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Experimental archaeology in Bronze Age mining and smelting – hard rock, hot metal, new ideas

ABSTRACT: *Experimental reconstructions of Bronze Age copper mining processes at Cwmystwyth, Wales by the author and the Early Mines Research Group (UK) in the 1990s were undertaken prior to, and also during the archaeological excavation of this mine. Adopting this approach (known as predictive experimental archaeology) enabled us to anticipate the sorts of tool remains and debris we might encounter, and as a result predict the finds of antler picks and hammerstone handles.*

More recent mining and gold extraction experiments carried out at the 4th–3rd millennium BC mine of Sakdrisi in Georgia as part of the joint Deutsches Bergbau-Museum Bochum-National Museum of Georgia investigation of this site has successfully shown how mining was undertaken within these hard silica-rich rocks, and how the iron oxide vein gossan was then pulverised and washed to recover the fine-grained gold. This work suggests that upwards of 9000 tons of wood may have been used in firesetting and the mining of 250-460 kg gold. In fact, there are a number of similarities between this site and the Early Bronze Age tin mine and processing settlement of Kestel/ Goltepe in Anatolia.

As regards smelting, a number of different models of potential Early Bronze Age-type furnaces have been experimented with over the years, but all of these had used manufactured charcoal as a fuel. However, in 2013 a successful smelt of a locally sourced oxidised copper ore was achieved at Pločnik in Serbia, using just an open wood fire over a pit. This was achieved by raising the temperature of the resulting ember heap using bag bellows. The simple technique produced a small slag cake containing copper prills which were then extracted and re-melted. This same experiment was repeated later in the UK, producing copper prills as well as melting raw copper droplets inside a sealed crucible under moderately oxidising conditions, perhaps providing a model for the earliest ‘bonfire-type’ furnaces. Recent experiments carried out on the Great Orme and at other Bronze Age mines in Britain have shown us how these fully or partially-oxidised ores may be smelted in simple hearths, providing us with a model for production alongside samples for analysis, and for comparing source metal with metalwork.

KEYWORDS: EXPERIMENTAL, MINING, FIRESETTING, GOLD EXTRACTION, COPPER SMELTING

Introduction

Mining and smelting are both activities which are difficult to interpret from the ancient archaeological record, since in many cases we are dealing with absent, confusing, or indeed negative evidence concerning the identity of the minerals being mined and the various stages of the subsequent extractive process. For this reason, pro-active experimentation based sometimes on very little surviving evidence has been used as a means to predict the types of traces which might be found; the route these experiments take invariably being guided subjectively, by attempting the simplest or minimalist approach, the only pre-condition here being a considerable familiarity with handling original materials and tools, as well as a ‘closeness’ to the relevant archaeological investigation – preferably as researcher, experimenter, and excavator. Such an approach may be deemed neither processual nor post-processual in nature (Hodder, 1982); being at the same time an ‘immersed’ activity undertaken as a craft, as well as an objectively pursued experiment.

Considering the task of metal mining, whatever minerals were being sought as an ore will in most instances have been extracted, processed, and then finally removed from site. With ‘primitive mining’, we might be looking at a quite time-consuming selection of ore, followed by hand-crushing, hand-picking and piecemeal separation of mineral. When we compare the prehistoric approach to that for modern mining, the former may sometimes appear to be the more efficient (or perhaps thorough) in terms of the removal of mineral, so much so in fact that what might seem a perfectly straightforward question, i.e. ‘was this a copper or lead mine’ might be a difficult one to answer, since both ores occur together, and there maybe little trace of either (Bick, 1999; Mighall, et al., 2000). Even if we could confirm it was a copper mine, we would still need to ask the question whether it was the sulphide or oxide minerals that they were extracting, or for that matter a combination of the two? (see Craddock, 1995, p.11 and p.32; Timberlake, 2003, pp.100-102; Timberlake and Marshall, 2013, p.80).

Mine spoil as an artefact of the mining process will normally survive the test of time, yet this may also have a subsequent history of re-deposition and mixing, including contamination with later infill. Few if any mines have not been re-worked at some point. Thus, the archaeology of these deposits can be complex and difficult to interpret. Even so, some prehistoric mining tools, such as stone hammers and crushing stones, have a good record of survival, yet these implements are often re-cycled (sometimes over hundreds if not thousands of years), then re-deposited, with the fragments of their use thus ending up scattered widely across a site.

A significant number of prehistoric tools would have been wholly or even partly made from organic materials (such as the handles of hammerstones), and once broken or worn these would have been discarded, and more often than not thrown down and used as floor materials within the waterlogged areas of the mine, where they might survive. Alternatively such objects might be consigned to the poorly-preserved oxidising environment of the waste heaps, where there was little chance of survival. On other occasions, these tools may have ended up being re-cycled and consumed as fuel within the next fireset hearth (Timberlake, 2003, p.71). Because of this, much less than expected ever survives of the full range of tools used, and still less of the minerals extracted. What we do have instead are the dispersed fragments of a known activity still poorly understood, alongside the negative evidence of the ore(s) removed.

Experiments in the mining and processing of prehistoric ores

Experimentation with stone mining tools

The earliest experiments in mining using un-modified stone tools against fireset and unfireset rock at our experimental site at Cwmystwyth Mine in Wales in 1987/1988 left us with the over-riding impression that such tools must originally have been used with some sort of fixed or flexible handle; for reasons of effectiveness as well as self-preservation (Pickin and Timberlake, 1988).

Handles made of hazel sticks or twisted willow withies were first used by us in mining experiments a year later (see Craddock, 1990). Large cobbles could be hafted this way without grooving them, sometimes with little or no notching of the stones required. Experimentally this was a distinct improvement, although the use of willow permitted too much ‘wobble’ in the hammer-head, thus reducing the effectiveness of the tool through delivering more glancing blows, a problem alleviated by using slightly more rigid hazel stick handles. Hemp twine and leather, later substituted by rawhide strips, were used for binding and knotting the cobbles in position. These were loosely modelled on the images of hafted tools recovered with the mummified remains of a 1800 year-old Indian miner euphemistically referred to as ‘Copper Man’ whose body was discovered within the Restauradora Mine, Chuquicamata within the Atacama Desert of Northern Chile in 1899 (Bird, 1979). My colleague Brenda Craddock then had the opportunity to study another similarly-hafted hammer from Chuquicamata (Fig. 1) when this item turned up on

Fig. 1. Hammerstone with wood and skin hafting and handle from Chuquicamata, Chile (photo: Paul Craddock).

loan at the British Museum in 2000 (Craddock, B., et al., 2003). That investigation confirmed our perceptions of how these tools were made; a design that in many specific details also resembled what we had found during the course of preliminary experimentation, the latter partly based on the model we had already predicted. However, a new analysis of the tool did help to refine this, which in turn fed into our experimental approach. In fact, the criterion we subsequently adopted for continuing to use these hafting techniques in our reconstructions was the global similarity we noted in the shape and modifications present in ‘prehistoric’ stone mining tools (ibid., p.63); it being reasonable also to assume that the hafting of these cobbles would likewise have been similar. We might refer to this phenomenon as being an example of a 'simultaneous or repeated re-invention' – where similar (or identical) designs are governed by similar utilitarian needs.

