, Wadi Khalid served as a major mining area in the Iron Age. A comparison of the Early Bronze Age and Iron Age mining waste there shows an increased need to excavate deeper shafts to encounter the copper-bearing veins within the DLS. In the Iron Age, this resulted in mine tailings at the foot or slope of the mountains or valleys, much further away from the exposure or mine shaft themselves. Surveys of Umm ez-Zuhur and Madsus revealed 24 mine tailings dated to the Iron Age, along with a series of gallery and shaft mines. Iron Age miners frequently dug vertical shafts to depths of

Fig. 20 – Double shafts mined in the Iron Age: a. Faynan at Wadi Ghuwebe, three post holes for a winch set up are visible (Weisgerber, 2006, fig, 21, 85); b. Timna Mine shafts S 2/1.2 (from Weisgerber 2006, fig. 20).

10–15 m below the surface. It is in Wadi Khalid that a single shaft mine dug up to 70 m deep was discovered (Weisgerber, 1989-1990). Hauptmann notes that this particular mine shows the upper limits of subsurface exploitation for the Iron Age miners (Hauptmann, 2020, p. 157–160), who operated within the confines of restricted air, light, and hauling abilities.

At Khirbat en-Nahas (KEN), enormous tailings near the mines and slag waste heaps at the settlement and copper production facilities (Strata M3–M1) to the northeast attest to the height of expansion of Iron Age exploitation efforts (Levy et al., 2014). Slag accumulations around KEN are estimated to measure somewhere between 50,000 to 80,000 tons. A similar, though smaller picture was found at nearby Khirbat al-Jariya, a smelting site sitting between the widely exploited Jabal al-Jariya mines and Ras al-Miya Complex (Ben-Yosef et al., 2010; Levy et al., 2014). The sites, along with 3 others, were occupied between the 13th to 9th centuries BCE according to radiocarbon dating and are considered the central locations of the early Iron Age industrial copper system controlled by local semi-nomadic peoples, predecessors to the Edomites (Ben-Yosef et al., 2010; Levy et al., 2014). As a proxy for understanding the magnitude of mining and smelting in the period, where only some shafts and galleries survive, Hauptmann estimated roughly a total of 100,000–130,000 tons of slag were generated at Faynan in the early 1st millennium BCE, resulting in ca. 6,500–13,000 tons of copper (Hauptmann, 2007, p. 147, table 5.3).

Timna

The Timna Valley forms a bowl off the western periphery of the southern Arabah Valley, 25 km north of the Gulf of Aqaba in the Red Sea. As at Faynan, travelers in the region were the first to document metal production activities in the valley. Upon visiting Timna, F. Frank (1934) and N. Glueck (1935) made connections between the mining works at Faynan (Weisgerber, 2006, p. 2). Glueck attributed the extensive remains of copper working to the early Iron Age, associating it with the period of the biblical Israelites. Formal research commenced at Timna in the late 1950's under the auspices of the Arabah Expedition led by Beno Rothenberg. The Arabah Expedition was a field defining endeavor, being the first archaeometallurgical-focused field project to ever be conducted. Over a nearly 40-year period, the Arabah Expedition surveyed and documented thousands of mine shafts, and hundreds of smelting and camp sites, tracking extensive occupation in the valley from the Chalcolithic to Islamic Periods (Conrad and Rothenberg, 1980; Rothenberg, 1990; 1999). Current research in the valley has been conducted since 2012 by the Central Timna Valley Project, directed by Erez Ben-Yosef.

