What is an Ore Deposit? Approaches from Geoscience and Archaeology in Understanding the Usage of Deposits

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Mining archaeology, ore geology, ore deposits, mineralogy, metal ages, alloys

Abstract

Metallogenic ore deposits can be construed and understood in different ways: it is easy for archaeologists and historians to oversimplify the mineralogical complexity of an ore deposit when conceptualising deposits as deliverers of raw materials such as copper or gold. Deposits are most of the time not monometallic; rather they are a mixture of various minerals that can significantly influence the metallic end products. Provenance data are often critically discussed on the basis of the explanatory value of ore mineralogy; however, archaeometallurgists may describe the complex mineralogical and chemical composition on a highly detailed level, disregarding the question of relevancy to the understanding of early societies, who tended to understand their environment on more empirical and practical levels. Archaeological theories are too often developed without regarding the specific quality of archaeometrical record, which needs detailed discussion about its quality and information value. Intense communication and close cooperation of specialists from diverse academic and scientific backgrounds are key in taking the study of metal resources forward.

Introduction

Mineral deposits are the backbone of many economic and historical perceptions of ancient societies. Debates regarding the extraction and use of metals are often connected with a certain bundle of notions held by archaeologists and archaeometallurgists. At the centre of this are perceptions of ore deposits that are located in remote landscapes, abstract, distant and difficult to access (a comment: Stöllner, 2017, pp.14-15). The vision of an exotic and distant origin of raw materials has been developed already by early urban societies, for example the Mesopotamian city states during the 3rd millennium BC. The legendary land of Aratta is a good example; it is a land ambiguously described by the Sumerian and Elamite upper society from where materials were acquired. It could be reached by travelling that passed the "seven mountain ranges" (Hansman, 1978; Majidzadeh, 1976, pp.105-113; Potts, 2004). Such perceptions of ore deposits are also shaped by the writings of V.G. Childes (e.g. 1936; 1951; Harris, 1994; Veit, 1984), who emphasised evolution and diffusion as principles of social and economic development. Childes' writings, though often criticised, have influenced generations of archaeologists because his Marxist and evolutionary perspectives still fit well to culturally inherited world views of European and American science communities. From the viewpoint of geology, a simple ore deposit model was published and became known to a broader audience by C. Strahm in 1994 (Strahm, 1994; recently modified by Hauptmann 2007; Strahm and Hauptmann, 2009; see Figure 1). The exemplary model suggests a clear vertical zoning of different parts of deposits, the surface near zone of oxidation (gossan), the zone of secondary enrichment (cementation zone) and the primary ore body (usually the sulphide-rich part). Archaeologists were ready to overtake this model as it potentially explained crises in mining and metallurgy when societies reached parts of the ore deposits requiring advances in technology. Strahm (1994; also Strahm and Hauptmann, 2009) himself explained the crisis of the South-East-European metallurgy by the exhaustion of the upper part of copper deposits (oxidation zone) usually enriched in readily smeltable ores. This functionalistic view has its shortcomings as it neither meets the geological reality of copper-bearing deposits nor the way in which earlier societies and

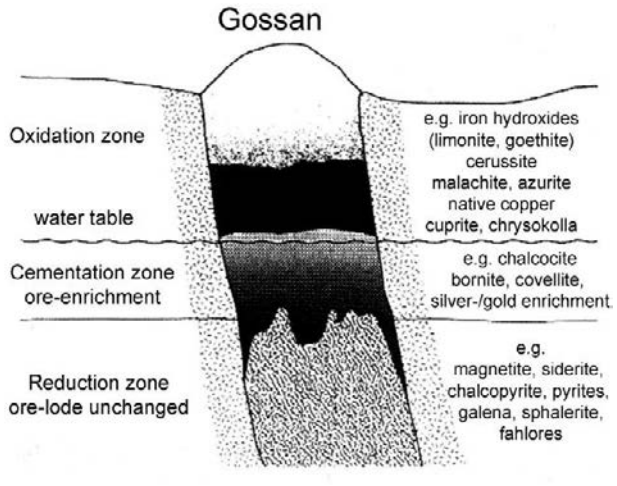


Figure 1. Simplified model of a hydrothermal ore deposit as used by Strahm (1994), modified, after Stöllner (2003, Fig. 2).

metallurgists handled the mixtures of minerals within ore bodies.[1] Neither the oxidation zone of Eastern European deposits (e.g. at the Slovakian or Transylvanian ore mountains) are completely exhausted nor are they clearly separated into primary and secondary ore zones (e.g. note 1).

The simple question where a metal object had been produced or even where the ores were mined that were used for its fabrication cannot be simply answered. There are many pitfalls, starting with assumptions made by researchers judging exploitation based on the minerals discovered only in old mine tailings, as in most cases the ore exploited is not abundantly represented there (Ixer, 1999). Conversely, the opposite is the case, as minerals that were considered as ores would have been collected by the miners and not disposed of. And the pitfalls end with the simple problem that the ore body itself may have been already mined to exhaustion and the mineral assemblages or "ore-cocktail" that may have once been exploited can no longer be found *in situ*.[2] This is especially true in complex supergene deposits with a massive occurrence of chemically weathered ores, such as it is observed for the Great Orme mine (Lewis, 1996; Ixer, 2001), where presumably the softer carbonate copper ores were mainly utilized while the sulphides were not smelted in significant quantities.[3] As with household production it was practical to transport concentrated ores in small quantities to settlements; a good example is the earlier Chalcolithic copper production at the Beersheba-basin (Shiqmim) where copper ores were smelted which probably came from the Faynan ore fields that are situated approximately 150 km away (Hauptmann, 2007).

Artefacts often were transported over some spatial distance, the site of fabrication not being the same as where it had been discovered. And even worse: The site of fabrication might have been far away from the deposits where the ores once were mined.[4] Generations of antiquaries studies have told us that the ancient distribution of artefact types might provide an answer to these questions, but instead they rather tell more about a range of cultural and social dimensions and exchange (Müller-Scheeßel and Burmeister, 2006, pp.26-30).

Despite these setbacks, generally speaking, there are many examples where it is possible to deduce the production chain as well as the consumption pattern. Archaeological excavations and archaeometallurgical studies provide insight into production and also fabrication processes making it possible to understand where metal once came from and where it went. This requires an intensive interdisciplinary cooperation and dialogue between archaeologists and archaeometallurgists to find coherent interpretative models.

A fundamental problem and a point of miscommunication is the (at times) over-simplistic usage of geochemical data, especially of results of Pb-isotope studies (for the method: e.g. Pernicka, 1995; Klein, 2007). Concerning provenance, geochemical data is most powerful when it is corroborated by cultural and archaeological evidence (see below). A recent debate on European Bronze Age provenance studies exemplifies the complexity of geochemical data interpretation. These studies still underestimate the necessity to interlink arguments based on the detailed mining operation phases with chronological phase of consumption of ores and metals (Radivojević, et al., 2018). This certainly needs extensive cooperation between mining archaeology and archaeometallurgy as it is shown by some projects (e.g. Hauptmann, 2007; Pernicka, Lutz and Stöllner, 2016).

As stated many times, lead isotope data can allow us to trace the provenance of metal objects to an ore deposit by excluding other possible deposits. However, it should be borne in mind that lead isotope analysis provides a single strand of evidence that must fall in line with others, for instance by other geochemical data, such as elemental composition and trace elements. Furthermore, it should be proven that these deposits were exploited or that there is indirect evidence of exploitation through chronological and spatial correlation between metal production and metal consumption. If we have reached this point, there is still the question if exchange, or access, can be evidenced by those who worked or consumed the metal in one way or another. Therefore, to build theories of the mining and distribution of metals, always a combination of various arguments and strands of evidence must be provided in tight cooperation between cultural and natural scientists. To

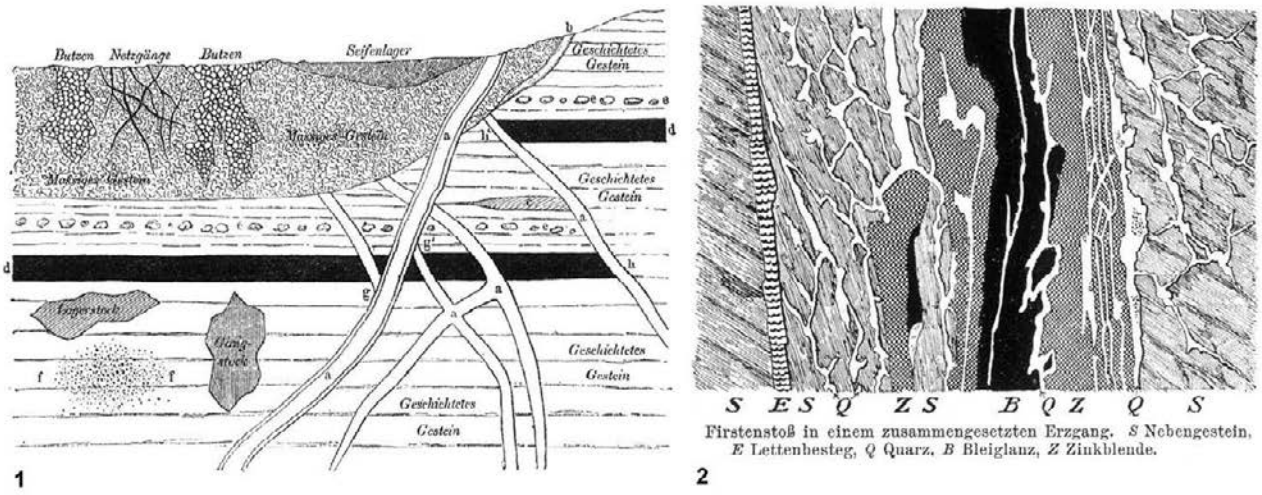


Figure 2. Early 20th century textbooks and their classification of mineral deposits, (1) after Meyers (1905, p.94) and (2) Heise and Herbst (1908, p.39, Fig. 49).

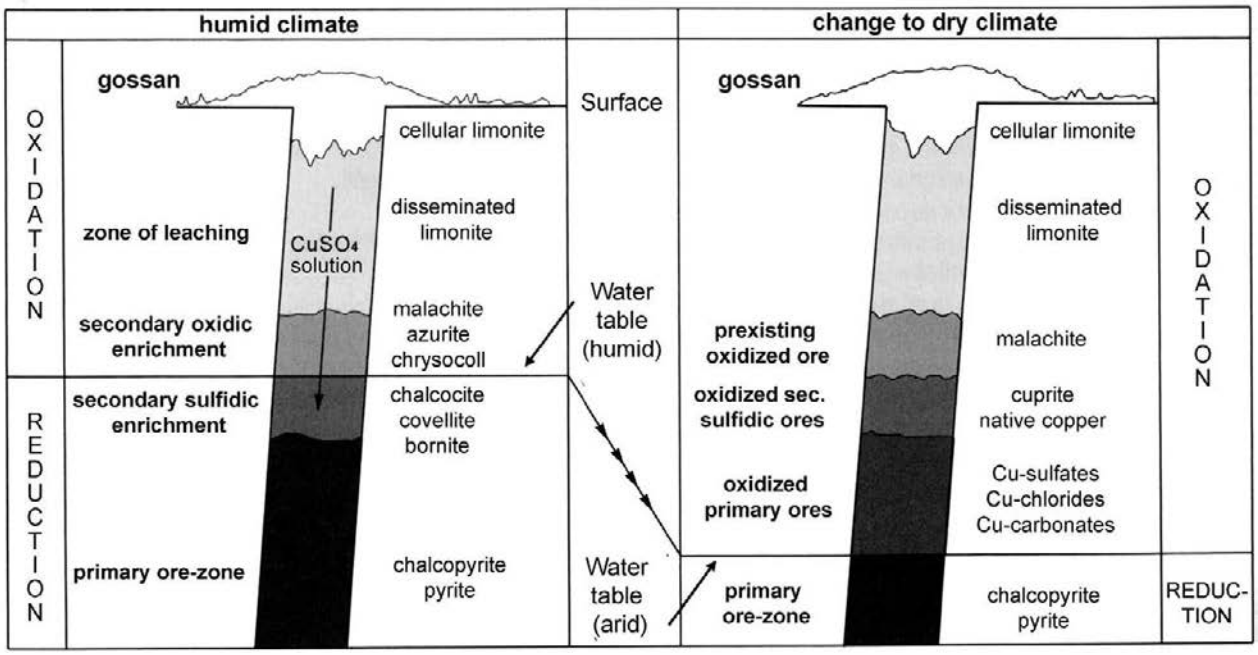


Figure 3. Scheme of an ore deposit in humid and arid climate zones after Barnes (1988) and Strahm and Hauptmann (2009).

make it simple, neither pure geochemical evidence nor a material culture reasoning can stand alone to argue sufficiently to positively and conclusively identify the provenance of metal objects.

The understanding of ore deposits is an ongoing learning process, which includes the investigation of the mineralogy and mineral properties, spatial dimensions, geologic background, formation processes, mineral enrichment processes and the extent and morphology of mineralisations in host rock and sediment (e.g. Pohl, Petrascheck and Petrascheck, 1992; Pohl, 2005; Okrusch and Matthes, 2008). Basic information still can be gained from the early geologic research and classifications of ore deposits already collected in the 19th century (Figure 2) that led to general models of ore deposits which are actively used in archaeometallurgy and mining archaeology (Figure 3). However impressive and holistic these schemes appear to be, the reality in the field is often different: Ore-lodes often are more divers and complex in their geometry as well as their mineralogical composition. Regarding past mining, typically all economically viable ore has been already exploited. Ancient mining cavities therefore especially indicate where richer minerals were extracted and can give an indication of the lower economic limit of ore. There is an enormous variety of the types and forms of mineralisations and deposits mined in the past, some being basically mono-mineral to complex and polymetallic, some are primary deposits others are secondary enrichments or alluvial deposits (Figures 4 and 5).