It did not take long to realize that such hammers could only have been used underarm, if the stones were to be retained within the haftings! This type of skill-acquisition in experimentation offered up simple yet obvious answers to a number of questions regarding the use of hammer-stones within the Bronze Age mine at Cwmystwyth (Timberlake, 2003); for example, how and why were large numbers of triangular-shaped cobbles used only at the broad end? Quite simply, with each use of the tool the cobble would be jammed back into the ligature of the hafting, whilst the use of the other end without extensive notching of the cobble would eject it (ibid., p.94).

The bruising of the fibres, their twisting, then the looping of a single withy (hazel) handle around the cobble and its fastening with rawhide suddenly seemed obvious as a simple technique for the hafting of short-lived mining hammers. As a result, the strength and efficiency of the experimental tools improved. Larger cobbles could now be hafted, whilst accurate work could still be achieved using smaller hammers (< 1 kg); in some cases these have dislodged up to a ton of rock with only minimal repairs to the haftings (Timberlake, 2007, p.30). The facets and spalling surfaces produced on these cobbles have since been examined with an eye to recognizing the very same types of wear amongst the tools recovered from the excavations. Similar sorts of bi-lateral notches pecked or ground into the sides of the experimental cobbles for hafting have now been recognized within excavated examples, as have the facets on the flat surfaces of pebbles for the insertion of wedges to secure this, alongside wear marks resulting from their use as ore crushing anvils. Interestingly we also predicted the re-use of some of the large stone flakes or spalls detached from the hammerstones during primary rock-breaking as chisels or wedges. We then found evidence for this tool use within the Bronze Age mine (Timberlake and Craddock, 2013, p.45), the wear on the flake edges clearly recognisable from the rounding-off of the fracture surfaces.

However, the true worth of this experimental approach was most impressively demonstrated following our examination of the broken bindings of the tools we had just been experimenting with. By documenting these we believed we would be able to predict how, why and where such handles might break, and more importantly, what these fragments might look like if we found them preserved within archaeological deposits. This familiarity with the material enabled Brenda Craddock to immediately recognize one half of a withy handle she saw lying within a waterlogged area of the excavations on Copa Hill in 1995 (Fig. 2). At the same time she was able to predict the probable find of a second half of the same broken handle some centimetres away from the first; both pieces being found where the broken haft for the hammer haft failed and was thrown down upon the wet floor of the mine

Fig. 2. Broken withy handle for a hammerstone found within the Bronze Age Copper Mine on Copa Hill, Cwmystwyth 1995 (photo: Simon Timberlake).

some 4000 years ago (Timberlake, 2002, p.345; 2003, p.72). Unknowingly, we had re-enacted the same event within one of our own experiments, and as consequence were well-informed as to what to expect.

Experimentation with the use of antler picks

Picks of red deer antler were first used in mining experiments at Cwmystwyth in 1990 as a means to test their effectiveness against hard rocks. These tools were used in a very different way to metal picks, functioning as quite effective mallets to knock out freshly fireset rock, or else as levers to prise away blocks after this rock had first been fractured and loosened-up by hammer stones (cf. the mode of antler pick use in Neolithic flint mines). Approximately 1.5 tons of fireset rock were removed using one experimental pick. This alternation between the use of stone and antler tools in breaking down the recently fireset rock use proved so effective that we suggested these picks might have been used regularly within the mines, despite the lack of archaeological evidence (Timberlake, 1990a). It wasn't that surprising therefore when we found examples of similar tools the following year within the mine on Copa Hill – these turned up just as soon as we encountered the right conditions for their preservation (as determined by the Eh / pH values and waterlogging of the surrounding mining sediments). Convinced by our experimental method, and a better understanding of the 'mindset' of the prehistoric copper miner, we adapted our excavation technique to work much more slowly and carefully within what we now recognised to be the more promising areas of the mine. Of the more complete tools we found, one was a broken pick and the other a hammer / pick; both made of red deer (*Cervus elephus*) antler. The latter implement had been roughly prepared (with the end of the shaft broken off and the second tine removed by an axe), then used first as a prising pick, subsequently as a percussive tool, until the first tine had been worn down to a stub. This was then turned around, and used on the hardest part of the antler (i.e. the crown) as a mallet. This type of secondary use and wear was exactly what we had

Fig 3. Pecking a notch around a cobble to make a hammerstone for hafting, Sakdrisi Mine, Georgia 2013 (photo: Simon Timberlake).

Fig. 4. 'Chuquicamata-type' experimental mining hammer used at Sakdrisi Mine in 2011 (photo: Deutsches Bergbau-Museum Bochum).

Fig 5. 'Mitterberg-type' experimental mining hammer used at Sakdrisi Mine in 2011 (photo: Deutsches Bergbau-Museum Bochum).

experienced ourselves during the course of our earlier experiments. It was a case of instant recognition.

Many other small fragments of antler have since been found within the mine – most of these indifferently preserved. From the quantification of all this and the evidence of our experimental work it has been estimated that each pick could have assisted in the removal of between 15 and 25 tons of rock. It is conceivable therefore that upwards of 100 to 300 antlers may have been brought up to site (Timberlake, 2003, p.84). It is useful to compare this sort of estimate with the evidence recovered from some of the Neolithic flint mines where antler picks were the main tools of extraction, typically in the very much softer chalk rocks. At Grimes Graves in Norfolk, several hundred picks were found per shaft (Mercer, 1981).

Experimental mining and gold extraction at Sakdrisi Mine, Kazreti, Georgia

In 2011 and 2013, firesetting, mining and gold extraction experiments were carried out at the site of a late 4th–early 3rd millennium BC gold mine of the Kura-Axes culture, a site being excavated by a joint German-Georgian archaeological team of as part of the 2007–2014 Bochum Caucasus project (Stöllner, et al., 2014).

Sakdrisi Mine has been claimed, with some justification, as being the earliest example of (hard-rock) gold mining in the ancient world (Stöllner, et al., 2008). Its greatest enigma is that the gold grains present within the quartz-hematite veins making up the gossan zone of this massive sulphide deposit are so small (< 0.5 mm) as to be invisible to the naked eye in hand specimen. Although it is possible that the source of this gold was once traced by progressive alluvial recovery along the bed of the nearby Mashavera River, it remains difficult to comprehend how this particular deposit consisting of quartz veins carrying only 10-100 ppm of gold in a very finely disseminated form was identified from amongst hundreds of other less-enriched ones. Moreover, how did they come up with an effective strategy to work it?