Chalcolithic to Bronze Age

Indications for early mineral exploitation were found in settlement sites outside the Arabah, echoing the spatial organization of copper craft that was observed at Faynan.[6] Analysis of ore recovered from late 5th millennium BCE smelting contexts at Tell Magass and Tell Hujayrat al-Ghazlan (Khalil, 1988; Kalil and Eichmann, 1999) provided evidence for copper minerals originating from Timna in the period (Hauptmann, 2007, p. 290). Rothenberg and Conrad originally claimed an earlier Late Pottery Neolithic period of exploitation (Site F2) in the valley (Rothenberg, 1978; Conrad and Rothenberg, 1980), but this has been refuted, particularly in regard to reports of smelting in the period (Adams, 1997; Craddock, 2000, p. 156; Ben-Yosef et al., 2010). The Timna mines indicate multi-period exploitation characterized by increased mining depths and developments in mining tools and strategies over time. The upper level of the mine fields in Areas T and S show marks of rock breaking with stone tools, 'pock marks' considered to be Chalcolithic Period works (Conrad and Rothenberg, 1980; Shaw and Drenka, 2018; see here fig. 21). Large numbers of hammerstones of the grooved and pierced/drilled types found in the mines have long served as a means for "rough chronological classification into the Bronze Age or earlier periods" (Hauptmann, 2007, p. 16; Weisgerber, 2006). Early mines followed a two-step process: first digging a shaft, then following a vein outward in a radial fashion, which was repeated over and over in the area of the mine field. Several mines in Area S (Mine S28, S28/2) produced radiocarbon dates in the early 3rd millennium BCE (Ordentlich and Rothenberg, 1980; Weisgerber, 2006, p. 10, table 1). Levy et al. (2002) note, however, that surveys and excavations at Timna produced very little Early Bronze Age materials, giving credence to the possibility that Faynan played a more significant role during the late 4th–early 3rd millennium.

Mining works found at lower levels, as well as places where effort was made to widen tunnel and shaft entrances, bear longer and thinner marks made from pointed metal tools, such as hafted picks and chisels (fig. 21). In their exploration of Area T, complementing the work of the Arabah Expedition, Shaw and Drenka (2018) found that gallery mines dug in the Chalcolithic/Bronze Age had been extended and expanded. Later miners worked to connect previously dug galleries into larger subterranean complexes. 'Exploration winzes', vertical or shallow sloping shafts dug from one level to another, took advantage of the depth already achieved in past campaigns (Shaw and Drenka, 2018). It is presumed that these expansion efforts took place sometime in the Late Bronze or early Iron Age, now known to be the pinnacle of copper production in the valley.

Iron Age

The discovery of an Egyptian 'mining temple' (Site 200) in the center of the valley in 1969 led to a blanket relative dating approach to many of the largest mine fields and copper production sites. For a considerable period of scholarship, the two most significant smelting camps, Site 30 and 34, located centrally in the valley, were thought to