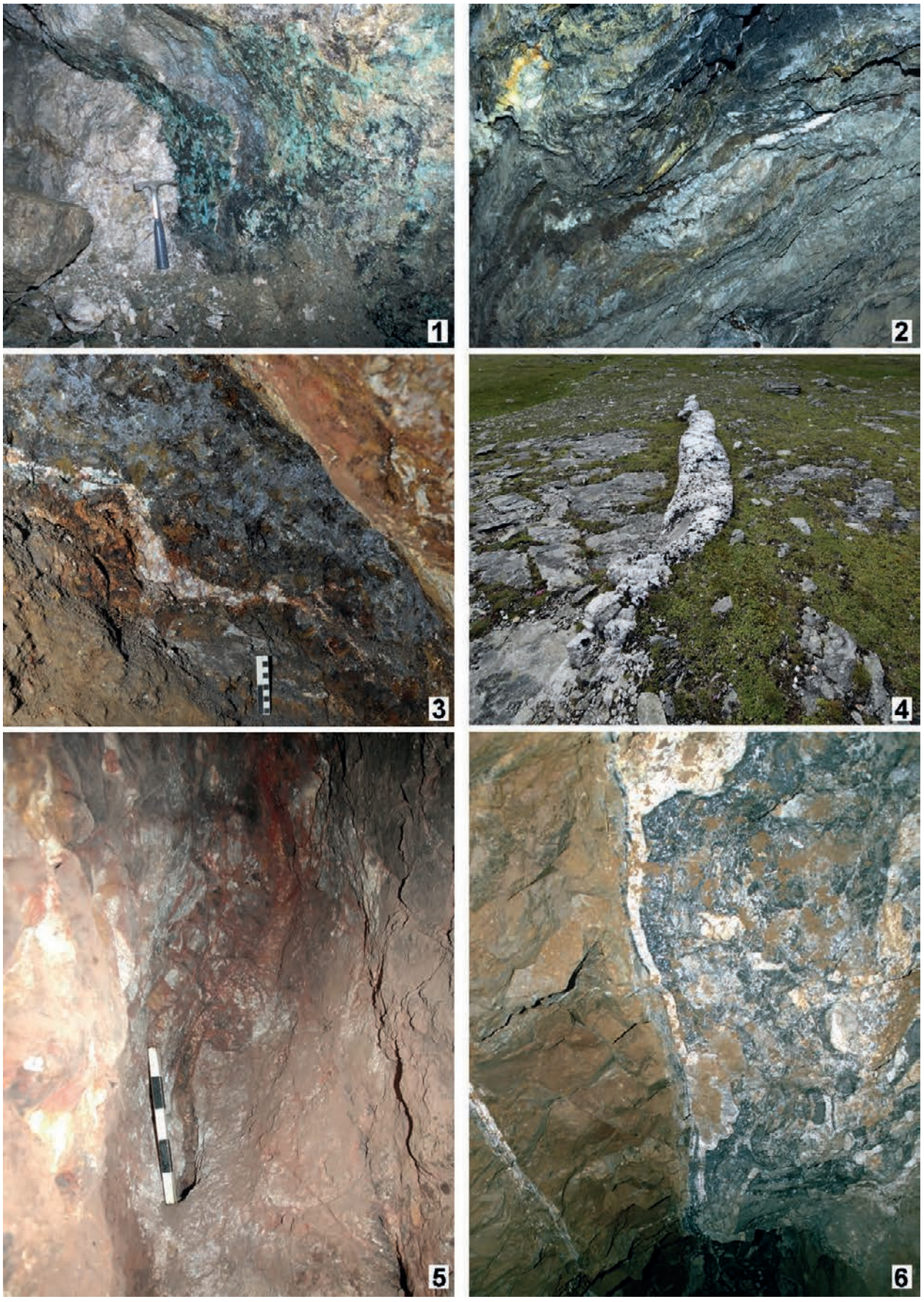


Figure 4. Hydrothermal and sub-vertical deposit, as exploited in ancient periods, 1: Mushiston, Stannite deposit; 2: Mitterberg mining region, southern district, Arthurstollen, chalcopyrite within the Brander-lode; 3: Siegerland, Victoria-mine, lode consisting of siderite, limonite and some lead-ore; 4: Gastein, surface alteration with quartz and without ore-mineralisation; 5: Sakdrisi, Georgia, Kachagiani hill, hematite quartz lode with free-gold enrichments; 6: Nakhlak, Iran, massive Galena lode with some sphalerite and quartz. Photos: DBM/RUB, J. Cierny (1), M. Dehling (2), P. Thomas (3), Th. Stöllner (4-6).

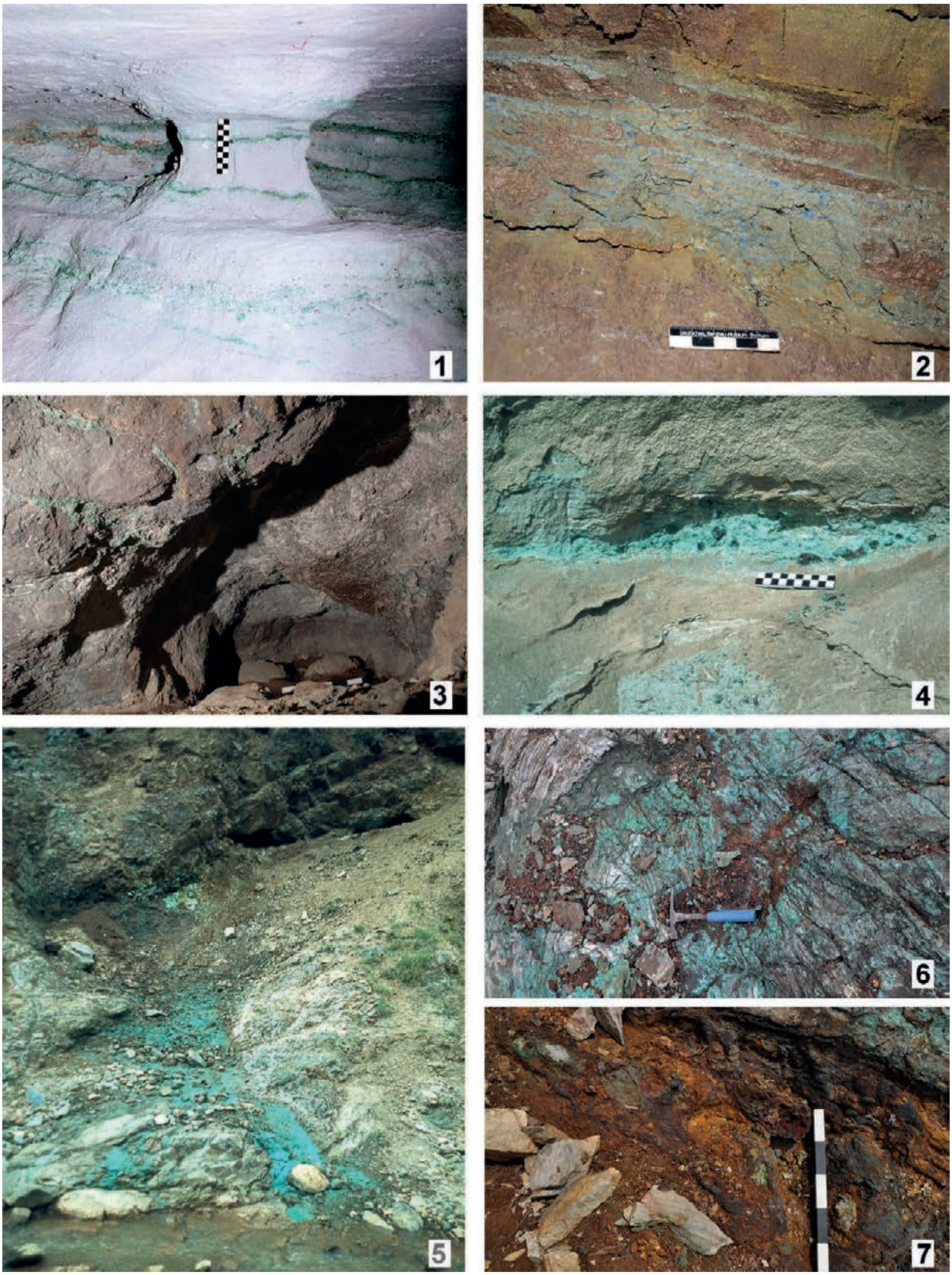


Figure 5. Sub-horizontal lodes and ore impregnations, intrusions and surface near gossan zones, as exploited in ancient periods, 1: Timna, Israel, malachite; 2: Wallerfangen, Germany, Azurite; 3: Veshnaveh, Iran, chalcocite; 4: Faynan, Jordan, malachite; 5: Sungun, Iran, oxidized gossan with copper oxides; 6-7: Rudna Glava, Serbia, gossan zone with malachite, limonite and other minerals. Photos: DBM, G. Weisgerber (1, 4-5), G. Körlin (2, 7), Th. Stöllner (3), P. Thomas (6).

It is common knowledge that modern classifications of deposits cannot be directly applied to understand pre-modern usage and the concepts of earlier societies (e.g. Stöllner, 2003, p.421; Stöllner, 2014, p.135; Strahm and Hauptmann, 2009, pp.121-122; Weisgerber, 1989/90; 2003). Different requirements and criteria were used in the past (on the social dimensions see Stöllner, 2015a). The metallogenic maps that are at our disposal were produced using a modern economic understanding of exploitability (Barnes, 1988; Jébrak, 2006) and can lead to a false estimation of a prehistoric raw material landscape. Equally the mineralogical investigation of mining waste and tailings to explore the question of what exactly was mined can be misleading, something that archaeologists occasionally do not consider.

In many cases the desired ore is scarcely available or has been exploited in its entirety in the past. This leads to an archaeological *bias* which is often ignored in the provenance debate. This is particularly the case by describing polymetallic deposits by the dominating minerals in the primary ore, which does not take into account secondary enrichment, the richest parts to have been exploited. This influences both archaeometallurgists' and archaeologists' arguments of what exactly had been used and skews our quantitative estimates. These issues have the capacity to impact all sorts of arguments within the nowadays complex and distinctive provenance-study field, which is more driven to seek lower and smaller analytical detection limits than ever before.

When it comes to mineral deposits, the basic problems are both quantitative and qualitative, either in respect of the amount of material once mined (of even the feasibility of mining) and furthermore to decide which minerals were the most sought, if not all of them were of economic interest (as it is today with modern exploitation: Jébrak, 2006). The aim of this article is to explore some examples from various mineral resources to discuss different views in the fields of mining archaeology and archaeometallurgy and to assess methodological concepts to achieve a better understanding of pre-modern production.[5]

What has been mined? Questions concerning the economic value of deposits for early societies

The economic and social value of a deposit used by ancient societies is not easy to assess. A number of aspects must be known if strategies of exploitation and production should be used for the reconstruction of past consumption patterns. In ideal conditions one would expect a definite ore deposit to object relationship that parallels a relationship of technical and social space which reflect also social and cultural perceptions that had led activities in a certain direction. Well-documented examples such as the copper deposit of Faynan in Jordan and the gold-deposit of Sakdrisi in the Lesser Caucasus Mountains will be used to demonstrate the role of ore deposits in understanding early societies.

At Faynan it became possible not only to investigate the mining and metallurgical production processes but also to understand which parts of the deposits had been exploited during different periods of time.[6] Let us focus on the transition from the Chalcolithic to the later Early Bronze Age between the mid of the 4th and the mid of the 3rd millennium BC, when copper-production developed from a sporadic and low level production to a full-time activity (Hauptmann, 2007; Hauptmann and Löffler, 2013; Löffler, 2018). International research projects have shown how the near-surface exploitation in the massive brown sandstone (MBS)-deposits changed to the deep mining of copper ore in the dolomite-limestone-shale unit (DLS)-deposits during the 3rd millennium and how the settlement and landscape management by agro-pastoralists changed during that time (Barker, et al., 2007). A detailed geochemical study of the ore-bodies allowed also the exploration of questions of consuming this copper in the southern Levant (Hauptmann, 2007).

When sophisticated copper ingot production started at the beginning of the 3rd millennium BC at local production centres like Khirbet Hamra Ifdan (EBAIII-IV, Levy, et al., 2002) (after an initial phase at sites like Wadi Fidan 4 where copper was smelted from the MBS-deposits [see Hauptmann, 2007]) mining groups initiated their access to the regional stratiform DLS-deposits that only were reachable by intensified mining efforts. The Chalcolithic and Early Bronze Age production circles allow an insight to how early societies conceptualized and processed well-visible copper-carbonate ores and how knowledge about the deposits grew over time. This knowledge allowed the adaptation of exploitation strategies to a new and more promising ore-deposit when the evolving urban societies in the Southern Levant required higher amounts of copper metal. The stratiform DLS-deposits of Faynan permitted an increase in production even if mining required greater amounts of labour (Löffler, 2018). Although the deposits have a comparatively simple mineralogical and chemical structure, it was possible also to trace the exchange and working of the Faynan ores to their final consumption (Hauptmann, 2007). The relatively straight-forward ore smelting process only altered trace-element patterns to minor degree, which made it possible to follow the ob-

jects casted from copper produced from these ores to its final deposition.

A very good example of the targeted exploitation of a deposit will now be discussed using the example of the prehistoric gold mine of Sakdrisi, Georgia. This however is more the exception than the rule in early archaeometallurgical studies: At Sakdrisi (Georgia) a late 4th millennium BC gold mine was investigated in detail over several field seasons; however, the amount of gold once extracted is a matter of debate[7] (Figures 4 and 5). Furthermore, it remains unknown in which regional and social contexts the gold was used at the beginning because ritual and social processes did not lead to larger deposition practices of metals in Kura-Araxes graves, especially at the beginning of this cultural compound (Stöllner, 2016; Stöllner, 2018).

The gold-bearing hematite-quartz lodes of the Sakdrisi deposit show variable gold contents. It is obvious that the Kura-Araxes only exploited the richest lodes of the Sakdrisi-stockwork-deposit; detailed investigation of the gold content of several of the ore lodes revealed that mining took place only in the richest veins (Stöllner, et al., 2014, Fig. 30, Tab. 4). This selection became most probably possible by systematic and empirical assaying by beneficiating, grinding and milling the ores at the site and washing them with the aid of a small cistern (Stöllner, et al., 2014; Stöllner, 2016). And although the gold itself can be characterized by mineralogical and geochemical studies (Hauptmann, et al., 2010),[8] it is still difficult to trace the gold on its way to consumers and to the final archaeological deposition. This is reasoned in part by the rather clean chemical trace-element pattern of the Sakdrisi gold but also by the fact that gold objects contemporary to the exploitation are extremely rare in the Transcaucasia (see also Jansen, et al., in press; Stöllner, 2018). In general, there are many other gold deposits in the Transcaucasian mountains and they are geochemically well-investigated (e.g. for Armenia, Wolf, et al., 2013), but still we are lacking both the evidence for ancient exploitation and the evidence of a prehistoric consumption on the basis of a geochemical relationship between ore deposits and prehistoric gold.

Therefore a very detailed description and geochemical investigation of each single vein was necessary in respect of their elemental composition and in respect of the amount most likely once exploited (Jansen, Stöllner and Courcier, 2014, pp.89-95, Tab. 4, Fig. 30). The detailed investigation made clear that the gold enrichment had considerable variation even in rich veins but also that the chemical composition could vary within a single mineralization. Recent estimates and data produced by economic geologists are not very helpful in answering questions about the prehistoric mine because of the focused exploitation strategies and extreme selectivity practiced by ancient miners.

Work pattern	Commends	Time consumption (min)
Wood work/wood transport	16,62 kg wood	90
Preparation of tools	(1 to 3 hammer tools' wastage each process, general estimate	60
Extraction/fire-setting	7,7 kg ore; 15,4 kg country rock	80
Beneficiation/ore separation	Separation of the ore/ gangue and country rock	30
Crushing/Sorting/Milling	7,7 kg ore	1725
Wet beneficiation	27 % of 7,7 kg=2,079 kg	462
Smelting of the Au-concentrate with 1g Au	Crucible-smelting	60
Entire time consumption		2507 min; Ca. 42 h
Expenditure of time estimated for the production of one gold earring (Paravani = 9,4 g)		395 h → 16 miners → 3 labor days (8-9 h labor days)

Figure 6. The "Paravani"-calculation shows the time-consumption for producing 1 g of gold in the ore-deposit of Sakdrisi in regard of the technical processes reconstructed by excavations and experiments after Stöllner (2016).