Experiments in mining were undertaken by Simon Timberlake, Thomas Stöllner and Brenda Craddock during the summer seasons of 2011 and 2013. The specific experimental sites consisted of several unworked veins exposed within a rock section located on the side of a modern prospection road immediately to the west of Mine no.2 (i.e. the 'face' and Veins A-C, see Fig. 6), another at an underground location within one of the modern mine galleries, and several further ones located inside of the ancient open works (i.e. Area B2/3 F.10135 and the nearby NW Rift). The hardness (i.e. degree of silicification) of the rhyodacitic country rock varied considerably between these various locations, this proving adifficult variable to quantify.

Making tools

Following a metrical/morphological study of the cobbles used as mining tools, a series of experiments were devised which involved collecting a range of suitably-sized,

	Fireset 1	Fireset 2	Fireset 3	Fireset 4	Fireset 5	Fireset 6	Fireset 7	Fireset 8	Fireset 9	Fireset 10	Fireset 11
wood (kg)	207	47	84	173	47	77.4	50	89	50	50	20
wood sp.	oak	oak	oak	oak	oak	oak	oak	oak	oak	oak	oak
wood size (m)	0.8-1.1	0.5-0.8	branch	0.3-0.8	branch	0.8	0.5	0.5–0.8	0.5	0.5	branch
duration (hrs)	2.4	2	1	1.75	2.15	2.6	1	2.4	1.2	1.4	1.1
max temp (ºC)		796	500	577	746	762	746	666	826	472	577
water douse (kg)	Y	N	N	Y	N	Y	N	Y	N	N	N
exfol rock (kg)	9.2			4.3	2	5.6		3.26	0.66	6.3	0.3
pick rock (kg)	35	14	12.2	9.4	7.7	7.5	69	22	6.6	5.1	1.4
hammer rock (kg)	134	86	26	34.5	24.1	15.75		16	2.9	6.6	7.8
depth (mm)						10-20		10			
site	face	vein A	underg	vein B	vein B	vein B	vein C	face	F10135	NW Rift	vein B
mining time (hrs)				1.5	1	1		1		0.5	0.5
TOTAL rock (kg)	178	100	38	48	34	29	69	41	10	18	10
ratio wood: rock	*1: 0.86*	*1: 2.13*	*1: 0.45*	*1: 0.3*	*1: 0.72*	*1: 0.4*	*1: 1.38*	*1: 0.46*	*1: 0.2*	*1: 0.36*	*1: 0.5*

Tab. 1. Experimental firesetting and mining experiments at Sakdrisi Mine (2011 + 2013).

ovate wedge shaped cobbles of mostly fine-grained crystalline igneous rocks weighing between 1-4 kg from the bed of the nearby Mashavera River. Some 32 of these cobbles were then hafted in a variety of ways for comparison in terms of their use style, effectiveness in removing rock, and robustness against both fireset and un-fireset rock.

All of the hammers were constructed by Brenda Craddock, the majority of the cobbles first being lightly notched or semi-grooved around their mid-points (i.e. centre of gravity of the stone), these being etched out through the repetitive percussive pecking action of small quartz or hard rock pebbles (Fig. 3); an incomplete and variably deep groove between 2-5 mm deep and 10-15 mm wide taking anything between 45 minutes and 90 minutes to fashion onto these hard diorite, basalt, andesite and rhyodacite porphyry rocks. At least five different haft types were experimented with; ranging from the 'Chuquicamata' type (Fig. 4) consisting of cobbles held within double twisted withies made from freshly collected green willow (*Salix* sp) and hazel (*Corylus* sp) with fastenings made from wet rawhide animal skin, the 'Mitterberg' type of stone pick-hammer (see Rieser and Schrattenthaler, 1998/99) consisting of elongated pebbles carefully mounted and tied onto the cut branch ends of thorn wood (Fig. 5), plus a variety of other forms including simple stick-held stones, wrapped 'slings' made from twisted hazel, plus a variety of plant fibre rope handles made from nettle, bramble etc. Hand-held stones were also experimented with, along with wooden picks, wedges, and several types of pick fashioned from red deer antler.

Firesetting

Over the two field seasons 11 different firesetting and mining experiments were undertaken at Sakdrisi; the results of which in terms of weight of rock mined using both fire, pick and hammers, with or without the use of water for dousing the rock are provided in table 1.

It is difficult however to see a clear pattern in these results. Much higher temperatures (up to 800 ºC) over a longer duration should have proved to be more effective in breaking-up the rock, yet this does not always appear to be the case. In fact, the most effective rock reduction took place in Fireset 2, without dousing, and using only 50 kg wood against Vein A. The next best result was Fireset 7 in the mining of Vein C, followed by Fireset 1 associated with the mining of the rock face exposed on the side of the prospection road, the latter producing 178 kg of mined rock. Possibly, the common factor here was the similarity between all these sites in terms of the weathering of the rocks, their relative hardness, presence of secondary iron oxidation, and the presence or absence of joints or cracks. This was certainly the case with the more recently broken rock face. In fact, the relative ease of working the latter sites contrasted with the hardness and resilience of the rocks found at the ends of prehistoric workings (such as F.10135 and the NW Rift); the re-mining of which resulted in the considerable fracturing of the experimental hammers. The extreme hardness of these rocks proved to be the main limiting factor here. Thus the relatively poor wood fuel: rock extraction average of 1:0.5 achieved here contrasts with the better results from Wales (between 1:1 and 1:2) in the case of similar experiments carried out against well jointed quartz-veined sandstones and shales (Timberlake, 2007, p.29).

However, one observation on the mining not immediately obvious from the calculation of rock produced was the ease with which the narrow hematite-quartz veins at Sakdrisi could be removed compared to the surrounding country rock as these excavations became deeper and more characteristically hollowed, as was found with Veins B and C (Fig. 6). The duration of burn time spent above

500 ºC was particularly important in this instance. We saw the effectiveness of this most clearly in Firesets 5 and 6 where the quartz vein became visibly calcined, then granulated and powdery enough to allow it to be 'scraped out' using just an antler pick (Fig. 7) after having been fired at a constant temperature of around 700 ºC. Professor Holman noted this same quartz granulation effect in his firesetting experiments carried out at the Royal School of Mines in London in 1927, as did James Mitchell when examining the Roman gold workings at Dolaucothi in South Wales in 1909 (Holman, 1927; Timberlake, 1990b, p.51). At Sakdrisi, no particular benefit was noted in firesetting using brushwood (i.e. thin wood) fuel. In fact the burning of short sections of split oak was generally found to be much more effective in the targeted mining of small veins.