6. See footnote 4.

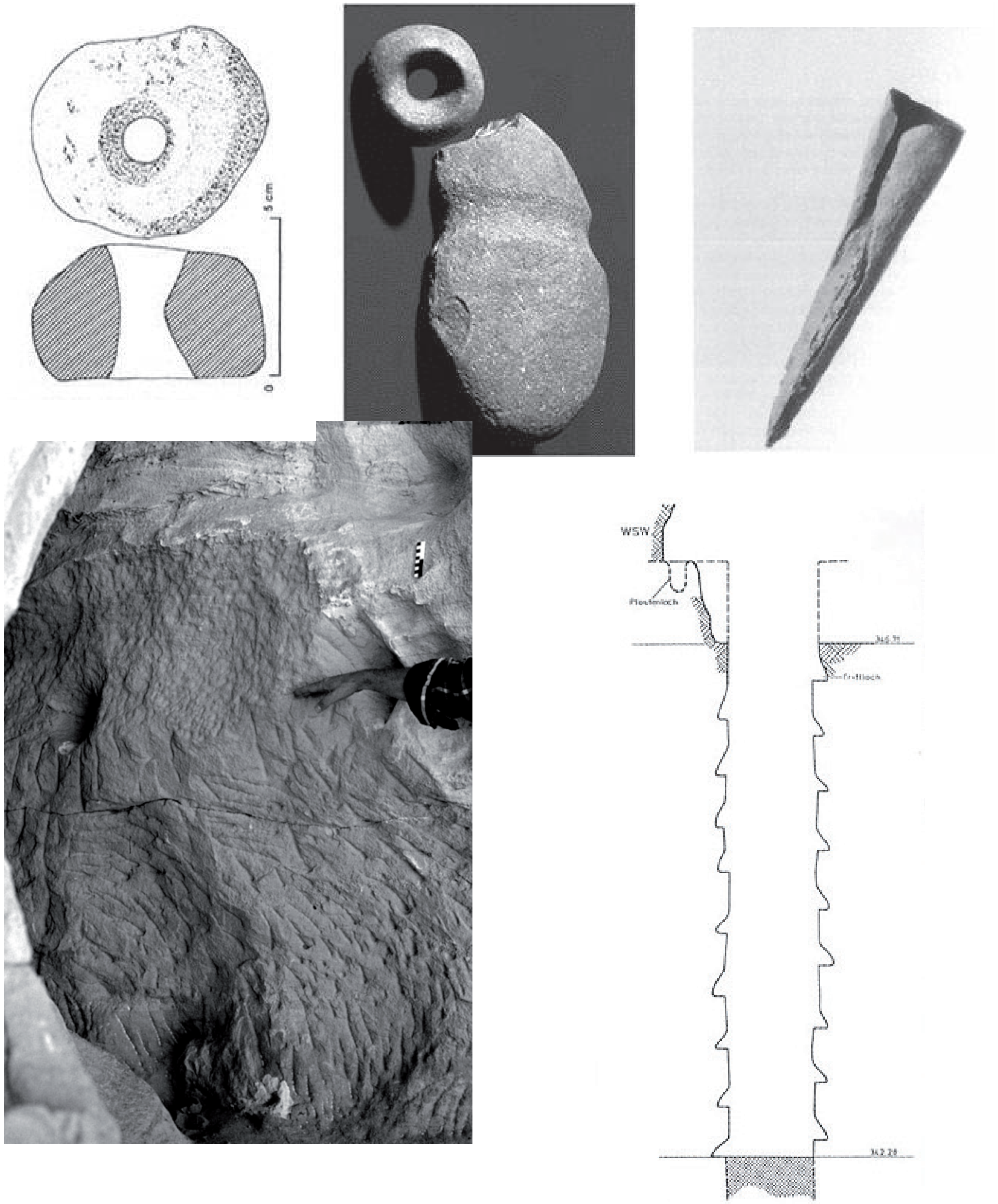

Fig. 21 – Characteristics of mining techniques at Timna: a. common tools and tool marks at the entrance of mine S 28/2. Peck or "pock" marks made from the percussion of hammerstones are visible above, while long thin depressions from mining with metal picks are seen marking the wall below (from Weisgerber, 2006: fig. 11); b. foot/hand holds carved into the wall of a deep shaft mine (from Conrad and Rothenberg, 1980, fig. 160).

be late 2nd millennium, coinciding with the years of Egyptian hegemony in the Levant (Rothenberg, 1988). Following extensive excavation and the archaeometric dating of Iron Age remains at Faynan (Hauptmann 2007; Levy et al. 2014), the previous chronological was called into question. Ben-Yosef and colleagues have used radiocarbon and geomagnetic-archaeointensity dating to establish an absolute chronological scheme for copper working sites at Timna (Ben-Yosef et al., 2008; Ben-Yosef et al., 2010; Ben-Yosef et al., 2012). Results (again) redated the prime period of exploitation at Timna to the early Iron Age, chronologically unifying the extensive copper industries in the eastern and western of the Arabah to the early first millennium. High resolution dating of slag deposits at Sites 30 and 34 have provided a range between the 11th–9th centuries BCE (Ben-Yosef et al., 2012; Ben-Yosef, 2016). Reattributing the mine fields and smelting camps, several thousand tons of smelting waste (Bachmann and Rothenberg, 1980) and ca. 900 mining shafts (Conrad and Rothenberg, 1980) to date to the Iron Age. Some of the most striking features in the Timna mining landscape are the thousands of 'plates' that dot the terrain. Excavations of select 'plates' showed that these are remains of pit mining in the conglomerate, alluvial/eluvial sediment containing copper ore nodules. Others found above bedrock are the remains of prospection mines, revealing a mass effort to identify and track ore veins. A recent archaeobotanical study on charcoal remains recovered from Iron Age Sites 30 and 34, found indications for abandonment due to the exhaustion of viable fuel resources in the local environment (Cavanagh et al., 2022).