Our more detailed view made it possible to develop an extraction model that considered an average gold content in the enriched parts in the different ore veins and the amount of gold lost in the debris backfilled by the miners themselves (Stöllner, 2016, pp.217-223, Fig. 7). These results had to be placed within the context of the organisation structure and mining method that was once applied, including the fire-setting technique used in small drifts underground (the so called Paravani calculation) (Stöllner, et al., 2014, pp.92-95; Stöllner, 2016, pp.217-223) (Figure 6). It is likely that the gold from multiple small veins was extracted to meet special social and ritual needs. The early miners could not determine the amount of gold within the single veinlets because of their tiny volume; instead, they only could test bulk amounts collected from multiple veins, crushed and washed on site, in order to determine where it was promising to continue the work. Such a winning mode, requiring the homogenisation of gold from multiple veins, means that it is difficult to identify characteristic elemental patterns in light of the extremely heterogeneous compositions of the different veinlets. Provenance determination of gold objects is made even more difficult when considering subsequent mixing of gold during recycling (see arguments in Stöllner, 2018). This is particularly true for the

Sakdrisi gold that is geochemically rather inconspicuous without distinctive trace markers.

As the prehistoric mine was destroyed by modern extraction, it is now much more difficult than before to estimate how much gold once was exploited at the Kachagiani hill (Sakdrisi). We only have information about a few single veins (e.g. the vein of mine 1/2), producing a rather rough estimate of a few hundred kilograms of gold exploited over a 400 to 600 year period. An annual production, therefore, would have not exceeded 1 kg of gold, which in the end provides rough insights into social and economic aspects of mining (Stöllner, et al., 2014, pp.104-105).

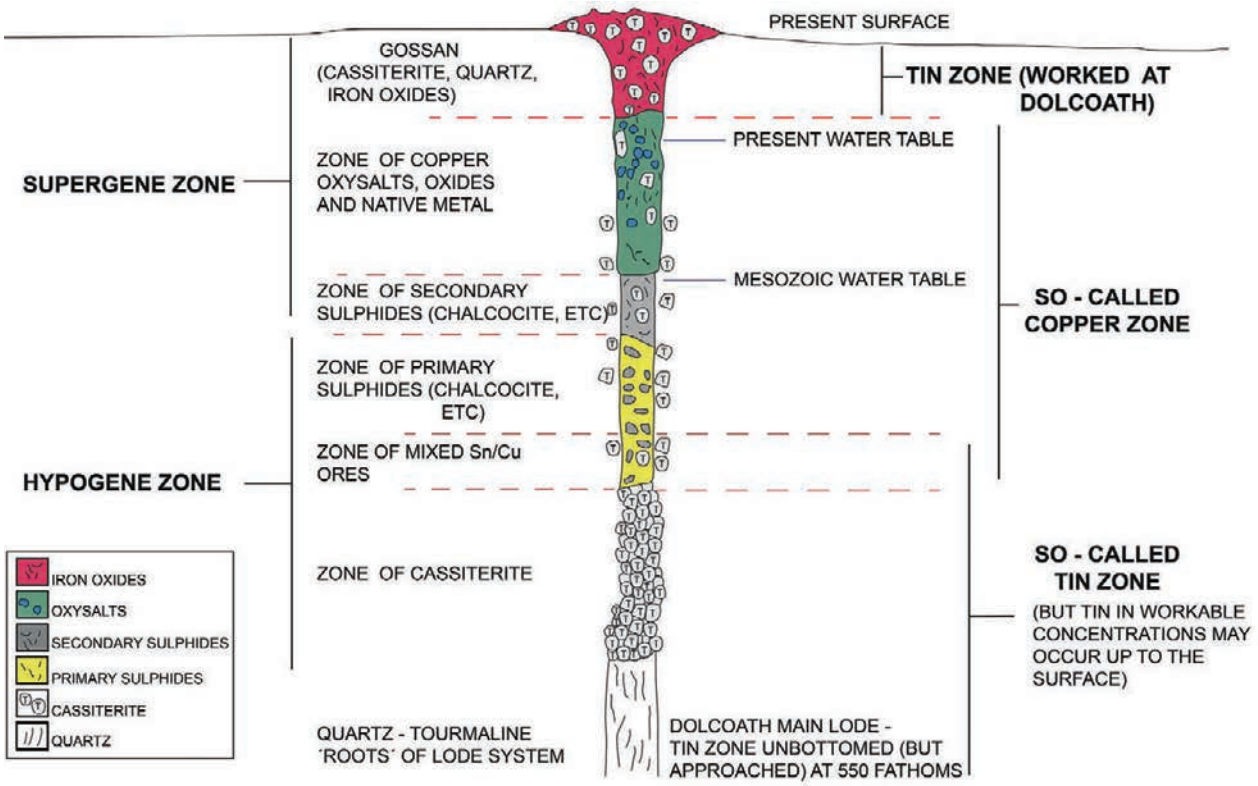
Sakdrisi and Faynan are rather good examples for the possibility to develop models of how ancient societies approached the use of ore deposits and how they might have conceptualised their exploitation in the frame of a cultural system. This is particularly possible as these deposits can be considered as monometallic.

Natural or deliberate alloys? The influence of the deposit on small scale smelting

Hydrothermal polymetallic deposits, such as commonly found in the Tethyan-Eurasian Metallogenic (TEMB) belt, have been used since prehistoric times, but understanding these deposits and their use is more difficult to follow. This has different reasons, much of which can be related to the zonation within the deposits and the complex intergrowths of mineral compounds in the ore deposits. In both cases it is of high importance to clarify the mining techniques and extractive metallurgy at the places with secure chronology/dating but also to identify which parts of the ore deposit were exploited and when. A look at the composition of polymetallic hydrothermal veins, like those that are known from some districts of the deposits of Cornwall, makes this apparent. At the Camborn-Redruth District (Hosking, 1988), the lodes (for instance from the famous Dolcoath-mine: Trounson and Bullen, 1999) are extremely complex (Figure 7). The lodes show decreasing mineralogical complexity with depth, but those near the surface, showing the effects of chemical and physical weathering (i.e. in the supergene zone), are truly complex polymetallic mixtures. Such supergene zones were easily accessible to pre-industrial mining and in Cornwall there is evidence for mining activities at least for tin that dates back to the 2nd millennium BC (Penhallurick, 1986, pp.173–224).[9]

Early mining also may have reached areas below the water table, as the water-levels fluctuate. Chalcopyrite and fahlore minerals, like tennantite, a copper-arsenic-sulphide, could have been used, despite the fact that the so called 'copper-tin zone' of the primary hypergene

Figure 7. Mineral "cocktail" at the Dolcoath-deposit, Camborn-Redruth District, redrawn after Hoskins (1988) (http://myweb.tiscali.co.uk/geologyofcornwall/Mineralisation.htm).



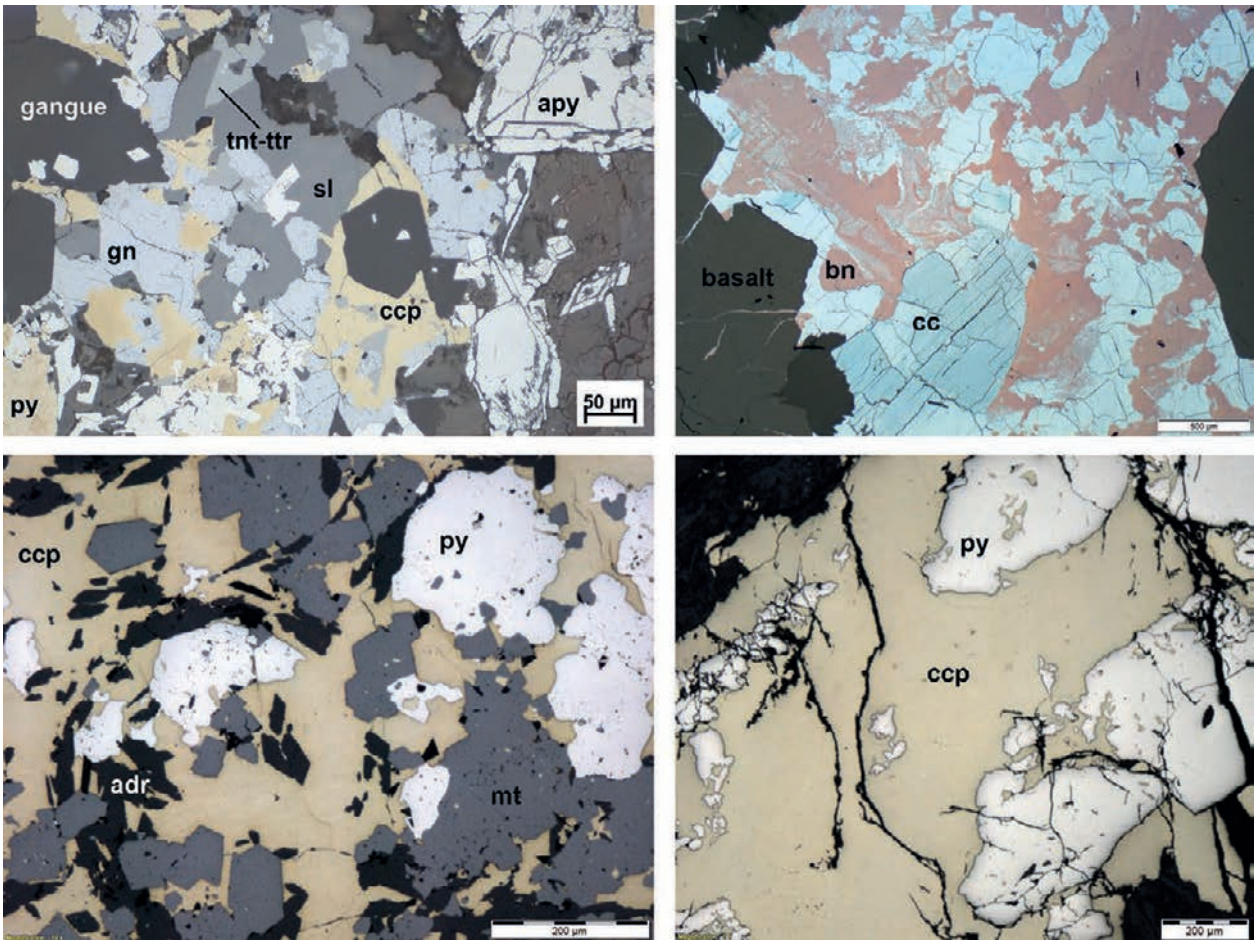


Figure 8. Intergrowths of ores: 1: polymineralic ore (DBM sample 13098: arsenopyrite (apy), galenite (gn), tetrahedrite/tennantite (ttr, tnt); sphalerite (sl), chalcopyrite (ccp), pyrite (py); in the gangue: quartz and iron rich-carbonates) from mining district Janjevo, Kosovo, from a tailing of field of glory holes; 2: ore of rich chalcocite/bornite (ccp, bn) with eutectic intergrowths of both minerals within a basaltic matrix, from the copper district Oberhalbstein CH, Cotschens (sample 4046-C2), reflected light; 3: ore of hypide-idiomorphe pyrite which likely was transformed to chalcopyrite (ccp) and magnetite (mt); within the chalcopyrite alto the mineral andradite (adr), from Oberhalbstein CH, Crap Fess, 4432-CF, reflected light; 4: pyrite, already removed by chalcopyrite, Oberhalbstein CH, Avagna-Ochsenalp, sample 4428-AO, reflected light. Photos: DBM, K. Westner (1), L. Reitmaier-Naef (2-4).

deposit was apparently too deep to be mined (around 500 m level from surface). The example of the Paleozoic tin-tungsten-copper deposits, such as from the Cornwall type, makes apparent that it is essential to know in which parts mining took place. When taking a detailed look at the mineral compositions in such supergene zones, the variability of minerals particularly has to be considered in regard to early small scale smelting activities.

Many textbooks emphasise the fine intergrowths of polymetallic ores by describing the diversity and variability of ore mineral combinations. Particularly older descriptions of the Renaissance and early modern times fire the imagination of the richness and variability of polymetallic ore. One example are the descriptions and publications made by the Bohemian minter and metallurgist Lazarus Ercker (1528/30-1594) who described various minerals from mines and their physical and chemical properties (Ercker, 1574). As the example of the 'Rotgültigerz' or 'ruby silver', a silver-rich ore (nowadays proustite $Ag_3[AsS_3]$ and pyrargyrite $Ag_3[SbS_3]$), shows, centuries ago miners and metallurgists realised the importance of special minerals. These descriptions of minerals and early ore classifications led to the beginning of a systematic gathering of information by a variety of mining specialists. The beginning of systematised ore mineralogy was further developed by advances in microscopy since the 19th century, and modern ore mineralogy was especially influenced by the work of Ramdohr in the mid-20th century (Ramdohr, 1960; Maucher and Rehwald, 1961; Friedrich, 1970; Taylor, 2009). Because of the science of mineralogy, the supergene parts of deposits can be described in more detail than ever before (e.g. Figure 8).

In order to be able to understand ancient ore mining, it is important to understand the mineralogical variety of the supergene parts of an ore deposit. Generally

Table 1. Some mineral components for a native polymetallic "cocktail"

(Secondary) minerals, oxides, carbonates	Malachite/Azurite/Atacamite/ Paratacamite/Brochantite/ Chalcopyrite/Cuprite/Tenorite/ Cassiterite
Gangue	Aragonite ($CaCO_3$), Hematite (Fe_2O_3), Siderite ($FeCO_3$), Pyrite (FeS_2), Quartz (SiO_2)
Arsenopyrite	FeAsS
Domeykite	Cu_3As
Enargite	Cu_3AsS_4
Këwhile	$Cu_2(Zn,Fe)SnS_4$
Mushistonite	$CuSn(OH)_6$
Olivenite	$Cu_2(AsO_4)OH$
Orpiment	As_2S_3
Skorodite	$FeAsO_4*2H_2O$
Realgar	As_2S_2
Stannite	Cu_2FeSnS_4
Stromeyerite	AgCuS
Tennantite-Tetraedrite-Freibergite	$Cu_{12}As_4S_{13}$; $Cu_{12}Sb_4S_{13}$; $Ag_6[Cu_4Fe_2]Sb_4S_{13-x}$

speaking, a high variety of minerals can be observed in polymetallic secondary ore (for example, Table 1). Ore minerals might have attracted ancient miners first by their colour, and over time ancient peoples learned how to produce different metals and alloys through nuanced smelting processes. Because of the mineralogical assemblage of some secondary polymetallic copper ores, it may have been possible to directly smelt particular alloys. A good example is olivenite, which is known in some quantity from the upper Gran-valley in Slovakia, from the Laurion, from Cornish deposits, in Namibia and Peru and many other localities. Olivenite is an arsenic-rich secondary copper mineral, $Cu_2(AsO_4)OH$, which can occur in coexistence with other copper-bearing minerals such as malachite, azurite, tennantite and chalcopyrite (Strunz and Nickel, 2001, p.444). The green colour might have been misleading for prehistoric and ancient prospectors who may have mistaken mixed copper-arsenic minerals for malachite during superficial gathering.