Much more work needs to be done to properly assess the efficacy of the range of prehistoric mining tools experimented with. However, it was noted that large cobble hammers weighing up to 4 kg and mounted within two hazel withy handles tightly wrapped in rawhide were quite effective in shattering the hard but well-fired country rock when hit in glancing underarm blows (Fig. 8), whilst small hammers of 1 kg or less, particularly when mounted in the 'Mitterberg' style, could be used both overarm and underarm to open up one side or other of a small vein working in order to facilitate the mineral removal using a combination of both hammer and pick.

Fig. 7. The use of antler picks to remove a fireset quartz vein at the experimental mining site at Sakdrisi Mine in 2013 (photo: Deutsches Bergbau-Museum Bochum).

Experiments in gold extraction

Our final role in this project was to try and reconstruct the gold mining, milling and washing process as suggested by the archaeological evidence.

Mining of the gold-bearing quartz-hematite was followed by the crushing of this ore by ourselves and the site workers using mortar stones, with the fine milling taking place upon grind stones recovered from the excavations. The subsequent recovery of the gold was achieved by washing (or panning) this in order to obtain a concentrate from which the 'head' of fine gold grains could be physically separated (see Stöllner, et al., 2012; Timberlake, 2014a). It is interesting to compare the account below with the gold mining and processing experiments carried out at the Bronze Age mine of Ada Tepe in Bulgaria, reported within the two papers by Popov, et al. and Stoychev, et al. in *Experimentelle Archäologie in Europa* 13 (2014).

Fig. 8. Mining using a large hafted hammerstone at the site of Vein A at Sakdrisi Mine (photo: Deutsches Bergbau-Museum Bochum).

Crushing and separation of the mined rock

All of the potentially gold-bearing vein stuff was carefully separated out from the rock waste, the hematite:quartz-waste rock ratio ranging from 1:2:3 to 1:3:2 (by weight). The quartz-hematite contact samples were then processed separately from the quartz vein material; in part because we knew that the Soviet-period assays suggested considerable variation in the gold values within and between individual veins, and partly because we could see that the prehistoric miners had followed certain veins, or parts of veins, but not others. It was decided therefore to experiment with assaying each metre of the vein (Fig. 9), both through milling and then panning this for gold recovery, and through PXRF analysis carried out upon the rock itself, and after crushing. We needed to know whether it would have been possible (as well as practical) for the prehistoric miners to visually determine where the richest gold values lay. Were these close to the vein contacts, within the quartz, or in the hematite?

Experimentally we arranged for different individuals to work on different parcels of ore; first crushing these on the anvil stones, then milling them within the hollows of

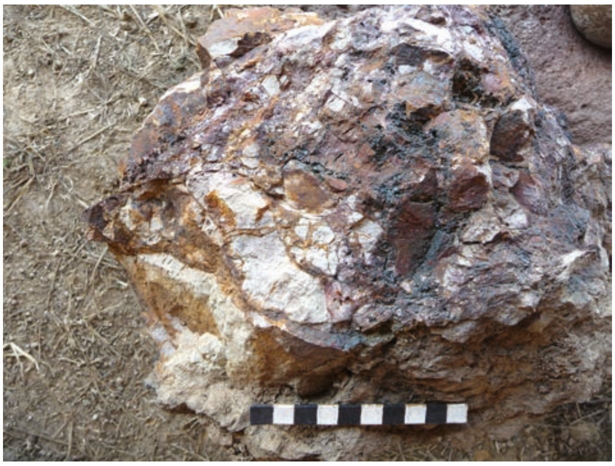

Fig. 9. Hematite-veined quartz as a gold ore for milling and assaying, Sakdrisi Mine 2013 (photo: Simon Timberlake).

Fig. 11. Experimental processing of ore at Sakdrisi Mine using saddle-quern-type grindstones (photo: Simon Timberlake).

Fig. 10. Using a multiple-hollow mortar stone for crushing quartz-hematite to a 'grit' sized fraction, Sakdrisi Mine 2013 (photo: Simon Timberlake).

multiple-hole mortar stones recovered from the Bronze Age mine (Fig. 10) using either small pounding cobbles or flat-sided crushers, the goal of this being the reduction of the ore to a grit (2-3 mm diameter) grain size.

The parcels of crushed ore were then fine-ground to a powder upon large 'saddle-quern type' grind stones using suitably flat or slightly convex worn rubbing stones (Fig. 11). Our washings of these residues showed that a grain size of between 0.25 mm-0.5 mm was probably the best fraction for gold recovery. By increasing this to > 1 mm the gold values of the same samples did not improve, but in some cases tailed off. As it turned out these large grind stones proved to be ideal for the final stages of milling the ore, providing some clarity as to the function of these within the mine and in the workshop areas of the nearby Kura-Araxian settlement of Dzedzvebi.

Gold washing and recovery

Samples of pulverised ore weighing between 0.5 and 1 kg were then panned in clean water. Pan washing these samples for 10-15 minutes removed the quartz and produced a dark concentrate of hematite. Given the very small grain size of the gold (the largest grains being only 0.5 mm in diameter), the remaining iron oxides proved difficult to remove, yet a number of the samples with significant hematite and goethite contents (30-40,% Fe_20_3 + FeO.H) did yield some of the best heads of gold (Fig. 12).

Visual determination (confirmed by analysis) suggested that most of gold was associated with the hematite, but that this was quite variable in its gold content, ranging from around 1 ppm to 180 ppm Au. Moreover, experimentation had shown us how it was possible to assay this ore on-site using really quite primitive techniques; following which reasonably informed decisions could be made as to which vein to exploit. Interestingly, this 'continuous vein assaying' technique is much the same as the approach to gold mining today; it is just done in a more sophisticated way.

A combination of PXRF and laboratory analysis of some of the ore samples remaining within those veins associated with the 'rich' shoots of Mine1/2 suggests that the gold ore recovered from the most completely stoped-out parts of this working could have had a mean value of around 130 ppm Au (g per ton), whilst for the mine as a whole it might have been as much as 77 ppm Au (g per ton) (Stöllner, et al., 2014, pp.91-92), with a minimum cut-off of about 1 ppm Au (ibid., pp.86-87). However, our experimental work suggests that a realistically achievable cut-off grade is more likely to have been around 5 ppm (Timberlake, 2014a, p.53). This we estimated was the absolute minimum that we could have extracted using a

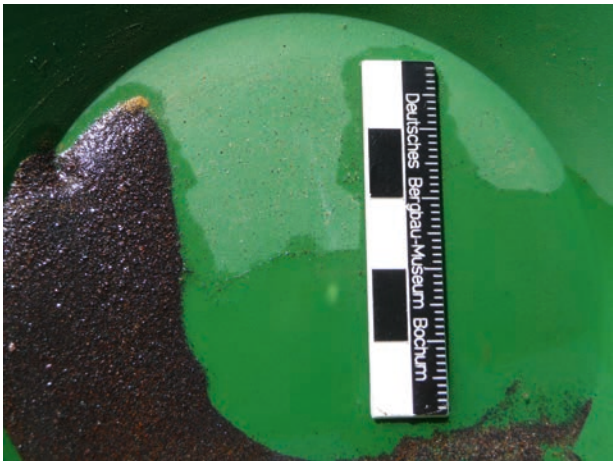

Fig. 12. A small head of gold flakes washed out of the powdered hematite as part of the wet assaying of the ore at Sakdrisi Mine 2011 (photo: Simon Timberlake).