CONCLUDING REMARKS

The above described five major published mining sites forms a rather sparse sample from which to draw much in the way of comparative conclusions concerning mining technology over time and over such a vast territory. In reviewing some of the best documented mining landscapes, basic trends in technological approach are evident. Most obvious is that mining and initial working stages (e.g., beneficiation, roasting, smelting) were determined by the available ore deposits—meaning humans adapted to the resources within their immediate environment, be that native copper, sulfidic or oxidic ores. Less predictable, naturally, are the trade routes and direction of exchange. Ore mineral or metal types could end up in circulation at great effort and under previously unforeseen circumstances.

Similar techniques for mining can be observed, potentially dictated by several parameters: (1) hardness and accessibility of the host geology, (2) availability of materials best suited for rock breaking (be that stone, bronze, or iron), and (3) the relative nature of ore richness to depth of deposit to sophistication of smelting technologies. These parameters, and more, have been summed under the umbrella of 'economic viability' of an ore deposit, a metric that can change minimally to substantially over time. It is obvious that open-pitting and shaft and gallery mining with sinuous tunneling through ore bodies are the common approaches used in early mining. The use of stone mining mauls and anvils of varying weights and sizes and fire-setting are also among the regular approaches to the act of mining as well as ore crushing/beneficiation. In mining regions with mineral wealth that was sustained over millennia, mining may follow temporal trends associated with technical innovation, resulting in increased mining and hauling capacities and ore acquisitions at increasing depths. A traditional view might assign causation, linked to a desire for more coupled with gradual technological sophistication related, for instance, to the availability of new utilitarian materials like tin bronze and iron. The impetuses behind these inclinations are more often found to be complex combinations of changes in societal organization resulting from regional cultural dynamics, along with fluctuating economic demands that together resulted in non-linear and non-cyclical phases of small-scale artisanal (or opportunistic) mining and mass resource exploitation (see Stöllner 2008; 2014). To this complex dynamic, we can introduce the possibility of exhausting a deposit or exhausting a particular resource within a deposit, say native copper from a gossan deposit or fuel resources from nearby smelting sites – all environmental limitations that invite another set of unique criteria with which to assess the use of a source.

All in all, a much larger sample is required before more can be said to adequately characterize technological and social trajectories in ore-related mining across antiquity, where persistent limitations arise from destructive long-term mining and absent datable remains. Regardless of restrictions imposed by preservation or access, in a region so large and culturally varied, at the end of the day each mining district within Southwest Asia deserves individualized study before being placed in dialogue. This work has vigorously continued throughout the last several decades, improving visibility of both the mining works and their chemical signature, which, when coupled together, contribute to a more coherent synthesis of exploitation, trade, and consumption systems.

Our discussion turns to focus on major research problems associated with the mining of native copper and copper and tin ores. As of late, in the study of the archaeometallurgy of Southwest Asia, finds of native copper and new evidence of this naturally occurring metal's geological availability have not received much scholarly attention. There is one recent exception, namely the remarkable discovery, excavation, and publication of the mines at Derekutugun in north central Anatolia. At present, this ca. 3rd millennium BCE mining site is unique in Eurasia first, because it is a native copper mine, and second because it has been excavated and presented in detail in a monograph (Yalçin and Ipek, 2016) and in various articles (e.g., Yalçin and Maass, 2013; Yalçin et al., 2019). For Southwest Asian copper and tin mining sites, this is indeed uncommon and, needless to say, we have so much more to learn.