If such minerals had an effect on the discovery and spread of the use of arsenical copper, it is ideal to know about the frequency, regularity and extent in which such minerals could be found in the supergene parts of ore deposits. This is not easy, considering that the supergene parts of many ore deposits have been already exploited or destroyed.

Higher arsenic levels indicate that arsenic levels beyond wt.-1% and even over wt.-3% could be the result of deliberate co-smelting or alloying processes and did not necessarily derive from arsenic levels from mixed polymetallic ores. A method of using arsenopyrites for the production of copper-arsenic alloys was discovered by findings of speiss at metallurgical hubs like Arisman (Rehren, Boscher and Pernicka, 2012), Tappeh Hesar (Thornton, Rehren and Pigott, 2009) and Shahr-i Sokhta (Hauptmann, Rehren and Schmid-Strecker, 2003, pp.200-201). Not only is the greyish to brownish arsenopyrite easier to recognize than the greenish olivenite within a matrix of mixed oxidized copper ores, associations of arsenic and iron minerals are far more common than associations of arsenic and copper minerals. The detachment of copper ore from arsenic-iron minerals is better suited to meet a high demand for standardised arsenical copper alloys and can be discussed as a major innovation in copper-arsenic metallurgy.

In the southern Caucasus region, it is obvious that with the later 4th millennium BC the production of copper-arsenic alloys became a standardised technology (Figure 9, based on 494 analyses) (already Selimchanov, 1977; Stöllner, in press (a), Fig. 4, Tab. 1). The standardisation of copper-arsenic alloy production can also be observed for many parts of western Asia, the Iranian plateau and Eurasia (Chernykh, 1992; Kohl, 2007), where copper-arsenic alloys became a basic metal material from the later 4th millennium BC onwards. There are still many open questions regarding the production methods of copper-arsenic alloys and how cultures were able to cope with the demand. Understanding the structure and mineralogical composition of ore deposits is key to the discussion as it is the availability of certain types of mineral assemblages that govern the mode and scale of production as well as the need for innovation.

Major large-scale deposits: Standard copper supply vs social networks in the light of methodological problems?

Small-scale, near-surface mining activities in ore deposits were often practiced to seek limited amounts of special ore minerals that were altered or enriched by geological processes. The mining of these minerals was tightly related to the extractive metallurgy techniques and possibilities. Such near-surface deposits had an important influence on the development of new techniques and certainly did induce the widening of metallurgical knowledge. Later large deposits such as massive sulphide deposits of Cyprus became periodically major

	without As	As 0-999ppm	As 1000-4999ppm	As 0.5-0.99%	As 1-2.99%	As 3-6%	As > 6%
Sioni/LC1-2 (n=55)	**14.5**	**36.4**	**16.5**	**3.6**	**14.5**	**12.7**	**1.8**
Leilatepe/LC3-4 (n=84)	**3.6**	**32.1**	**28.6**	**7.1**	**17.9**	**10.7**	
Kura-Araxes, LC5/EBA1 (n=59)	**1.7**	**3.4**	**8.5**	**6.7**	**40.7**	**30.5**	**8.5**
Kura-Araxes, 3rd millenium (n=173)	**1.2**	**3.5**	**4.6**	**5.8**	**49.1**	**28.3**	**7.5**
Martkopi/Bedeni (n=132)		**2.3**	**3.8**	**7.6**	**60.6**	**20.4**	**5.3**

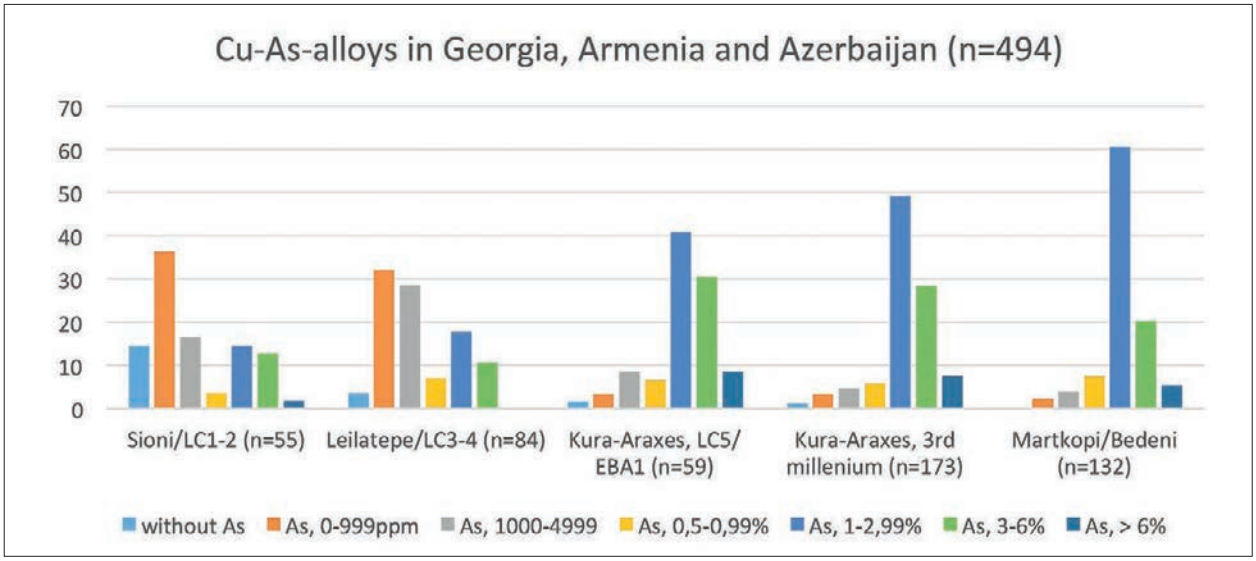


Figure 9. Frequency in percent of Cu-As-metals between the 5th and the 3rd millennium BC in Georgia, Azerbaijan, Armenia, unpublished data DBM.

and important suppliers for larger regions in the Old World, especially from the 2nd millennium BC onwards (e.g. Hauptmann, 2008) (Figure 10). This had its consequences also for the metallurgical processes and thus the metals being produced. Even before, larger deposits of carbonate-based copper ore, such as Faynan, Jordan (Hauptmann, 2007) and the Great Orme, Wales (Ixer, 2001) and elsewhere in Wales (Timberlake, 2009), could hold such an importance for centuries, but lost their prominence when the mass-production from massive sulphide ore deposits started to dominate the copper exchange markets. A prime example, Cyprus was a major player in parts of the Bronze Age, and it was still important during the early Iron Age but was accompanied by large scale production of other centres such as the Alps and Faynan (Kassianidou, 2014; Levy, Najjar, and Ben-Yosef, 2014; Kiderlen, et al., 2016; for Alpine copper: Jung, Mehofer and Pernicka, 2011). Recent studies impressively have demonstrated this 'copper' shift for the British Isles, where Late Bronze Age copper does significantly differ from older metal compositions (Needham, Parham and Frieman, 2013). One of the explanations could be the decline of regional production in relation to imports from larger production centres as hinted by the Salcombe metal assemblage (possibly from a shipwreck) (Wang, et al., 2016).

Cyprus and the Alpine deposits became important suppliers of copper in the 2nd millennium BC, when it became possible to smelt copper-iron sulphides using a shaft-furnace that allowed the reduction of sulphur and iron contents stepwise reducing the sulphur contents in stages (see Hanning, et al., 2015; generally for the usage of copper deposits: O'Brian, 2015). Deliberate alloy production on a massive scale certainly reflects increased access to ores. This is especially true for periods when tin-bronzes started to imprint the global metal production of the Old World (generally see Pernicka, 1998): One may assume that requirements of standardised products, such as a bronze with 10 wt.-% tin, also directed metal production towards immense monometallic deposits but also revolutionised the production concepts themselves. The large-scale usage of ore deposits included also social

Figure 10. Cyprus, Mathiatis, massive sulfide ore deposit with very large gossan that was selectively exploited in antiquity (right: gallery) and during the 20th century. Photos: DBM/RUB, Th. Stöllner.

concepts that allowed the involvement and integration of larger parts of societies into the networks of metal supply and demand. One could argue that copper deposits such as found at Mitterberg in Austria, Rio Tinto in southern Spain and Cyprus now became backbones of economic and technical concepts of the 2nd millennium BC that were further developed during the latter 1st millennium BC and the Roman period in the wider Mediterranean and temperate European spheres (e.g. the summaries of Domergue, 2008; Stöllner and Bartelheim, 2015).

In comparison to small-scale and selective usage of supergene deposits as discussed above, large-scale deposits are the reverse. In many cases, mining regions like at Mitterberg applied deep mining and standardised processes to produce masses of raw copper that were inducted to large-scale and wide-reaching exchange networks.[10] Copper of the Mitterberg type was used between the southern Scandinavia, Central and Eastern Europe (Pernicka, Lutz and Stöllner, 2016). Mitterberg can also be taken as an example for the methodological challenges that are connected with large scale deposit usage. One problem is the variation caused by geochemical differences, especially if the standardised technological strategies were to be applied on an extensive regional scale; however, there are examples where this problem appears to have been overcome. For a long time it was only possible to generally discuss East Alpine copper as a whole.[11] Two effects are responsible for this. East Alpine mining regions followed standardised beneficiation and smelting practices (Bartelheim, 2007; Stöllner, 2009) that led to homogenised smelting products. This is caused by the geochemically more homogeneous chalcopyrite ores that were exploited on large scale, which in turn led to a higher geochemical homogenisation of the final products.[12] A change occurred especially, during the Late Bronze Age, when Alpine communities started to produce deliberate copper alloys from fahlore-chalcopyrite ore mixtures, probably to utilize the material properties of elements found in fahlore to harden the relatively clean chalcopyrite copper and to minimize the amount of tin required for alloying (see recently the debate: Stöllner, et al., 2016, pp.95-97).

Although large-scale deposits, like the Mitterberg main lode, do show a high variability of different mineral components (besides the most important chalcopyrite, there are also nickel-bearing ores and fahlores). It was difficult to geochemically differentiate parts based on mineralogical differences, simply as sampling strategies often neglected these minute differences.

Large scale deposits logically require also large scale geochemical and mineralogical sampling and archaeological dating.[13] Recent research did provide new insights because systematic sampling revealed geochemical differences between the major mining districts of Kitzbühel and Mitterberg as a whole, but also distinctions could be made within single ore bodies or a group of ore bodies (Figure 11, a and b).[14] Although these data cannot circumvent the effects of homogenisation and

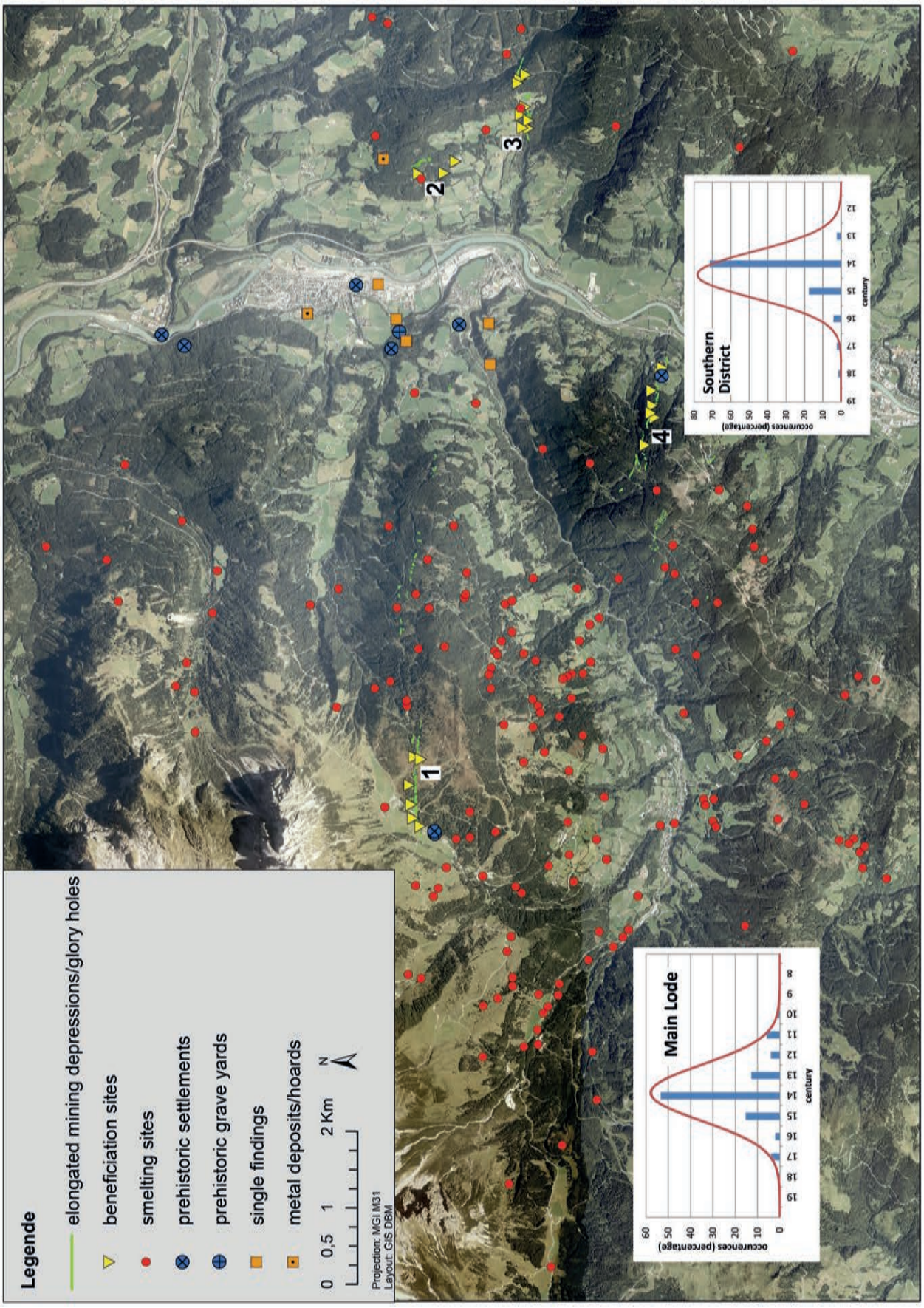
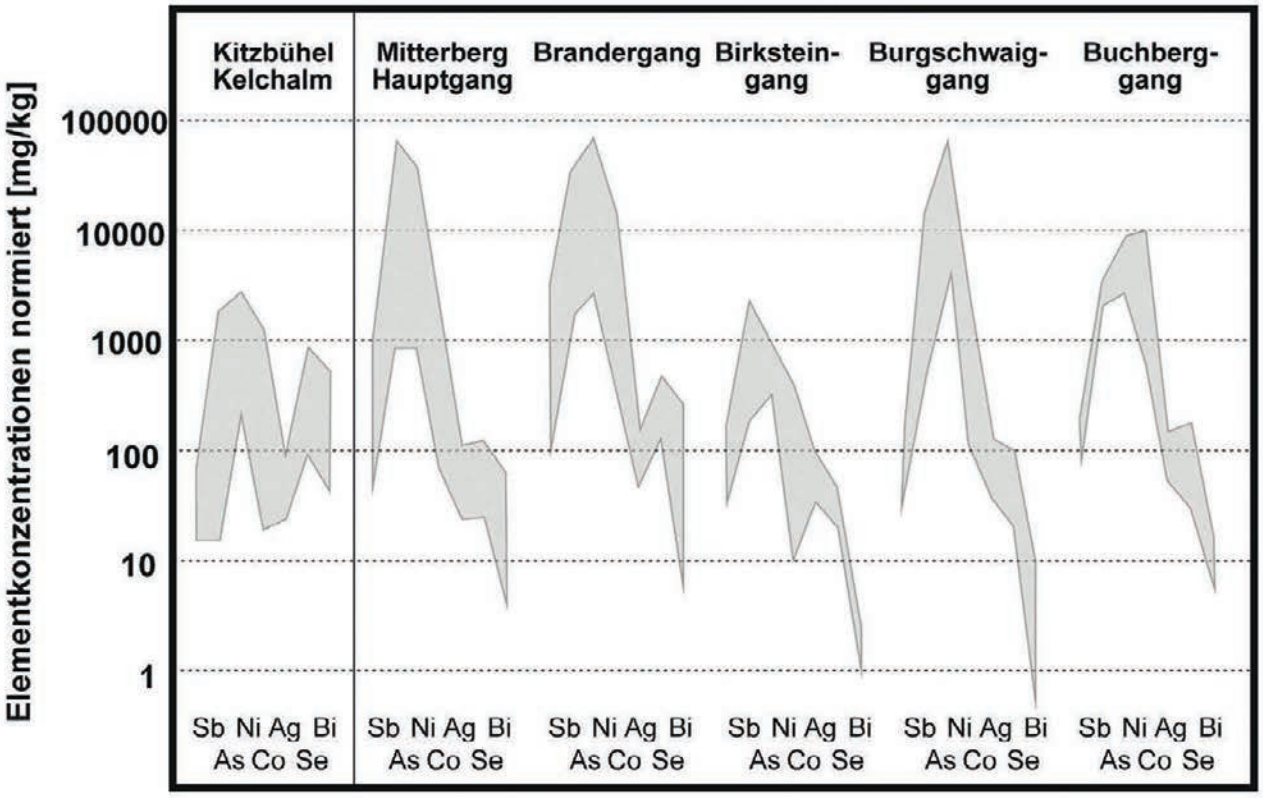