Fig. 13. The rock-cut assaying cistern within the Kura-Araxian mine (Mine no.2), Sakdrisi 2011 (photo: Simon Timberlake).

feather quill to remove gold (approximately 50 < 0.5 mm wide flakes) from a pan, which also turns out to be the best grade we obtained from processing 0.87 kg of hematite crushed from what was probably a rejected prehistoric ore. However, we mus not lose sight of the fact that here we have to calculate from evidence which is now absent. In fact, we are always making such assumptions when estimating the richness of an anciently worked-out mine, assumptions which are based on what was left. All of the above experiments show that gold-winning at Sakdrisi was practically possible, yet would have been a very difficult task, with the method described above being just one approach to the working of this ore body and the recovery of gold.

Our engagement in the totality of this mining process confirmed to us that 'continuous assaying' was probably an essential part of the labour-intensive prehistoric mining operation necessary to extract fine-grained (and macro-invisible) gold. Because of this, we recognized the importance of there being an 'assaying place' located somewhere within the heart of the mining complex from which future directions in the mining operation could be dictated. Experimental prediction in this case was conveniently answered by our recognition of an original working area (the same one as used by us for milling ore during our experiments), and a few metres away from this a neatly cut oval-shaped cistern which had been dug into the rock outcrop on the edge of Mine no.1 (Fig. 13). We used this cistern as a water supply as well as a drain for the washing of the gold assays (Stöllner, pers com.). As we raised water in buckets to pan with from this naturally rain-filled cistern, it seemed obvious to us that through undertaking these experiments on-site we were in a much better position to understand the processes involved, thus more easily predict the sorts of materials and features we should be using.

Although assay washing for gold would have been carried out the mine, the extracted ore once coarse or fine crushed at the mine would have been removed to a processing site located on the banks of the Mashavera River for washing and gold recovery. This activity would have been carried out on a much larger scale using some sort of sluice box system, or else brushwood, sheep fleeces or stretched skins to collect the gold, which would then have been burnt to recover the metal (the so-called 'Golden Fleece' of ancient Colchis as related in the Greek mythology of Jason and the Argonauts; see also Agricola, 1556: Hoover and Hoover, 1950, p.330). A washing site for gold is much more likely to have been located mid-way between the mine and the settlement at Dzedzvebi.

Production estimates

Based on experimental work, field archaeological evidence and sample analysis it is possible to make some very rough calculations as to the scale and resource implications of the mining work and the production of gold. Much of this has been looked at already by Stöllner (et al., pp.88-92), although my own rule-of-thumb calculations based in part upon mining experiments suggest that upwards of 9000 tons of wood may have been used in firesetting operations during the estimated 300–400 year period of Kura-Araxian mining, when between 250-460 kg gold may have been extracted (the upper fig. here is that calculated by Stöllner, et al., ibid., p.92). Figures based just on provisional experimental parameters suggest that it might have taken 4 workers up to 4 days of 7-8 hours each to mine and prepare 30 kg of ore concentrate ready for washing (this is based on a ratio of time divided between mining and ore preparation of 1:3.2). Therefore in total, using the equation of 15 man years (330 days of 8 hours each) to produce 1 kg of gold (Stöllner, et al., 2014), we could be looking at between 3750 and 6900 man years to excavate the Kura-Araxian workings of Sakdrisi and extract the 250-460 kg of gold. If mining was continuous throughout this 400 year period (which seems very doubtful) we would be looking at a minimum workforce of between 10-20 full-time miners, ore processors and goldwashers, alongside an equivalent workforce of approximately the same number to provide food, collect and prepare firewood, and to make and repair tools. A much more likely scenario is that both the mining and gold washing were seasonal activities, perhaps with the same individuals involved in both (during alternate seasons), possibly alongside their contributions to the normal agricultural year. Periodic working implies a much larger number of people being involved, and a more community-organized operation (see also Stöllner, et al., 2014, pp. 104-105).

Comparison with Kestel and Ada Tepe

There are certain similarities between this site and the Late Bronze Age gold mine of Ada Tepe in Bulgaria. Both deposits are gossan exposures which have been worked by firesetting and 'primitive' mining methods for gold. However, at Ada Tepe the rock appears considerably more weathered and joint-filled, making it easier to break up with fire and remove large pieces of rock using just wooden wedges and hammers (Popov, et al., 2014, p.34). Much more interesting I think is the similarity between Sakdrisi and Dzedzvebi and the Early Bronze Age tin mine and processing settlement sites of Kestel and Göltepe in the Taurus Mountains of Southern Anatolia (see Yener, et al., 1989; 2003).

Working at the Kestel Mine in 1996 we were faced with similar sorts of issues regarding the nature of the mineral being mined, and how an 'invisible ore' (in this case tin) was known about and extracted. As with Sakdrisi the mine appeared to be a hematite deposit, which it could be argued was much more likely to have been worked for pigment (Muhly, et al., 1991), yet in places this ore body contained up to 1 % cassiterite (tin oxide). Fortunately a combination of archaeological excavation, geochemical and mineralogical sampling, and experimental work carried out at these sites I think aptly demonstrated that the finely dispersed tin within this hematite was extracted from the mineral by further pulverizing this ore in a series of different workshops located at the nearby settlement of Göltepe. This process employed a complex sequence of enrichment which involved winnowing (or washing) as well as blowpipe smelting of the tin into beads upon the surface of large flat crucibles. The important ingredient here (apart from their obvious metallurgical skills) was the ingenuity of the processors, alongside a quite different approach to timescale, economy, and the effort of collective labour.

Reconstructing the earliest smelting processes

Preservation of all stages of a smelting operation would be a rare occurrence within the archaeological record. Furnaces are broken down to extract metal from incomplete smelts, and the components of the furnace walls and tuyeres are recycled. Meanwhile slags produced in the earlier smelting operations could have been broken up and crushed in order to release entrapped prills of metal for re-melting; the ground residue of these slags being used as temper within ceramics or refractory materials, and in the walls of new furnaces. Indeed, it is quite possible that proper slags were never produced at all during these operations, at least not in the earliest and most primitive smelting hearths typical of the Chalcolithic–Early Bronze Age (Craddock, 1994, p.75). Paul Craddock has succinctly summarised the situation: *'….. at best the evidence is enigmatic and at worst non-existent'* (Craddock, P., 2003, p.8).