The LIA of native copper from Derekutugun suggests isotopic signature compatibility with artifacts from sites in relative proximity to it (Yalçin and Ipek, 2016, p. 71–76). Given the considerable amounts of native copper that must have been mined from Derekutugun and how much new LIA data has been published since that time for Southwest Asia, it may well be worth revisiting this mine's signature to see if it might be compatible at a number of settlement sites across a far wider region. It is hard to imagine that this large and rich deposit of native copper, signaled by pieces of the metal in the local stream bed, was not exploited earlier than the 3rd millennium BCE, as well as after, and a renewed LIA program just might reveal an earlier exploitation of the deposit.

Turning once again to Iranian native copper, it was mentioned above that the Anarak deposits had often been discussed as a major source of this metal in prehistory (e.g., Pigott, 1999, p. 78–79) and they have often been discounted (Pernicka, 2004). It is worth noting that these deposits are known for the co-occurrence of native copper and two, rare copper arsenides, algodonite (Cu_6As) and domeykite (Cu_3As), which if dropped into molten copper in a crucible would dissolve like sugar in water (W. Rostoker: pers. comm).

However, Weeks (2008) points out that potential examples of the Anarak deposits' exploitation, via LIA conducted on artifacts from Sialk I and at Tal-i Iblis, have been noted. Furthermore, he analyzed 16 artifacts from sites in Fars excavated by the Japanese mission: Tol-e Nurabad, Tall-e Mushki, Tall-e Jari in Fars - and 5 native copper samples from Talmessi. Analyses revealed that:

> "….the uncorroded copper-base artefacts from Fars are characterised by their high purity, with only trace levels of Ag. Corroded samples show more variability, although pure (oxidised) copper phases dominate and inclusions of metallic Ag are regularly seen. These silver inclusions commonly incorporate a few weight percent of copper and uranium. Arsenic-rich inclusions (Cu_3As-domeykite) were also occasionally seen in the archaeological samples. Interestingly, Talmessi native copper samples exhibit identical metallic Ag-Cu-U inclusions in a matrix of high-purity copper with common vein-like inclusions of arsenic-rich material (Cu_3As). These compositional characteristics serve to suggest that the metal used in Neolithic Fars may have come from Talmessi on the Iranian plateau, implying long-distance exchange of this material already by the late seventh millennium B.C. (Weeks, 2008, p. 341)."

At the same time, generally speaking, he also points out the caveats that not only are there countless numbers of copper ore bodies with 'old workings' on the Iranian Plateau and that the Anarak deposits have not been properly characterized compositionally or isotopically in terms relevant to the deposits' archaeometallurgical significance. However, in closing, it remains difficult to discount that these rich deposits were exploited in antiquity given the fact that in 1935 it was reported that native copper was being extracted from a depth of 80m at a rate of 300kg per meter (Pigott, 1999, p. 78).

One final thought regarding native copper, might there be some value in spending some research time, for comparative purposes, on the considerable literature devoted to the massive native copper occurrences known from the Lake Superior region of the US and their associated prehistoric exploitation over millennia (e.g., Martin, 1999; Ehrhardt, 2005, p. 61ff; Ehrhardt, 2014; Peterson 2024a, b).

This article concludes with some thoughts on the subject of tin-bronze. As was made clear early on, tin deposits are exceedingly rare in Southwest Asia. As noted above there are 3 known deposits: the massive Kestel-Göltepe complex, the small fumarole derived deposits at Hisarcik with some modest mining evidence, and lastly the extensive mining locus at Deh Hosein. Interestingly, both Kestel and Deh Hosein are stannite (Cu_2FeSnS_4) containing. This ore when smelted can produce a tin-bronze of uncontrolled tin content. Did the initial use of such a complex ore contribute to the early 'discovery' of tin-bronze? This remains an interesting speculation.