Figure 11a. Mitterberg mining region, the temporal intensity of Bronze Age mining in the southern and main-lode district and the geochemical characterisation of the various ore-lodes of the Mitterberg mining district, after Pernicka, Lutz and Stöllner (2016).



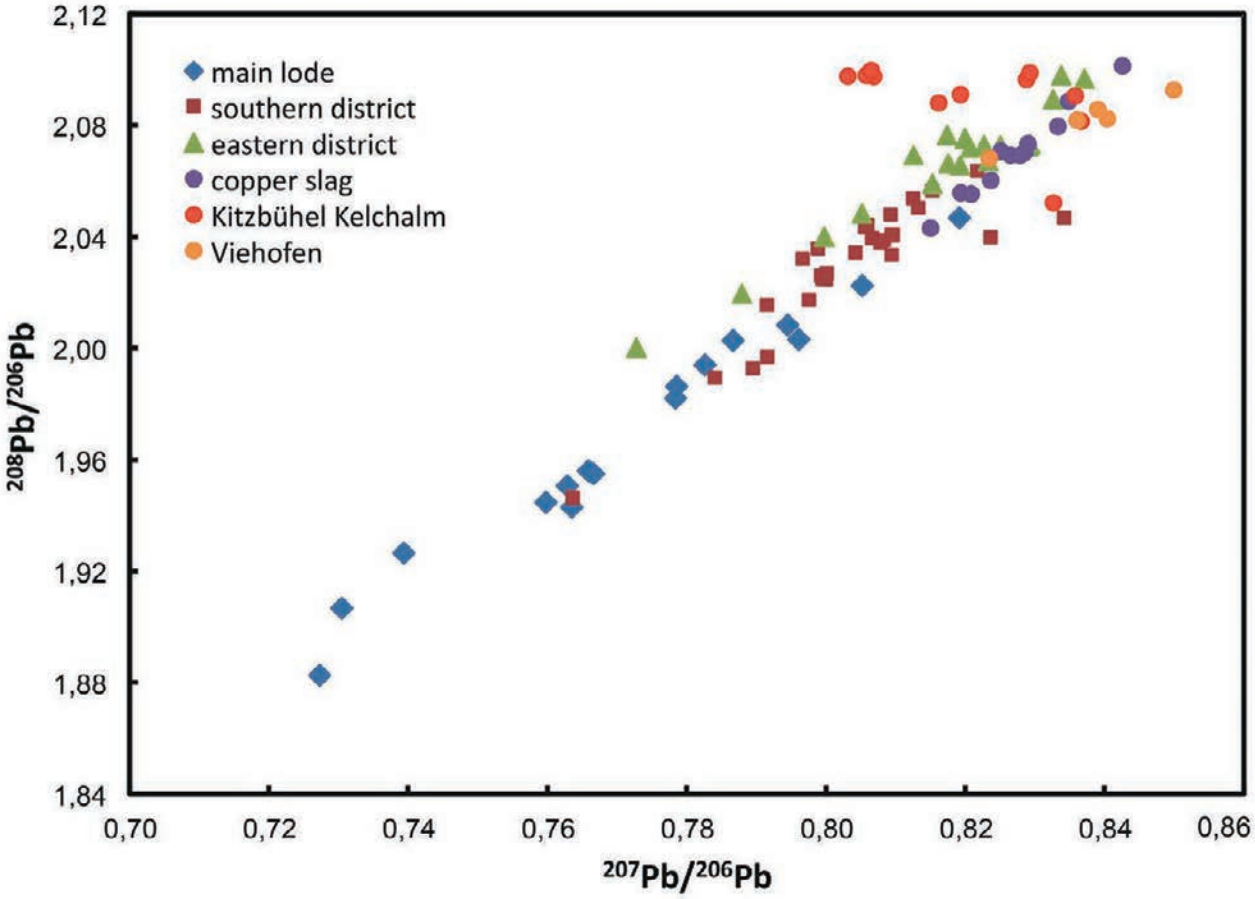


Figure 11b. Mitterberg mining region, the temporal intensity of Bronze Age mining in the southern and main-lode district and the geochemical characterisation of the various ore-lodes of the Mitterberg mining district, after Pernicka, Lutz and Stöllner (2016).

recycling, they can be used to support distinct provenance arguments in periods when exploitation focused only on a few large-scale deposits. For the Alps, this is especially true for the Middle Bronze Age when Mitterberg copper production dominated copper consumption on a massive scale (see Pernicka, Lutz and Stöllner, 2016). For this period, the dominating position of Mitterberg allows assigning the provenance of metals even to single ore veins, thus providing excellent insight into single production units.

Cyprus held the same importance for the central and eastern Mediterranean.[15] The introduction of shaft-furnace smelting can be considered as the decisive technological change, which permitted successful and efficient smelting of the rich copper-iron-sulphide ores. Is it necessary to discuss where the "shaft furnace technology" for the smelting of massive chalcopyrite ores was first in use (or invented) - at Cyprus or at Mitterberg, or maybe elsewhere. This smelting technique appears to have been introduced during the 16th century BC, which led to a sudden increase in metallurgical activities in the hinterland nearby the deposits in the pillow lava zone and inside the coastal sites (Knapp, 2003; Knapp and Kassianidou, 2008). The coastal urban complex of Enkomi certainly is the most important example for the earlier stages of copper-refining activities (Kassianidou, 2012), and could have been connected to smelters in the hinterland, such as the site of Apliki-Karamallos (Kassianidou, 2018). Following experiments and investigations of the oxhide ingots themselves it is likely that these trading copper units were cast in larger quantities for the over-sea-trade.[16] It is most likely that hinterland communities, who controlled mining and the production of matte (an intermediate product containing copper, iron and sulphur), sent metallurgical products to coastal settlements for further processing (for instance as chunk-furnace conglomerates do indicate).[17]

At the beginning, mining had been operated most likely in mixed supergene deposits that delivered larger portions of both carbonate and sulphide ores. Smelting sites, like at Politiko-Phorades, have shown the importance of the slag formation to produce sulphide-iron-rich copper-mattes as a first intermediate product (Knapp and Kassianidou, 2008). It is clear that during that stage ore processing, smelting and refining were focused on single large-scale deposits, like Apliki, Mathiatis or Kalavassos (Figure 10).

It is a major difference if copper was made for oxhide-ingot export, such as the high level-impurities of the oxhide ingots indicate (Maddin, et al., 2002), or for regional/local use. This can be seen also by the lead-isotope investigations of oxhide ingots in relation to single deposits (Gale and Stos-Gale, 2012), which indicate a tight relation of the export-production to smelting at single deposits. For the Uluburun shipwreck ingots, for instance, it became possible to attribute the copper ore origin probably to the Apliki deposits, which have a more distinctive lead-isotope range than the general lead-isotope field of Cyprus; however, a closer look at the data makes the interpretation less clear and the contribution of other Cypriot deposits is possible (Gale and Stos-Gale, 2012).

Does the Uluburun cargo reflect smelting products from different deposits? Although one may consider the lack of detailed trace element study as a critical point, especially for inland products,[18] it was assumed that inland communities delivered matte-intermediate products to different recipients. This assumption, however, remains to be proven correct. With other words: The present state of research on the copper of the oxhide ingots cannot conclusively explore questions on finely nuanced exchange patterns on a small regional level. As the position of the copper-bearing pillow-lava zone is in its position in-between but also remote to the coastal settlement foci, relationships between matte-production and copper-refining are unlikely found to be exclusive. This may have changed during the Early Iron Age, when territorial concepts had been established in the frame of the well-known Cypriot kingdoms (Kassianidou, 2013).

Major large-scale deposits do not automatically lead to mass-produced and geochemically homogenous metal that can easily be interpreted in the framework of simple exchange networks, even if the scale of trade (Cyprus, Eastern Alps) or production (Eastern Alps) could indicate this. Therefore, a third example was chosen that shows the problems of a major but chemically diverse deposit in regard to diverse and small-scale utilization concepts. The major copper deposits of central Kazakhstan, like Zhezkazgan, were already considered by Soviet-period archaeometallurgists and archaeologists as possibly the largest and most important copper supplier within the Central Asian steppe and forest-steppe zones (Kadyrbaev and Khurmankulov, 1992; Margulan, 2001). Zhezkazgan has been considered a major supplier of copper-ores during the Bronze Age, and more than a million tons of copper ores were estimated to have been exploited during the 2nd millennium BC (Zhauymbaev, 2001; 2013). So it should be expected that, such as with Cyprus or the Eastern Alps, metal production should be easily recognisable using the geochemical data. But the opposite is the case: Recent studies within the framework of the Bochum-Kazakhstan project have shown that there is enormous elemental and lead isotope variability as well as overlaps between artefacts found in the

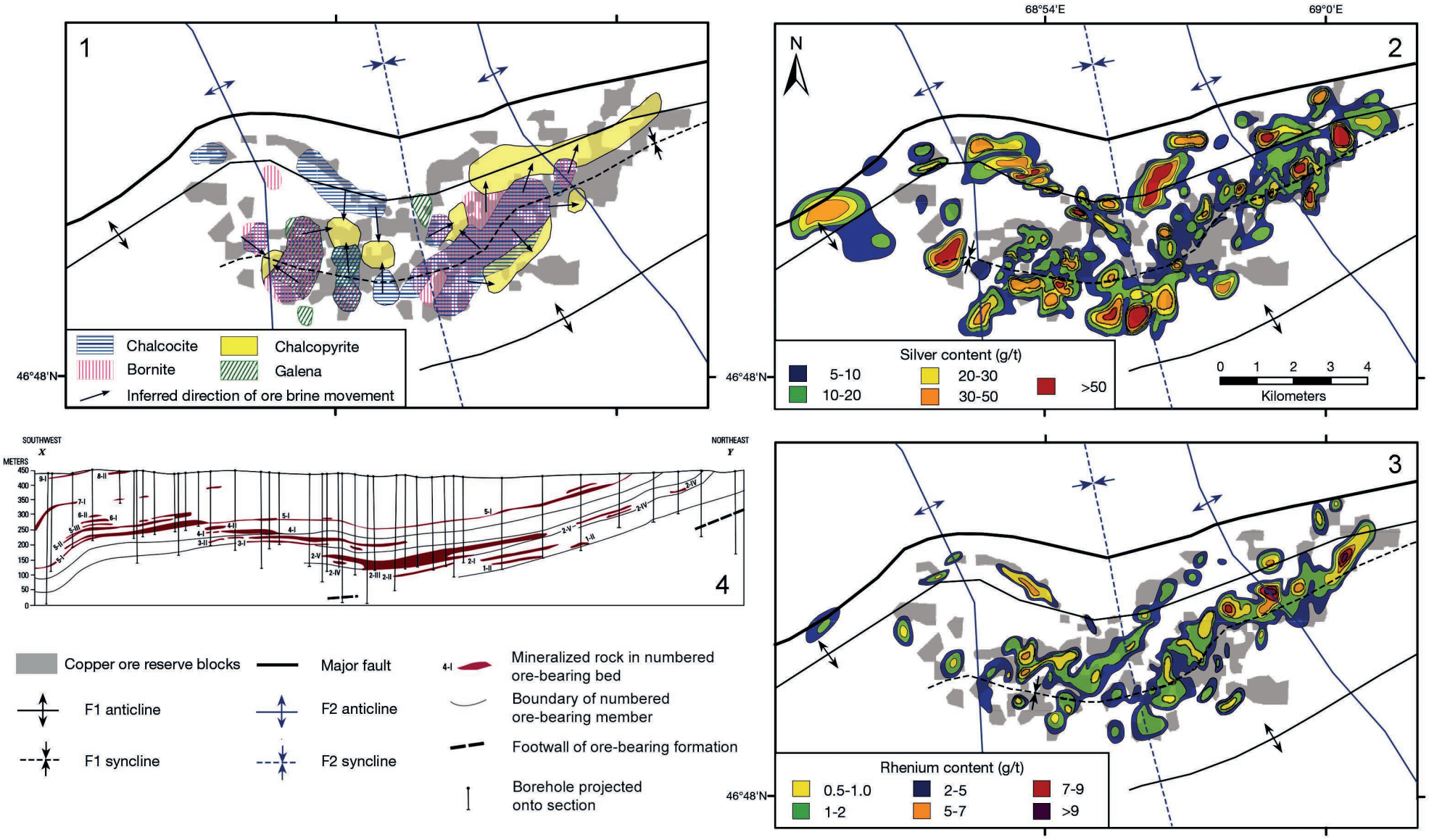


Figure 12. Zhezkazgan, Zhaman Aibat deposit, geometry and lateral geochemical variation of the ore deposit, after Box, et al. (2012) and by courtesy of R. Seltmann.