The nature of copper ores

Some 10 years of experiments attempting to smelt Welsh chalcopyrite using simple pit furnaces and various combinations of roasting and co-smelting reduction, led us to re-assessing the types of ores mined and the sorts of mineral deposits worked at the beginning of the British Bronze Age (Timberlake and Marshall, 2013). Whilst it is true that tiny amounts (perhaps just 0.5 %) of the iron-copper mattes produced during these experimental smelts were, after roasting and reduction, converted to copper metal (see Timberlake, 2007, p.34; Craddock, et al., 2007), it seems much more likely that the ores they used were instead carefully selected samples rich in oxidised copper minerals removed from the surface and sub-surface deposits of partially or fully weathered low-grade chalcopyrite. Their ability to do this has been suggested by recent experiments carried out on 'rotted chalcopyrite'/ malachite mixtures, the smelting of which within simple 'hole in the ground' furnaces produced copper prills inside of a spongy slag; the 'slag' consisting of little-altered pieces of chalcopyrite surrounded by a copper-iron sulphide matte, fused quartz and iron oxides. The most recent experiments have neither been fully analysed nor properly published, yet the possibility of this has previously been suggested (Timberlake, 2010, p.291). In fact, our current work suggests that this could have been a viable strategy for the exploitation of these near-surface deposits alongside a more selective hand-picking of rich oxide or other supergene minerals.

Experimentation with primitive furnaces

Since 2004 experiments have been carried out at Butser Ancient Farm (UK) in an attempt to gain a better idea of the evidence and processes associated with the earliest production of metal (Timberlake, 2005, 2007 and 2013) (Fig. 14). This same work has been repeated on numerous occasions during the teaching of prehistoric experimental archaeometallurgy during a short course undertaken within the grounds of the Archaeological Institute, Bochum in December 2014. Hand-picked malachite or crushed mixtures of malachite, gangue minerals and rock (containing a minimum of 50% copper) have been

Figure 14. Undertaking an experiment with a ‘hole in the ground’ copper smelting furnace during the Prehistoric Metallurgy Course held at Butser Ancient Farm, UK (photo: Simon Timberlake).

Figure 15. Smelting within a wood fire ember pile using bag bellows. Experiment 6A, Pločnik, Serbia 2013 (photo: Simon Timberlake).

successfully smelted within an open wood or charcoal fire in which marginally reducing conditions have been maintained at atemperatures of around 850-900 ºC. Such roasting / reduction to copper oxide, then to copper metal will have taken place in the solid state, but for this new metal to melt and coalesce into copper prills, a temperature of at least 1100 ºC is needed. Our experiments using different-sized pits have demonstrated how 500 g of malachite can be easily smelted using just a shallow pit or posthole 20 cm in diameter and 10 cm deep under 15 cm of burning charcoal, with the process completed in less than 25 minutes. However, such a hearth will become effectively more reducing if it is clamped using a piece of turf to form an oven. In fact, the digging of a pit can be avoided completely if the charcoal pile is large enough, and the ore lies towards the bottom. However, to create sufficiently reducing conditions and a high-enough temperature to smelt copper within a wood fire, a much larger pile of embers is required; up to 30 cm deep and a minimum of 50 cm wide (Fig. 15). In both cases a constant forced draught needs to be directed downwards, but just above the level of the ore being smelted. This can be done using a clay tuyere or organic pipe linked to a pair of bag bellows, or under optimal conditions through channelling a moderately constant velocity wind. The position of the tuyere is critical, but in other respects the nature of these furnaces or hearths may be quite simple, variable in form, and with few recognizable features.

A successful smelt may be carried out if attention is paid to maintaining the temperature within the interior of the fire (i.e. the presence of a bright yellow-orange colour seen beneath a dark surface indicates a temperature of between 1050 and 1100 ºC), and by ensuring the continuation of sufficiently reducing conditions (i.e. the presence of a blue-mauve colour flame upon the surface). Similarly, sufficient time should be allowed for a smelting conversion to take place (as indicated by a strong green colour to the flame), whilst at the same time preventing too much oxidation. A second green flame ‘event’ will almost certainly indicate that the smelted copper is now being re-oxidised, a cindery mass of red copper oxide often being the end result. This re-oxidation process can be halted fairly quickly by removing some of the burning charcoal and then dousing the fire with water. An alternative would be to re-reduce the copper oxide by adding fresh charcoal, then clamping the furnace down. In essence therefore, the evidence for the simplest Bronze Age copper smelting furnace may just be that for a controlled fire, with or without a pit underneath, and perhaps with the traces of a burnt turf surround or capping. We should thus be aware of this model when trying to identify such activity in the archaeological record. Where slag, cinders, metal prills, or copper ore are not visibly associated with the charcoal and ash, such early furnaces may prove quite difficult to recognize. In fact, some smelting features may well have been identified as domestic hearths, and vice versa.

Our experimental experience of constructing and operating such simple furnaces has enabled us to predict what hasn't yet, but may eventually be found within the UK – i.e. traces of Early Bronze Age copper smelting (Timberlake, 2009). The careful examination of any sediment found associated with these hearths will be the deciding factor in all this. Small traces of crushed ore, calcined rock, and some finely broken conglomeratic 'slag' containing magnetic iron oxides and traces of (now largely oxidised) copper metal prills may be all that remains of such a process. This seems to have been the case at the Late Bronze Age copper smelting site of Pentrwyn on the Great Orme's Head (North Wales), where some of the metal associated with the metallurgical sediment appears to have been removed following the crushing of the slag pieces, the washing or hand sorting of the fines, and the picking out of the metal prills (Williams, 2013, p.107). Yet, it could be the charcoal itself which provides the best clue as to the function of the hearth. Charcoal is a great adsorber of heavy metals, and because of this geochemical soil sampling using a PXRF may be the simplest and quickest way to determine the *likely* metallurgical function of a burnt pit (Jenkins and Timberlake 1997, p.29, p.65). Although there are other possible explanations for pits or hearths associated with copper anomalies, this method does at least have potential in the search for the earliest evidence of smelting and metallurgy.