In addition, at least at Deh Hosein, the tight lead isotopic signature(s) of its ores makes it an ideal candidate for tracking this site's signature. Since the site's publication a substantial number of newly excavated and dated tin-bronze artifacts are known in greater Southwest Asia. Given how much time has passed since the comparisons of LIA results from the Deh Hosein ores with regional tin-bronzes, there must be new LIA results to which the DH ore signatures might be compared.[7] In the initial LIA of Deh Hosein ores, the researchers argued that these ores were used extensively across the greater Near East. New analyses comparing the Deh Hosein ores to the latest LIA results from tin-bronzes in the region may well add further weight to just how extensively this site's ores might have been used. It is clear that tons of complex copper ores were excavated at that site – where did it end up? Additionally, a renewed effort to use LIA to compare the isotopic signatures of the ores from the Kestel mine and the Bolkardağ district with the most recently analyzed tin-bronzes (other than the much-discussed Uluburun shipwreck tin ingots) may well prove quite rewarding as well.

The final discussion here will focus on questions concerning the movement, trade if you will, of tin metal and/or tin ores. The well-known and well-researched early 2nd millennium BCE Old Assyrian Period tin trade comprises one of the few textually documented accounts of actual tin being moved considerable distances from southern Mesopotamia north to the entrepôt of Karum Kanesh/Kültepe in central Anatolia (e.g., Yoffee and Barjamovic, 2018). The trade statistics are notable that "one may carefully suggest that some 1,500 donkeys made the journey to Anatolia each year during the best documented period carrying with them 15 tons of tin and 32,000 textiles" (Barjamovic, 2018, p. 141). But what did the donkeys carry, tin ore or tin ingots or both (see Larsen, 2015, p. 171–188)?

7. For recent LIA study of late third millennium BCE objects see Oudbashi et al., 2022; for Iron Age examples see and Oudbashi, Rademakers et al., 2021; Oudbashi, Renson et al., 2021).

In general, in Southwest Asia, tin ingots are quite rare as are, in fact, artifacts in tin until the later 2nd millennium BCE (e.g., Nessel et al., 2018, p. 69–71). Despite the recent flurry of LIA-based investigations of known tin ingots from the Eastern Mediterranean and their potential sources (e.g., Berger et al., 2023a, b; cf. Killick et al., 2020; Powell et al., 2022; 2024), the following facts remain and will be discussed briefly below. The texts discuss tin coming from the East, i.e., east of Mesopotamia; there is the early 2nd millennium BCE Old Assyrian Period tin trade that flows northward from unknown suppliers in southern Mesopotamia and that Dilmun was a known entrepot from which tin was obtainable.

However, as early as the later 3rd millennium BCE, texts speak of "tin from the east" presumably east of Mesopotamia (Muhly, 1973; 1976, p. 97). Levantine cultures, as well as Egypt, were late adopters by comparison. The Early Bronze to Middle Bronze shift, stretching the late 3rd to early 2nd millennia BCE, saw a change from the consumption of pure copper with the rare find of arsenical and tin alloys, to cultures increasingly reliant on tin bronze. Prior to ca. 2500 BCE, neither tin bronze nor arsenical copper artifacts appear with any frequency in the Levantine archaeological record (Greenberg, 2019, p. 116). By the mid-2nd millennium BCE, the demand for tin had doubled and that of arsenic halved (Kaufman, 2013, p. 663). Kaufman (2013) and others posit that the change coincides with a "cultural reorientation from the Egyptian to Mesopotamian sphere", corresponding with the weakening of Canaanite cities in the Beer Sheva basin and a strengthening of those in the north. Copper trade from the Arabah decreases and, along with an increase of other imports, copper metals with possible Cypriot or Anatolian origins begin to appear (Kaufman, 2013, p. 684). Interestingly, there is little chemical overlap between Middle Bronze arsenical copper and tin bronze artifacts, with tin rarely being added to an arsenic-containing object (Rosenfeld et al., 1997; El Morr and Pernot, 2011). Mari letters, discussed in more detail below, mention the importation of tin to the palace of King Zimri-Lim (18th c. BCE) and to the royal family in Aleppo, moving from Elam to Mari via Babylon. Letters specify some end points of these shipments as Carchemish, Qatna, Tel Dan, and Hazor (Sasson, 1966; Kaufman, 2013,p. 680).