Figure 13. Nurataldy I, objects from metal hoard near grave 2. Photo: DBM/RUB, A. Gontsharov; after Stöllner and Gontsharov (in press).

central and eastern parts of Kazakhstan, which should have utilised different copper sources.[19]

Two factors make it difficult to isolate single production series. For one, it is the high variability of the deposits, as investigations of the stratiform deposits of Zhezkazgan ore-field already indicated (Syusura, et al., 1987; Box, et al., 2012). Several ore mineralisations developed from different paragenetic events that outcrop at the surface, and there are even ore-conglomerates, which demonstrate the complexity of the ore supply. The deposit of Zhaman Aibat (Box, et al., 2012) may serve as a good example as the recent very detailed geochemical investigation also demonstrate the high variation of trace-elements like silver and rhenium within this ore-field (Figure 12).

For second, it is the social dimension of small scaled metal artefact exchange pattern. An illustrative example to understand the various dimensions of Central Asian artefact assemblages is the hoard of Nurataldy I (Karaganda district, central Kazakhstan, Figure 13).[20] According to the Sejma-Turbino-like deposition mode (Chernykh and Kuzminych, 1989, Tab. 17), [21] it is clear that the Nurataldy I hoard assemblage possibly derived from different original sets of equipment. The hoard consists of two spearheads and three daggers together with a bodkin and three pieces of metal, a wrapped metal sheet, a cast piece of metal and a broken metal fragment (Figure 13). Some objects lend themselves to typological assessment that could help with the question of provenance (Figure 14). All the daggers (KZ 651-653) contained a high percentage of tin (around 10 wt.-%), but with a close look at the LI-ratios,[22] it is clear that two daggers, the rolled metal sheet and one spearhead are not consistent with ore from central Kazakhstan and thus came from outside (KZ 651-652, 680, 694). The one spearhead and one of the daggers are very close to each other (KZ 652, 694) and are consistent with east Kazakhstan copper ore and therefore these tin bronzes were likely produced there. This matches also with the elevated bismuth and lead contents, which are known from east Kazakhstan ores and metals (Stöllner, et al., 2013, pp.388-389). On the other hand, there is material which has lead isotope ratios and trace elements that are more consistent with data from the "Kent"-field of central Kazakhstan (KZ 653, 682, 695, 731): a dagger, spearhead, bodkin and metal cast. The metal cast, perhaps a

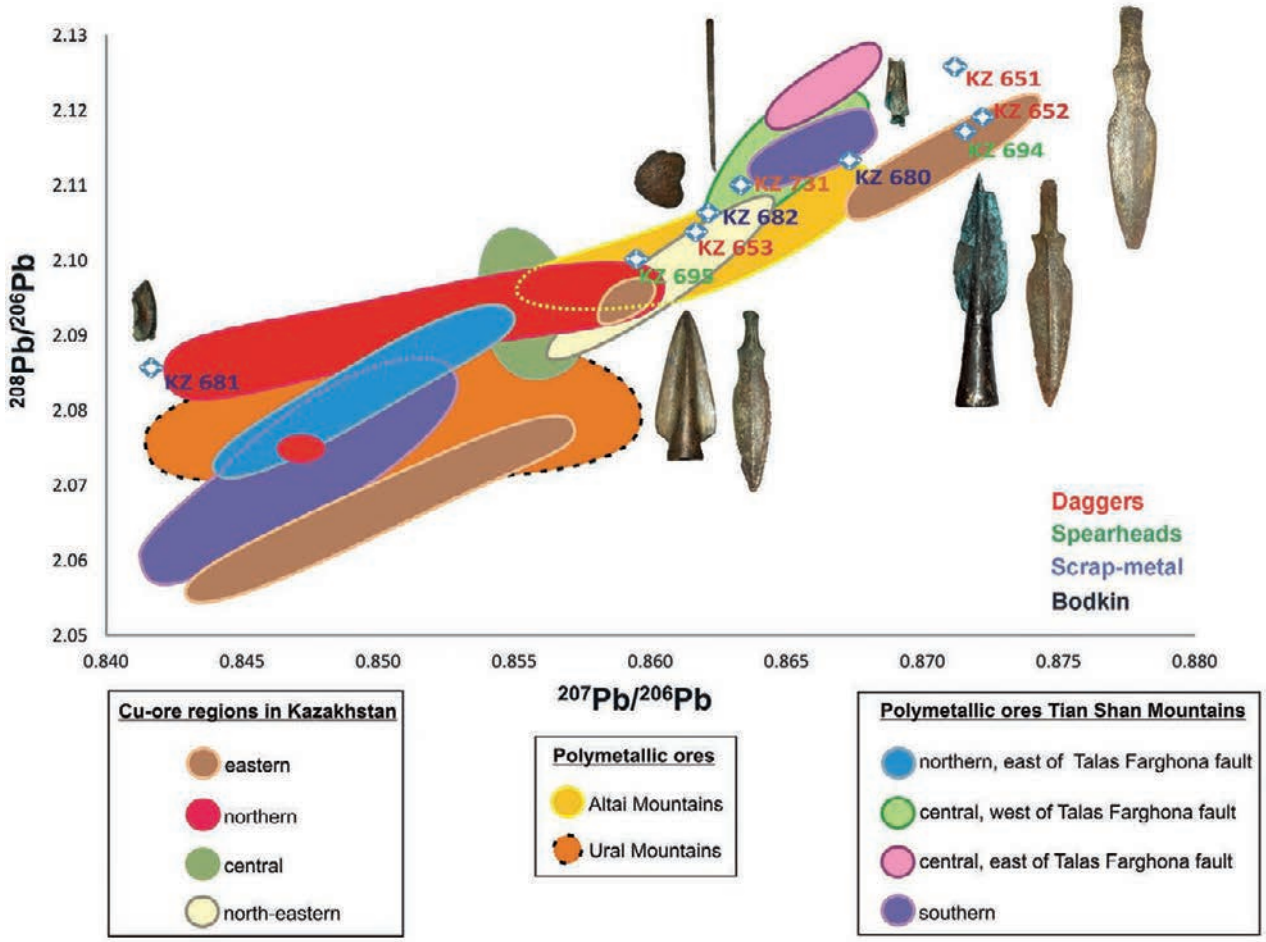


Figure 14. Lead isotope ratios of ore samples from Nurataldy I, Sejma-tradition hoard; source: DBM/RUB, M. Bode, Th. Stöllner, after Stöllner and Gontsharov (in press).

small ingot, best resembles regional copper. It is a rather pure copper with few impurities and it is unalloyed, containing nearly no tin. In contrast, the spearhead with the short socket has a low tin-level and some antimony and lead; this is dissimilar to east Kazakh metal and could come from central Kazakhstan.

The hoard is exemplary in showing social practice within small scale steppe-communities during the 1st half of the 2nd millennium BC: one or two foreign daggers were probably combined with a foreign spearhead while another ensemble consisted of a dagger and a spearhead that rather had a regional origin. The accumulation of such diverse sets of equipment can be explained best as a result of an intercommunal exchange and gift practice over larger distances. Such a practice would not favour a directional exploitation-to-consumer pattern of raw materials and products.

Returning to the topics of ore deposits and provenance studies, when ore deposits with complex geochemical patterns are combined with small-scale mining and long-distance exchange practices of the societies involved, it can be extremely difficult, if not impossible, to conclusively link metals and mining districts. Although it is possible to develop theories based on geochemical information, as the example demonstrates, combinations of geological and cultural factors can significantly complicate the interpretation of the provenance of metal objects.

Conclusions

The different approaches used by archaeologists and archaeometallurgists to understand metallogenic ore deposits often have to do with different expectations from each side. It also has to do with the specialisation of archaeologists and archaeometallurgists, on the one side focused on understanding social and economic practice of past societies and on the other to understand the complexity of mineralogical and geochemical variability of raw materials and the technological processes behind their extraction. It is important to accept that humans do not always behave in logical ways either to maximize productivity or to minimize effort and work-load. There are certainly different approaches to how humans interacted with ore deposits and how they experienced them

(e.g. Stöllner, 2015a). Therefore we can expect to find large variety of modes of production that are not always able to be explained by simple theories that we regard as a best "fit". Neither should we expect a simple homogenised chemical pattern from a major ore deposit, nor should we blindly adopt the viewpoint that there were similar social practices in different cultural settings.

Focussing on a smaller scale, mono-mineral deposits (also such that have been utilized to exploit one specific mineral source), it is often questioned whether the economic quality of a deposit has been judged correctly. The classification of small-scale or large scale production obviously cannot only be determined from a modern standpoint. Researchers need to know the qualitative and quantitative aspects of the chaîne opératoire in regard to the mode of production and the potential output but they must also relate these to consumption strategies of contemporary communities. Significant amounts of high-resolution data from different sources are needed to securely approach these economic and social aspects. The examples of Faynan and Sakdrisi demonstrate how, in rather simple cases, appropriate models can be developed.

This is certainly more difficult, if polymetallic deposits were exploited on a rather small, pre-industrial level. Old textbooks but also modern investigations provide an illustrative insight to mineral "cocktails" that were found in the supergene parts of ore-deposits. The seeking and processing of these natural ore mixtures is conceptually totally different from co-smelting to produce copper alloyed with arsenic or tin and in ancient times the results presumably were also more difficult to predict. An appropriate methodology, therefore, should not only include a detailed mineralogical view of ores, smelting residues and metals but must involve the empirical and sensory qualities of these "ore-cocktails" to understand ancient material selection and recipes.

Whether the exploitation of massive large-scale ore deposits finally is mirrored in homogenous and distinctive metal compositions that dominated temporally specific artefact series or not, depends on various factors. Large-scale deposits normally reveal a larger discrepancy in geological, mineralogical and geochemical variation, which needs to be determined with a sufficient resolution. In the best case, it requires a full understanding of the complex ore petrology of the entire mining district of interest. But even then, it is the accessibility of ore and the exploitation mode that has a major impact on whether researchers are able to link analytical data on artefacts to production modes and strategies of exchange. Intensive, locally focused ore processing and smelting, generally speaking, are more likely to provide chemically distinct signatures that can be found in artefact series that can be related with temporally distinct exploitations. Extensive, sporadic and locally diverse winning modes, however, tend to disguise such relationships, even if the deposit itself would be regarded as large and important. Therefore, archaeological expectations do not always meet the 'reality' formed from analytical data, even if the methodological approaches are well selected and correctly applied.

A thorough interdisciplinary study to model the ancient utilisation of metallogenic ore deposits therefore requires that a multitude of aspects has to be considered. Starting from a critical assessment of the sources of information (archaeological sources as well as from archaeometry), we need a sufficient understanding of the production techniques and practices, including an assessment of how this has influenced the representability of our geochemical trace-element and isotopic evidence. Once a framework of data and arguments are developed, information lacking in some areas can be made up for or supported by others. Cultural and social aspects including subsistence strategies as well as contexts of knowledge and experiences are nonetheless essential to interpret and link the strategies of metal production, the usage and deposition. These aspects are closely connected to the question of whether a large-scale deposit became a major metal supplier or not. This certainly does not solely depend on quantitative quality of an ore deposit but also depends on application of technological, social and economic concepts by past societies. A holistic approach to understand the ancient use of ore deposits requires a broad vision and a close and respectful cooperation of the many disciplines involved.

Acknowledgments

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Notes

1 Barnes, 1988; for a discussion see Hauptmann, 2008; Strahm and Hauptmann, 2009, pp.121-125.

2 The expression "cocktail" is introduced by S. Klein, Bochum in her lectures 2016-2017.

3 This coincides with the lack of smelting sites in the surroundings: see Timberlake, 2009.

4 This is especially true for regions where mineral deposits are unknown but to which metal was imported from abroad, for instance Mesopotamia, which always was dependent from mineral sources from its neighbourhood. See for instance Reiter, 1997; Hauptmann and Pernicka, 2004; small-scale distribution can be observed for instance for Central Asian metals: e.g. Stöllner, et al., 2013; Stöllner and Gontsharov, in press.

5 Many of the examples used in this article have been taken from the author's own research; other special examples are added.

6 Hauptmann, 2007; Hauptmann and Löffler, 2013; Barker, et al., 2007; Levy, et al., 2002; Levy, Najjar, and Ben-Yosef, 2014; for the mines see Löffler, 2018.

7 Hauptmann, et al., 2010; Stöllner, et al., 2014; Stöllner, 2016.

8 M. Jansen within his PhD-study performs a detailed study of the Sakdrisi gold: see also Jansen, et al., in press.

9 Recently the antler found in the Carnon tin-streams (Penhallurick, 1986) could be dated by radiocarbon dating to the mid-2nd millennium BC thus indicating the earlier phases of tin-exploitation in Cornwall: lecture Timberlake at the Mannheim conference, 15th of March 2018; pers. comm. S. Timberlake.

10 For the Mitterberg see: Zschocke and Preuschen, 1932; recently on behalf of the new research since 2002: Stöllner, 2015b.

11 For instance: Krause, 2003.

12 It is therefore rather unlikely to assume specialised raw metals such as fahlore-metal being a product in such large scale production centres as this would require a deliberate selection of rich ore parts according their mineralogical component. It is rather likely that rich ore fragments were directly brought to the smelting sites while intergrown-ores had been beneficiated and separated by beneficiation that not only produced purified ores but also included auxiliary minerals that also were required to produce standardised smelting loads: Stöllner, in press (b).

13 For a long time East Alpine copper was taken geochemically as one (see for instance on the basis of the SAM-data: Krause, 2003); for the Mitterberg deposit see Bernhard, 1965; Clasen, 1977.

14 E.g. Lutz, et al., 2010; Pernicka, Lutz and Stöllner, 2016; see also the debate: Radivojević, et al., 2018.

15 Summarising e.g. Bartelheim, 2007, pp.151-183; see for the mining landscape at the Troodos mountains: Given and Knapp, 2003.

16 There is a long-lasting debate on the character of these oxhide-ingots: But it is undoubtable that these ingots were not produced for use in Cyprus but for external exchange; the ingots were intentionally made heterogeneous and brittle for ease of fragmentation for re-melting and trade purposes (Hauptmann, Maddin and Prange, 2002; Laschimke and Burger, 2012).

17 This model already was proposed first by Muhly (1989), Hauptmann (2011) argues in a similar way for the transportation of matte and metal-enriched slags to the coastal centres.

18 The problems are manifold: A more detailed geochemical investigation of Cypriot copper deposits was not carried out (such as the investigations in the Eastern Alps). As Hauptmann, Maddin and Prange (2002), have argued it also would be difficult to assess the trace element with the copper ingots as they were not melted and homogenised like the final metal produced from them (homogenisation did obviously take place at the final fabrication stage which was probably not on the island). It would however be interesting to look at inland copper products in relation to metallurgical centres in more detail to understand the variability of trace-element compositions.

19 Stöllner, et al., 2013; Stöllner and Gontsharov, in press; the PhD-study of A. Gontsharov will deal in detail with these aspects.

20 The graveyard consisted of four slab cists, of which three were manipulated and one remained untouched. Two horse burials were discovered nearby. The complex, which remained unpublished so far, has been dated by the excavators V.G. Loman and I. Kukushkin to the early phases of the Andronovo/Alakul'-culture We are grateful to V.G. Loman, who enabled the sampling and provided us with additional information of the site: see also Kukushkin and Loman, 2014.

21 Like Rostovka, Šajtanskoe Ozero II and Turbino Matjuščevko and Sinicina, 1988, Figs. 51, 53; Serikov, et al., 2009, pp.69-70.

22 For a first definition of the LI-ratio of central and eastern Kazakh ore deposits, Bronze Age slags and metals see Stöllner, et al., 2013; also Stöllner and Gontsharov, in press.