The smelting of Bronze Age copper ores (UK)

The Great Orme Mine, Llandudno, North Wales

A number of smelting experiments were carried out at the Great Orme Bronze Age mine in May 2015 in support of research work being carried out by Alan Williams at the University of Liverpool. The smelting was done using pre-analysed Great Orme ores that had been gathered by him from the Bronze Age working and then hand sorted. The ores were mainly an intimate mixture of goethite and malachite, with a copper content of around 25 % and which contained significant minor amounts of arsenic and nickel impurities. This is a more realistic secondary copper ore than the tropically-weathered pure malachite which is commonly used in smelting demonstrations. One experiment was carried out within a charcoal-filled pit hearth using animal skin bag bellows and ore crushed to less than 5 mm which was dropped loose into the charcoal. A maximum temperature of 1192 ^{o}C was recorded in the area of the hearth where the ore was introduced. This experiment produced some good, well-formed copper prills after 53 minutes of smelting. Full analytical results are still being obtained, and will appear in a future paper, but the initial results suggest relatively high levels of arsenic and nickel being transferred into the copper metal. These results are consistent with the composition of some Acton Park metalwork as suggested by work on the ores and on copper prills from the nearby smelting site at Pentrwyn (Williams, 2013, pp.103-104). Another smelting experiment was then carried out using a wood fire, as described earlier in this paper. Whilst some copper metal was formed, the separation of this from the slag to pure copper prills was incomplete, either because of the redox conditions, the duration of the smelt, or the temperature (up to 779 ºC was recorded using a fixed thermocouple, although a moveable thermocouple recorded temperatures in excess of 1200 ºC at various different points in the wood ash pile). Unfortunately, the copper from this smelt could not be separated sufficiently from the slag to allow a macro-analysis of both minor and trace elements.

Cupriferous sandstone and azurite-rich nodules from Alderley Edge, Cheshire

Copper smelting experiments were conducted in 1997 and in 1998 at Church Quarry on Alderley Edge. Pisolitic nodules of azurite were gathered from the Engine Vein Mine nearby, then crushed to a paste (Fig. 16) and mixed with charcoal, sawdust and horse dung and rolled into balls of about 40 mm diameter which were then dried and roasted upon the top of small clay-lined charcoal-filled bowl hearths (Timberlake, 2007, pp.31-32). These ore-dung balls were then smelted at temperatures of around 1000 ºC for an hour and a half before removal. Many of these proved to be incompletely smelted, yet the surface of the balls were coated with a copper film which had replaced some of the organic, whilst inside copper prills were found which were in the process of being formed – an example of a smelting process frozen in time.

Yet, other samples of malachite and azurite collected from Early Bronze Age workings on Alderley Edge were

Figure 16. Azurite nodules as a copper ore from Engine Vein Mine, Alderley Edge, being prepared for smelting in 1997 (photo: Simon Timberlake).

collected for an experiment which took place in September 2011 within the grounds of West Dean College, Chichester (Timberlake, 2013). These ores were first concentrated through crushing and hand-picking, and then smelted at temperatures of between c. 900–1100 ºC within three lidded crucibles inside of a bowl furnace blown by bag bellows. Copper prills formed during this smelt were separated by hand from the surrounding (loose) calcined sand, the latter having disaggregated but not fused; hence no trace of a slag was produced. The malachite-cemented sandstone which was probably the most abundant 'prehistoric' ore contained less than 20 % copper, which when smelted gave a metal with 6-20 % lead. However, the azurite nodules considered by us to be a 'rich' ore that was relatively easy to extract from the surrounding mudstone beds contained only 25 % copper by weight, although the metal produced from this was very pure (i.e. up to 97 % Cu). The filmy 'vein' malachite on the other hand contained up to 75% copper oxide, yet in most cases, this mineral would have proved far too difficult and time consuming to separate from the rock by hand. All of the copper prills from these smelts were then combined and re-melted. The metal produced was poured into an open soapstone mould and cast into a miniature copper axe, with just a small amount of excess metal and copper oxide waste remaining. The analysis of this axe showed a relative loss in lead (to just 0.3% Pb), indicating the possible refining effect of re-melting and casting the metal. However, the arsenic content remained high (0.5 % As).

Smelting of zinc-rich copper carbonate ores from Ecton, Staffordshire

In 2009, a closed crucible smelt of a small quantity of copper ore collected from the robbed spoil heap at the Clayton Pipe (Ecton Mine) was undertaken by the author within an open bowl hearth at Butser Ancient Farm in Hampshire. This yielded prills of metal consisting of 77-79 % copper, 10-14 % zinc and 2-7 % lead (a natural leaded brass) without producing a slag (SEM-EDS analysis by D. Dungworth). Analysis of the ore suggested that it was composed of tenorite, malachite and aurichalcite with smaller amounts of cerussite and smithsonite, a similar composition to some of the ores from the Bronze Age workings at Stone Quarry and The Lumb nearby (Timberlake, 2014b, pp.167-8). A not dissimilar metal type could well have been produced in the Bronze Age. The lead content of this might well be reduced by more careful ore selection, but a moderate zinc content would probably still be characteristic of this source.

Supergene copper minerals from the prehistoric spoil tips on Copa Hill, Cwmystwyth

Copper minerals were collected in 2013 from the tips of this Bronze Age mine by the author and Alan Williams (Timberlake and Marshall, 2013, p.80). A few of these

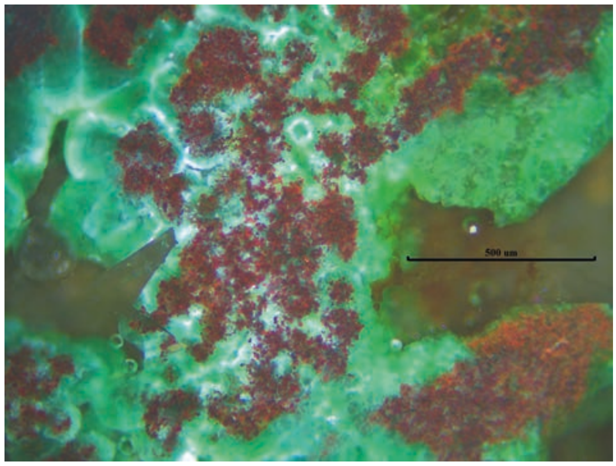

Figure 17. Microscope view (under x-polars) of malachite surrounding cuprite and native copper from the Comet Lode Opencast tips on Copa Hill, Cwmystwyth (photo: Alan Williams 2013).

specimens were looked at under a polarising microscope and revealed cores of native copper and cuprite surrounded by malachite and azurite replacing chalcopyrite (Fig. 17). Up to 20 g of this 'ore' was then crushed and hand-picked for crucible smelting within a small bowl furnace. Unfortunately most of the metal produced was lost, but at least 1 g consisting of sub-millimetre prills of copper and at least one or two discrete prills of lead were recovered, all of which await full analysis. Such experiments as this carried out on a larger scale, and repeated, should help to characterize the type of metal produced from this mine during the Early Bronze Age.

Experimental wood-fired smelting of a 'Chalcolithic-type' copper ore at Pločnik, Serbia 2013

In September 2013, the author was invited to participate in an experimental archaeometallurgical workshop held at Pločnik in southern Serbia as part of the AHRC-funded 'Rise of Metallurgy in Eurasia' project. The purpose of these experiments was to attempt to replicate through a range of possible models one of the earliest 'metal-making' recipes, as reconstructed from the analysis of 7000 years old smelting debris from Vinča culture sites in Serbia (Radivojević, et al., 2010; 2014). One of the important experimental findings of this workshop was the success achieved in smelting copper and producing a fully-formed slag cake within the ash-pile of a wood fire using a forced air draught. I am grateful to Miljana Radivojević for permission to report on this work in advance of full publication.