Based on current evidence this leaves us with three choices: Deh Hosein, the vast, but archaeologically undocumented reserves of Afghanistan (e.g., Stech and Pigott, 1986; Thomalsky et al., 2013; Thomalsky, 2016), and the numerous excavated mines of southwestern Central Asia (e.g., Boroffka et al., 2002; Garner, 2015; Stöllner et al., 2011). For purposes of discussion here we will focus first on Deh Hosein and the environs of the Elam in southwestern Iran. In this regard, the still unanswered question remains as to where the tin that was being traded north to Karum Kanesh was originating.

Donkey caravans, it has been argued, moved south into southern Mesopotamia and to Elam and back (e.g., Reiter, 1999). Helwing (2009, p. 210) points out that texts support the idea of southwestern Iran, the lands of Anšan, as being tin bearing. Moreover, Joannès (1991) notes that the two, Elamite sister capitals of Susa and Anšan (Tal-e Malyan) were road stations for the donkey caravans enroute to points north and west, e.g., to Mari via Eshnuna and the Diyala Valley. Texts found at Mari indicate that agents with Elamite names were moving standard weight tin ingots (Helwing, 2009, p. 211). Thus, the strength of texts alone implicate Elamite (middlemen?) in carrying out a trade in tin moving into Mesopotamia and across it to major capitals like Mari. Additionally, Helwing's point above that the lands of Anšan were tin-bearing, of necessity brings into focus the major, mined tin source at Deh Hosein, positioned on the immediate northern periphery of Elam. Was this mining complex supplying tin in some form to the Elamite donkey caravans travelling north to sites in Mesopotamia (Pigott, 2021, p. 843, fig. 29.10)? Further complicating this picture is that scholars, as yet, have no idea where ores mined at Deh Hosein were being smelted to metal; perhaps in its hinterland or perhaps in major urban centers along the caravan routes north in Mesopotamia?

Speaking of further complications, we turn briefly to what we might call the 'Dilmun Conundrum'. There is little question that there is a considerable body of research devoted to Dilmun, centered on the island of Bahrain and its hinterland in the Gulf north of Oman and south of southern-most Mesopotamia. Dilmun had considerable involvement with Gulf polities, Mesopotamian urban centers as well as southwestern Iran (e.g., Crawford, 1989; Laursen and Steinkeller, 2017). In this regard, Ben Foster (Foster, 1997, p. 59; see also Helwing, 2009, p. 210) has stated that "Sumerian and Babylonian merchants went to Dilmun to buy copper and tin, while traders from Dilmun came to Mesopotamia, for example, to Sargonic Umma, Lagash, and Agade as well as to Susa when it was under Sargonic rule" (Pigott, in press). Helwing (2009, p. 214) makes the point that Elam obtained tin being traded from Dilmun. In addition, Helwing (2021, para. 67) argues that Elam's 2nd millennium BCE copper supply was coming from Gulf regional sources, thus involving Elam even deeper in interaction with Gulf traders. Once in the hands of the Elamites, tin could well have joined the trade networks headed north to various Mesopotamian urban centers located along the main routes. We end our discussion with this question, from where was Dilmun obtaining the tin which it was trading so actively? Two possibilities exist. Either Deh Hosein tin was traded by the Elamites to Dilmun in return for commodities not available in Elam or we must look east to across the Indian Ocean to the Indus Valley (Meluhha) known to be trading with Mesopotamian ports. Tin sources in the Hindu Kush and Afghanistan's reserves could well have been the Indus Valley traders' sources of this tin (e.g., Crawford, 1989; Thornton, 2013; Laursen and Steinkeller, 2017; Weeks, 2003; Pigott, in press).

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