References

Barker, G., Gilbertson, D.D. and Mattingly, D.J. eds., 2007. *Archaeology and Desertification. The Wadi Faynan Landscape Survey, Southern Jordan*. Oxford: Oxbow.

Barnes, J., 1988. *Ores and Minerals: Introducing Exonomic Geology.* Wiley: Open University Press.

Bartelheim, M., 2007. *Die Rolle der Metallurgie in vorgeschichtlichen Gesellschaften. Forschungen zur Archäometrie und Altertumswissenschaft,* 2. Rahden/Westfalen: VML.

Bernhard, J., 1965. Die Mitterberger Kupferkieslagerstätte. Erzführung und Tektonik. *Jahrbuch der Geologischen Bundesanstalt,* 109, pp.3-90.

Box, S.E., Syusura, B., Seltmann, R., Creaser, R.A., Dolgopolova, A. and Zientek, M.L., 2012. Dzhezkazgan and Associated Sandstone Copper Deposits of the Chu-Sarysu Basin, Central Kazakhstan. *Society of Economic Geologists, Inc. Special Publication,* 16.

Chernykh, E.N., 1992. *Ancient Metallurgy in the USSR*. Cambridge: Cambridge Univeristy Press.

Chernykh, E.N. and Kuzminykh, S.V., 1989. Древняя металлургия Северной Евразии (сеймо-турбинский феномен). Москва: Наука.

Childe, V.G., 1936. *Man makes himself*. London: Watts.

Childe, V.G., 1951. *Social evolution*. London: Watts.

Clasen, D., 1977. *Nebengestein und Erzführung der Kupferlagerstätte Mitterberg (Salzburg).* PhD. Naturwissenschaftlichen Fakultät der Universität Heidelberg.

Domergue, C., 2008. *Les Mines Antiques. La production des métaux aux époques grecques et romaine*. Paris: Picard.

Ercker, L., 1574. Lazarus Ercker, *Beschreibung, Aller furnemisten Mineralischen Ertzt vnnd Bergkwercks arten : wie dieselbigen, vnd eine jede in sonderheit, jrer Natur vnd eygenschafft nach, auff alle Metalla probirt, vnd im kleinen Fewr sollen versucht werden, mit erklarung etlicher furnemer nutzlicher Schmeltzwerck, im grossen Feuwer, auch scheidung Goldts, Silbers, vnd anderer Metalln, Sampt einem Bericht des Kupffer saigerns, Messing brennens, vnd Salpeter siedens, auch aller saltzigen Minerischen proben, vnd was denen allen anhengig, in funff Bucher verfast*. Prague: Georg Schwartz.

Friedrich, O.M., 1970. Kurzer Rückblick auf die Entwicklung der Erzmikroskopie. *Archiv für Lagerstättenkunde der Ostalpen,* 10, I-VIII.

Gale, N.H. and Stos-Gale, Z., 2012. The role of the Apliki Mine region in the post c. 1400 BC copper production and trade networks in Cyprus and in the wider Mediterranean. In: L.V. Kassianidou and G. Papasavvas, eds. 2012. *Eastern meditarrenean metallurgy and metalwork in the second millenium BC*. Oxford: Oxbow. pp.70-83.

Given, M. and Knapp, A.B., 2003. *The Sydney Cyprus Survey Project: Social Approaches to Regional Archaeological Survey.* Monumenta archaeologica, 21. Los Angeles: Cotsen Institute of Archaeology, University of California.

Hanning, E., Herdits, H. and Silvestri, E., 2015. Alpines Kupferschmelzen - technologische Aspekte. In: Th. Stöllner and K. Oeggl, eds. 2015. *Bergauf Bergab. 10000 Jahre Bergbau in den Ostalpen. Wissenschaftlicher Beiband zur Ausstellung Bochum und Bregenz. Veröffentlichungen aus dem Deutschen Bergbau-Museum Bochum,* Nr. 207. Bochum: Deutsches Bergbau-Museum. pp.225-231.

Hansman, J., 1978. The Question of Aratta. *Journal of Near Eastern Studies,* 37, pp.331-336.

Harris, D.R. ed., 1994. *The archaeology of V. Gordon Childe. Contemporary perspectives. Proceedings of the V. Gordon Childe Centennial Conference held at the Institute of Archaeology, University College London, 8-9 May 1992 under the auspices of the Institute of Archaeology and the Prehistoric Society.* London: UCL Press.

Hauptmann, H. and Pernicka, E. eds., 2004. *Die Metallindustrie in Mesopotamien von den Anfängen bis zum 2. Jahrtausend v.Chr.: Katalog, Tabellen und Tafeln. Orient Archäologie,* 3. Rahden/Westfalen: VML.

Hauptmann, A., 2007. *The Archaeometallurgy of Copper. Evidence from Faynan, Jordan. Natural Science in Archaeology.* Berlin: Springer.

Hauptmann, A., 2008. Erzlagerstätten im östlichen Mittelmeerraum. In: Ü. Yalçın, ed. 2008. *Anatolian Metal IV. Der Anschnitt, Beiheft,* 21. Bochum: Deutsches Bergbau-Museum. pp.55-66.

Hauptmann, A., 2011. Slags from the Late Bronze Age metal workshops at Kition and Enkomi, Cyprus. In: S. Ferrence and P. Betancourt, eds. 2011. *Metallurgy: Understanding How, Learning why. Studies in Honor of James D. Muhly*. Philadelphia: INSTAP Academic Press. pp.189-202.

Hauptmann, A., Maddin, R. and Prange, M., 2002. On the Structure and Composition of Copper and Tin Ingots Excavated from the Shipwreck of Uluburun. *Bulletin of the American Schools of Oriental Research,* 328, pp.1-30.

Hauptmann, A., Rehren, Th. and Schmid-Strecker, S., 2003. Early Bronze Age copper metallurgy at Shahr-i Sokhta (Iran), reconsidered. In: Th. Stöllner, G. Körlin, G. Steffens and J. Cierny, eds. 2003. *Man and Mining. Studies in honour of Gerd Weisgerber. Der Anschnitt, Beiheft,* 16. Bochum: Deutsches Bergbau-Museum. pp.197-213.

Hauptmann, A., Bendall, C., Brey, G., Japariże, I., Ġambašiże, I., Klein, S., Prange, M. and Stöllner Th., 2010. Gold in Georgien. Analytische Untersuchungen an Goldartefakten und an Naturgold aus dem Kaukasus und dem Transkaukasus. In: S. Hansen, A. Hauptmann, I. Motzenbäcker and E. Pernicka, eds. 2010. *Von Maikop bis Trialeti. Akten des Symposiums Berlin 1.-3. Juni 2006. Kolloquien zur Vor- und Frühgeschichte,* 13. Bonn: Habelt. pp.139-160.

Hauptmann, A. and Löffler, I., 2013. Technological innovations and organisational structures of prehistoric mining and metal production – examples from Faynan, Jordan. In: St. Burmeister, S. Hansen, M. Kunst and N. Müller-Scheeßel, eds. 2013. *Metal Matters. Innovative technologies and social change in Prehistory and Antiquity. Menschen - Kulturen – Traditionen.* Rahden/Westfalen: VML. pp.65-89.

Heise, F. and Herbst, F., 1908. *Lehrbuch der Bergbaukunde: mit besonderer Berücksichtigung des Steinkohlenbergbaus, Volume* 1. Berlin: Springer.

Hosking, K.F.G., 1988. The World's Major Types of Tin Deposit. In: C.S. Hutchison, ed. 1988. *Geology of Tin Deposits in Asia and the Pacific*. Berlin: Springer.

Ixer, R.A., 2001. An assessment of copper mineralization from the Great Orme Mine, Llandudno, North Wales, as ore in the Bronze Age. *Proceedings of the Yorkshire Geological Society,* 53/3, 2001, pp.213-219.

Jansen, M., Hauptmann, A., Klein, S., Gambaschidze, I. and Jalilov, B., in press. Geochemistry of gold from the prehistoric mine of Sakdrisi and Transcaucasian gold artefacts between the 4th and 2nd millennia BC. In: C. Marro and Th. Stöllner, eds. *On salt, copper and gold: the origins of early mining and metallurgy in the Caucasus. Proceedings of the conference held in Tbilisi (Georgia), June 16th-19th 2016*, Lyon.

Jansen, Stöllner and Courcier, 2014. Appendix: Recent results from laboratory work on the gold of Sakdrisi. In: Stöllner, Th. Craddock, B., Gambaschidze, I., Gogotchuri, G., Hauptmann, A., Hornschuch, A., Klein, F., Löffler, I., Mindiashvili, G., Murvanidze, B., Senczek, S., Schaich, M., Steffens, G., Tamasashvili, K. and Timberlake, S., 2014. Gold in the Caucasus: New research on gold extraction in the Kura-Araxes Culture of the 4th millennium BC and early 3rd millennium BC. With an appendix of M. Jansen, T. Stöllner, A. Courcier. In: H. Meller, E. Pernicka and R. Risch, eds. 2014. *Metalle der Macht. Tagungen des Landesmuseums für Vorgeschichte Halle,* 11. Halle: Landesamt für Denkmalpflege und Archäologie Sachsen-Anhalt, Landesmuseum für Vorgeschichte. pp.89-95.

Jébrak, M., 2006. Economic Geology: Then and Now. *Geoscience Canada,* 33/2, pp.81-93.

Jung, R., Mehofer, M. and Pernicka, E., 2011. Metal exchange in Italy from the Middle to the Final Bronze Age (14th–11th cent. BCE). In: S. Ferrence and P. Betancourt, eds. 2011. *Metallurgy: Understanding How, Learning why. Studies in Honor of James D. Muhly.* Philadelphia: INSTAP Academic Press. pp.231-248.

Kadyrbaev, M.K. and Kurmankulov, S.K., 1992. Культура древних скотоводов *и* металлургов Сары-Арки. Алма-Ата.

Kassianidou, V.L., 2012. Metallurgy and metalwork in Enkomi: the early phases. In: V.L. Kassianidou and G. Papasavvas, eds. 2012. *Eastern Mediterranean Metallurgy in the Second Millennium BC*, Oxford: Oxbow. pp.14-25.

Kassianidou, V.L., 2013. The exploitation of the landscape: metal resources and the copper trade during the age of the Cypriot city-kingdoms. *BASOR*, 370, pp.49-82.

Kassianidou, V.L., 2014. Cypriot copper for the Iron Age world of the Eastern Mediterranean. In: J.M. Webb, ed. 2014. *Structure, Measurement and Meaning. Studies on Prehistoric Cyprus in Honour of David Frankel. Studies in Mediterranean Archaeology*, 48. Uppsala: Paul Forlag Astroms. pp.261-271.

Kassianidou, V.L., 2018. Apliki-Karamallos on Cyprus: The 13th century BCE miners' settlement in context. In: E. Ben-Yosef, ed. 2018. *Mining for Ancient Copper: Essays in Memory of Beno Rothenberg*. Tel Aviv: The Institute of Archaeology of Tel Aviv University. pp.345-356.

Kiderlen, M., Bode, M., Hauptmann, A. and Bassiakos, J., 2016. Tripod Cauldrons Produced at Olympia Give Evidence for Trade with Copper from Faynan (Jordan) to South West Greece, c. 950 - 750 BC. *Journal of Archaeological Science*, *Reports,* 8, pp.303-313.

Klein, S., 2007. Dem Euro der Römer auf der Spur - Bleiisotopenanalysen zur Bestimmung der Metallherkunft römischer Münzen. In: G.A. Wagner, ed. 2007. *Einführung in die Archäometrie.* Berlin: Springer. pp.139-152.

Knapp, A.B., 2003. The Archaeology of Community on Bronze Age Cyprus: Politiko Phorades in Context. *American Journal of Archaeology,* 107, pp.559-580.

Knapp, A.B. and Kassianidou, V.L., 2008. The Archaeology of late Bronze Age Copper Production. Politiko Phorades on Cyprus. In: Ü. Yalçın, ed. 2008. *Anatolian Metal IV. Der Anschnitt, Beiheft,* 21. Bochum: Deutsches Bergbau-Museum. pp.135-147.

Kohl, Ph., 2007, *The Making of Bronze Age Eurasia.* New York: Cambridge World Archaeology.

Krause, R., 2003. *Studien zur kupfer- und frühbronzezeitlichen Metallurgie zwischen Karpatenbecken und Ostsee. Vorgeschichtliche Forschungen,* 24. Rahden/Westfalen: VML.

Kukushkin, I.A. and Loman, V.G., 2014. Краткие итоги исследования элитных курганов эпохи бронзы Центрального Казахстана. In: Труды, *IV (XX)* Всероссийского Археологического съезда. Т. *1.* Казань. pp.584-587.

Laschimke, R. and Burger, M., 2011. Versuche zum Gießen von bronzezeitlichen Ochsenhautbarren von Kupfer. *Zeitschrift Metall,* 65, pp.85-92.

Levy, T.E., Adams, R., B., Hauptmann, A., Prange, M., Schmitt-Strecker, S. and Najjar, M., 2002. Early Copper Age metallurgy: newly discovered copper manufactory in southern Jordan. *Antiquity,* 76, pp.425-437.

Levy, T.E., Najjar, M. and Ben-Yosef, E., 2014. *New Insights into the Iron Age Archaeology of Edom, Southern Jordan. Surveys, Excavations, and research from the University of California, San Diego – Department of Antiquities of Jordan. Edom Lowlands Regional Archaeology Project / ELRAP. Los Angeles: Cotsen Institute Press.*

Lewis, C.A., 1996. *Prehistoric mining at the Great Orme. Criteria for identification of early mining.* PhD. University of Bangor.

Löffler, I., 2018. Key features for deducing technological innovations and organizational structures in the Bronze Age Mining district of Faynan, Jordan. In: E. Ben-Yosef, ed. 2018. *Mining for Ancient Copper: Essays in Memory of Beno Rothenberg*. Tel Aviv: The Institute of Archaeology of Tel Aviv University. pp.259-269.

Lutz, J., Pernicka, E., Pils, R., Tomedi, G. and Vavtar, F., 2010. Geochemical characteristics of copper ores from the Greywacke Zone in the Austrian Alps and their relevance as a source of copper in prehistoric times. In: P. Anreiter, K. Brandstätter, G. Goldenberg, K. Hanke, W. Leitner, K. Nicolussi, K. Oeggl, E. Pernicka, V. Schaffer, Th. Stöllner, G. Tomedi and P. Tropper, eds. 2010. *Mining in European History and its Impact on Environment and Human Societies – Proceedings for the 1st Mining in European History-Conference of the SFB-HiMAT, 12.–15. November 2009.* Innsbruck: Innsbruck Univeristy Press. Conference Series, Innsbruck. pp.145-150.

Majidzadeh, Y., 1976. The Land of Aratta. *Journal of Near Eastern Studies,* 35/2, pp.105-113.

Margulan, A. Ch., 2001. Сарыарка. Горное дело и металлургия в эпоху бронзы. Сочинения. Том *2.* Алматы 2001, pp.8-21.

Matjuščevko, V. I. and Sinicina, G.V., 1988. Могильник *у* деревни Ростовка вблизи Омска, Томск.