Assumptions are often made by archaeometallurgists concerning the need for charcoal to produce temperatures sufficiently high enough and conditions reducing enough for smelting; hence the requirements for charcoal production for which there is little convincing evidence of in the prehistoric archaeological record. It was for this reason that a model was suggested for a

Figure 18. A slag cake with copper prills formed during Experiment 6A, Pločnik, Serbia in 2013 (photo: Simon Timberlake).

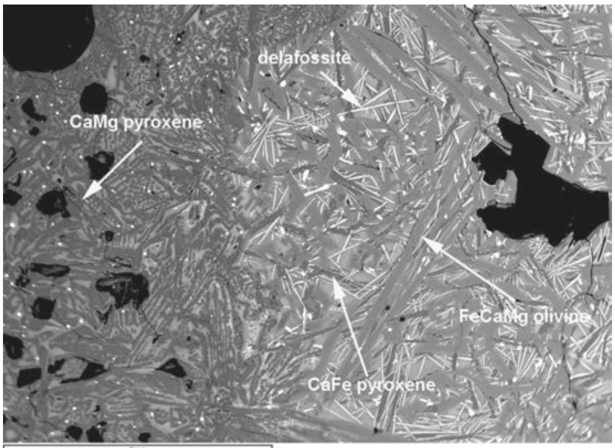

Figure 19. SEM image of Ca-Mg pyroxene-rich slag containing delafossite and prills of copper. Experiment 6A, Pločnik, Serbia 2013 (photo: M. Radivojević).

Figure 20. Copper re-melted within a crucible beneath the blown embers of a woodfire during the Prehistoric Metallurgy Course held at Butser Ancient Farm in 2014 (photo: Simon Timberlake).

possible bonfire-type wood smelting hearth within Experiment 6A.

A shallow (200 mm deep) and 0.5 m long pit or ‘scoop’ was dug at the experimental site, on top of which 50 kg of seasoned and split oak cordwood consisting of c. 0.3 m long pieces plus brushwood kindling was piled. This was lit and burnt as a large fire for approximately 2 hours, at times reaching temperatures of 800-900 ºC, following which a circular pile of ashes and embers about 1m across remained. These were then raked up into a cone over the centre of the pit and a hole dug into the edge down to the level of the sloping floor. Into this was placed a pile of finely-crushed hand-picked ore consisting of malachite and other oxidised copper minerals collected from one of the possible mine sources at Ždrelo (‘Ždrelo green’). This was placed close to the tip of a 300 mm long clay tuyere which was connected up to animal skin bag bellows. The embers of the fire were then built up over this ore pile as smelting commenced, with fresh embers being continually raked forward to cover these as they burnt down to an ash. Temperatures up to 1300 ºC were recorded near the tuyere end, with average temperature inside the pit of almost 1000 ºC.

After 2 hours of smelting, a molten slag cake weighing more than 250 g was removed using tongs (Fig. 18). After quenching in water hundreds of copper prills (some up to 5 mm in diameter) could be seen embedded within a dense black slag; the latter consisting of Ca-Mg pyroxene (diopside) and Ca-Mg-Fe olivine rich slag containing both iron oxides and delafossite (Fig. 19). Delafossite suggests the presence of very marginally reducing conditions which might be expected within the slightly less-oxidising ash bed or ash pit associated with a wood fire, or else an open and shallow charcoal hearth. The pyroxene in the slag may well have come from the re-melting of the diopside-rich rock associated with the Ždrelo ore, which was quartz-poor, and potentially therefore a good self-fluxing furnace charge. Interestingly, the formation of the slag cake may well have protected the enclosed copper prills from re-oxidation. The prills were removed from the slag following its crushing and added to a collection of smelted metal from which a casting was attempted.

This wood-fired copper smelting experiment has now been repeated several times back in the UK using different types of ore, and with varying degrees of success. The production of a proper slag was not repeated, the only significant amount of copper made having been smelted inside of a crucible. However, copper metal was also melted in a crucible placed within the blown embers (Fig. 20), suggesting that these wood-fired hearths might also have been used in copper alloy metalworking, including that undertaken for the casting of objects.

Summary conclusions

The experimental investigations described in this paper should be of interest to both mining archaeologists and archaeometallurgists, which have been given the sorts of questions tackled and the types of insights gained.

Mining experiments undertaken by the author and his colleagues in Wales and Georgia have demonstrated how hard rocks may be mined effectively using just unmodified cobbles held within stick and withy handles. The use of antler picks in mining was also predicted, then proved archaeologically; these tools proving to be both resilient and effective when used to remove previously fireset rock. However, experimentation has shown just how difficult and slow firesetting can be, yet these same experiments have also provided us with clues as to how the small veins might be removed prior to the larger rocks being broken down.

At Sakdrisi it has been possible to show how sub-visible gold present within the hematite-quartz veins can be extracted using just the most basic of stone tools. This vein mineral was processed using mortars and grindstones, the powder then being washed to remove the lighter quartz and heavier iron minerals in order to recover the gold. It seems likely that this was a technique used on-site as a means of continual assay within a variable ore body composed of hematite veins with differing gold concentrations.

Experimental archaeometallurgy has been crucial in helping reconstruct the earliest (and probably simplest) smelting furnaces, the archaeological traces for which we can predict, but at present have little evidence of. Experimenting with credible Bronze Age ores from known Bronze Age copper mines in the UK has provided us with some interesting findings which can now be used as a basis for further work. These include ideas on the types of smelting installations, the likely trace elements to be found in the metal, and any changes associated with re-melting.

Of greatest significance though was an experiment carried out in Serbia which demonstrated how wood might have been used to smelt copper within simple pit hearths through the production of an ember heap into which a forced draught was then blown using bag bellows. Oxidised copper and gangue minerals were then smelted to produce copper metal and a slag. Repeat experiments in the UK have also produced copper, some of which was then re-melted in a crucible under wood embers, raising the question as to whether these hearths could also have been used in casting and metalworking.

Postscript

Almost all of the above ideas concerning the nature of mining and early metallurgy have been generated through experiment, and almost all of them are in their infancy, still awaiting the follow-up of systematic experimental research and laboratory analysis. In many ways the Deutsches Bergbau-Museum Bochum FA Montanarchäologie and Archaeological Institute of the Ruhr University are well-placed to encourage this type of work in the form of funded PhD research. Today, the growth of experimental archaeological studies bears a fitting testimony to the ethos of the RITAK school.

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