Maucher, E. and Rehwald G., 1961. *Bildkartei der Erzmikroskopie.* Frankfurt/Main: Umschau Verlag.

Meyers 1905. *Meyers Großes Konversations-Lexikon. Ein Nachschlagewerk des allgemeinen Wissens. Band 6. 6. gänzlich neubearbeitete und vermehrte Auflage.* Leipzig/Wien: Bibliographisches Institut 1902–1908.

Müller-Scheeßel, N. and Burmeister, S., 2006. Einführung: Die Identifizierung sozialer Gruppen. Die Erkenntnismöglichkeiten der Prähistorischen Archäologie auf dem Prüfstand. In: S. Burmeister, N. Müller-Scheeßel, eds. 2006. *Soziale Gruppen – Kulturelle Grenzen. Die Interpretation sozialer Identitäten in der prähistorischen Archäologie.* Münster/New York: Waxmann. pp.9-38.

Muhly, J.D., 1989: The organisation of the Copper industry in Late Bronze Age Cyprus. In: E. Peltenburg, ed. 1989. *Early Society in Cyprus.* Edinburgh. pp.298-314.

Needham, S. Parham, D. and Frieman, C., 2013. Claimed by the Sea: Salcombe, Langdon Bay, and other Marini Finds of the Bronze Age. *Council for British Archaeology*, *Research Report* 173.

O'Brian, W., 2015. *Prehistoric Copper Mining in Europe 5500-500 BC.* Oxford: University Press.

Okrusch, M. and Matthes, S., 2008. *Mineralogie. Eine Einführung in die spezielle Mineralogie, Petrologie und Lagerstättenkunde*. Berlin: Springer.

Pernicka, E., 1995. Gewinnung und Verbreitung der Metalle in prähistorischer Zeit. *Jahrbuch des Römisch-Germanisches Zentralmuseums,* 37/1, 1992, pp.21-129.

Pernicka, E., 1998. Die Ausbreitung der Zinnbronze im 3. Jahrtausend. In: B. Hänsel, ed. 1998. *Mensch und Umwelt in der Bronzezeit Europas. Abschlusstagung Die Bronzezeit: Das erste goldene Zeitalter Europas, Berlin 1997.* Rahden/Westfalen: VML. pp.135-147.

Pernicka, E., Lutz, J. and Stöllner, Th., 2016. Bronze Age Copper Produced at Mitterberg, Austria, and its Distribution. *Archaeologia Austria*, 100, pp.19-55.

Pohl, W., 2005. *Mineralische und Energie-Rohstoffe. Eine Einführung zur Entstehung und nachhaltigen Nutzung von Lagerstätten*. Stuttgart: Schweizerbart.

Pohl, W., Petrascheck, W. and Petrascheck, W.E., 1992. *Lagerstättenlehre – Eine Einführung in die Wissenschaft von den mineralischen Bodenschätzen*. Stuttgart: Schweizerbart.

Potts, D.T., 2004. Exit Aratta: Southeastern Iran and the Land of Marhashi. *Nāme-ye Irān-e Bāstān,* 4/1, pp.1-11.

Penhallurick, R.D., 1986. *Tin in Antiquity, its Mining and Trade throughout the Ancient World with particular reference to Cornwall*. London: The Institute of Metals.

Radivojević, M., Roberts, B.W., Pernicka, E., Stos-Gale, Z., Martinón-Torres, M., Rehren, Th., Bray, P., Brandherm, D., Ling, J., Mei, J., Vandkilde, H., Kristiansen, K., Shennan, S. and Broodbank, C., 2018. The Provenance, Use, and Circulation of Metals in the European Bronze Age: The State of Debate. *Journal of Archaeological Research,* 27/2, pp.1-55.

Ramdohr, P., 1960. *Die Erzmineralien und ihre Verwachsungen*. Berlin: Akademie Verlag.

Rehren, Th., Boscher, L. and Pernicka, E., 2012. Large scale smelting of speiss and arsenical copper at Early Bronze Age Arisman, Iran. *Journal of Archaeological Science,* 39, pp.1717-1727.

Reiter, K., 1997. *Die Metalle im Alten Orient unter besonderer Berücksichtigung altbabylonischer Quellen. Alter Orient und Altes Testament,* 249. Münster: Ugarit.

Selimchanov, I.R., 1977. Zur Frage einer Kupfer-Arsen-Zeit. *Germania*, 55, p.1-6.

Serikov, Y.B., Korochkova, O.N., Kuzminykh, S.V. and Stefanov, V.I., 2009. Shaitanskoye Ozero II: New Aspects of the Uralian Bronze Age. *Archaeology, Ethnology & Anthropology of Eurasia,* 37 (2), pp.67-78.

Stöllner, Th., 2003. Mining and Economy. A Discussion of Spatial Organisations and Structures of Early Raw Material Exploitation. In: Th. Stöllner, G. Körlin, G. Steffens and J. Cierny, eds. 2003. *Man and Mining. Studies in honour of Gerd Weisgerber. Der Anschnitt, Beiheft,* 16, Bochum: Deutsches Bergbau-Museum. pp.415-446.

Stöllner, Th., 2009. Prähistorische Montanreviere der Ost- und Südalpen – Anmerkungen zu einem Forschungsstand. In: K. Oeggl and M. Prast, eds. 2009. *Die Geschichte des Bergbaues in Tirol und seinen angrenzenden Gebieten. Proc. 3. Milestone-Meeting SFB HiMAT 2008.* Innsbruck: Innsbruck University Press. pp.37-60.

Stöllner, Th., 2014. Methods of Mining Archaeology (Montanarchäologie). In: B. Roberts and C. Thornton, eds. 2014. *Archaeometallurgy in Global Perspective. Methods and Syntheses.* New York: Springer. pp.133-159.

Stöllner, Th., 2015a. Humans approach to resources: Old World mining between technological innovations, social change and economical structures. A key note lecture. In: A. Hauptmann and D. Modarressi-Tehrani, eds. 2015. *Archaeometallurgy in Europe III. Proceedings of the 3rd International Conference Deutsches Bergbau-Museum Bochum 2011*. Bochum: Deutsches Bergbau-Museum. pp.63-82.

Stöllner, Th., 2015b. Der Mitterberg als Großproduzent für Kupfer in der Bronzezeit. In: Th. Stöllner and K. Oeggl, eds., 2015. *Bergauf Bergab. 10000 Jahre Bergbau in den Ostalpen. Wissenschaftlicher Beiband zur Ausstellung Bochum und Bregenz. Veröffentlichungen aus dem Deutschen Bergbau-Museum Bochum,* Nr. 207. Bochum: Deutsches Bergbau-Museum. pp.175-185.

Stöllner, Th., 2016. The Beginnings of Social Inequality: Consumer and Producer Perspectives from Transcaucasia in the 4th and the 3rd Millennia BC. In: M. Bartelheim, B. Horeijs and R. Krauss, eds. 2016. *Von Baden bis Troia. Ressourcennutzung, Metallurgie und Wissenstransfer. Eine Jubiläumsschrift für Ernst Pernicka. Oriental and European Archaeology*, 3. Rahden/Westfalen: VML. pp.209-234.

Stöllner, Th., 2017. Resources, innovation, technology. Theoretical approaches to abstract concepts and research content. In: P. Eisenach, Th. Stöllner and A. Windler, eds. 2017. *The RITaK conferences 2013–2014. Raw Materials, Innovation, Technology of Ancient Cultures RITaK 1. Der Anschnitt, Beiheft,* 34. Bochum: Deutsches Bergbau-Museum. pp.11-23.

Stöllner, Th., 2018. Das älteste Gold in Georgien im Kontext. Unter Mitarbeit von I. Gambaschidze und Moritz Jansen. In: L. Giemsch and S. Hansen, eds. 2018. *Gold & Wein. Georgiens älteste Schätze. Begleitband zur Sonderausstellung Frankfurt 2018/2019.* Oppenheim am Rhein: Nünnerich-Asmus. pp.121-139.

Stöllner, Th., in press (a). From generalists to specialists? Transcaucasian communities and their approach to resources during the 5th and the 3rd millennium BCE. In: C. Marro and Th. Stöllner, eds. *On salt, copper and gold: the origins of early mining and metallurgy in the Caucasus. Proceedings of the conference held in Tbilisi (Georgia), June 16th-19th 2016*, Lyon.

Stöllner, Th., in press (b). Between Mining and Smelting in the Bronze Age – Beneficiation Processes in an Alpine Copper Producing district. Results of 2008 to 2017 excavations at the Sulzbach-Moos Bog at the Mitterberg (Salzburg, Austria). In: *Alpenkupfer II. Der Anschnitt, Beiheft*, in press.

Stöllner, Th., Bode, M., Gontscharov, A., Gorelik, A., Hauptmann, A. and Prange, M., 2013. Metall und Metallgewinnung der Bronze- und Früheisenzeit. In: Th. Stöllner and Z. Samašev, eds. 2013. *Unbekanntes Kasachstan. Archäologie im Herzen Asiens. Katalog der Ausstellung des DBM. Veröffentlichungen aus dem Deutschen Berg-*

bau-Museum Bochum, Nr. 192. Bochum: Deutsches Bergbau-Museum. pp.383-397.

Stöllner, Th. Craddock, B., Gambaschidze, I., Gogotchuri, G., Hauptmann, A., Hornschuch, A., Klein, F., Löffler, I., Mindiashvili, G., Murvanidze, B., Senczek, S., Schaich, M., Steffens, G., Tamasashvili, K. and Timberlake, S., 2014. Gold in the Caucasus: New research on gold extraction in the Kura-Araxes Culture of the 4th millennium BC and early 3rd millennium BC. With an appendix of M. Jansen, T. Stöllner, A. Courcier. In: H. Meller, E. Pernicka and R. Risch, eds. 2014. *Metalle der Macht. Tagungen des Landesmuseums für Vorgeschichte Halle,* 11. Halle: Landesamt für Denkmalpflege und Archäologie Sachsen-Anhalt, Landesmuseum für Vorgeschichte. pp.71-110.

Stöllner, Th. and Bartelheim, M., 2015. Metallgewinnung und –verarbeitung, In: A.M. Wittke, ed. 2015. *Frühgeschichte der Mittelmeerkulturen. Historisch-archäologisches Handbuch. Der Neue Pauly*, *Supplement* 10. Stuttgart/ Weimar: Metzler. pp.1014-1028.

Stöllner, Th., Rüden, C.v., Hanning, E., Lutz, J. and Kluwe, S., 2016. The Enmeshment of Eastern Alpine Mining Communities in the Bronze Age. From Economic Networks to Communities of Practice. In: G. Körlin, M. Prange, Th. Stöllner and Ü. Yalçın, eds. 2016. *From Bright Ores to Shiny Metals. Festschrift for Andreas Hauptmann on the occasion of 40 Years Research in Archaeometallurgy and Archaeometry. Der Anschnitt*, *Beiheft,* 29. Bochum: Deutsches Bergbau-Museum. pp.75-107.

Stöllner, Th. and Gontsharov, A., in press. Social practice and the exchange of metals and metallurgical knowledge in 2nd millennium Central Asia. In: N. Boroffka and E. Luneau, eds. *Farmers, Traders and Herders. The Bronze Age in Central Asia and Khorasan (3rd - 2nd Millennium BCE). Conference DAI Berlin 30th November - 1st December 2015* (in press).

Strahm, C., 1994. Die Anfänge der Metallurgie in Mitteleuropa. *Helvetia Archaeologica,* 25, 1994, pp.2-40.

Strahm, C. and Hauptmann, A., 2009. The Metallurgical Developmental Phases in the Old World. In: T.L. Kienlin and B. Roberts, eds. 2009. *Metals and Societies. Studies in honour of Barbara S. Ottaway*. Universitätsforschungen zur Prähistorischen Archäologie, 169, Bonn: Habelt. pp.116-128.

Strunz, H. and Nickel, E.H., 2001. *Strunz Mineralogical Tables*[9]. Stuttgart: Schweizerbart.

Syusura, B.B., Glybovskiy, V.O., Khalilov, V.A., Yurgens, A.V. and Sal'kov, S.A., 1987. Participation of sulfur in the genesis of copper sandstone ores of the Dzhezkazgan-Sarysuysk region. *Izvestiya Akademii Nauk Kazakhskoy SSR, Seriya Geologicheskaya = Khabarlary Kazakh SSR, Fylym Akademiyasynyn*, 1987/3, pp.31-41 (in Russian).

Thornton, C.P., Rehren, Th. and Pigott, V.C., 2009. The production of speiss (iron arsenide) during the Early Bronze Age in Iran. *Journal of Archaeological Science,* 36, pp.308-316.

Timberlake, S., 2009. Copper mining and metal production at the beginning of the British Bronze Age. In: P. Clark, ed. 2009. *Bronze Age Connections*. Oxford: Oxbow. pp.95-122.

Trounson, J. H. and Bullen, L. J., 1999. Dolcoath. In: *Mining in Cornwall. Volume One: The Central District.* Stroud: Tempus Publishing Ltd. pp.35-54.

Veit, U., 1984. Gustaf Kossina und V. Gordon Childe: Ansätze zu einer theoretischen Grundlegung der Vorgeschichte. *Saeculum,* 45, 3/4, pp.326-363.

Wang, Q., Strekopytov, S., Roberts, B. and Wilkin, N., 2016. Tin ingots from a probable Bronze Age shipwreck off the coast of Salcombe, Devon: Composition and microstructure. *Journal of Archaeological Science,* 67, pp.80-92.

Weisgerber, G., 1989/90. Montanarchäologie - Grundzüge einer systematischen Bergbaukunde für Vor- und Frühgeschichte und Antike, Teil 1. *Der Anschnitt,* 41/6, 1989, pp.190-204; Teil 2. *Der Anschnitt,* 42/1, 1990, pp.2-18.

Weisgerber, G., 2003. Montanarchäologie. In: J. Hoops, ed. 2003. *Reallexikon der Germanischen Altertumskunde,* 20. Berlin: De Gruyter., pp.180-199.

Wolf, D., Borg, G., Meliksetian, K., Allenberg, A., Pernicka, E., Hovanissyan, A. and Kunze, R., 2013. Neue Quellen für altes Gold? In: H. Meller and P. Avetisyan, eds. 2013. *Archäologie in Armenien II. Halle/Saale: Veröffentlichungen des Landesamtes für Denkmalpflege und Archäologie Sachsen-Anhalt*, 67. pp.27-44.

Zhauymbaev, S., 2001. Горное дело и металлургия бронзового века Сарыарки. Караганда, 2001.

Zhauymbaev, S., 2013. Bergbau und Metallurgie Zentralkasachstans. In: Th. Stöllner and Z. Samašev, eds. 2013. *Unbekanntes Kasachstan. Archäologie im Herzen Asiens. Katalog der Ausstellung des DBM. Veröffentlichungen aus dem Deutschen Bergbau-Museum Bochum,* Nr. 192. Bochum: Deutsches Bergbau-Museum. pp.429-440.

Zschocke, K. and Preuschen, E., 1932. *Das urzeitliche Bergbaugebiet von Mühlbach-Bischofshofen. Materialien zur Urgeschichte Österreichs,* 6. Wien: Anthropologische Gesellschaft.

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