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Predictive experimental archaeology as a tool in the study of ancient mining and metallurgy

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***Zusammenfassung – Voraussagende Experimentelle Archäologie als Werkzeug der Untersuchung des Bergbaus und der Metallurgie in der Vorgeschichte**. In Ergänzung der von Coles 1973 definierten Prinzipien, auf denen die Experimentelle Archäologie in Großbritannien beruht, möchten wir eine neue Herangehensweise vorstellen, die auf die Voraussage der Beschaffenheit archäologischer Befunde abzielt und in manchen Fällen dabei helfen könnte, vorab die am besten geeigneten Grabungs- und Untersuchungsmethoden festzulegen. Experimente zu bronzezeitlichem Bergbau in einem Minenfeld in Wales zwischen 1987 und 2003 belegten die Techniken, mit denen Steinschlägel einfach geschäftet und benutzt werden konnten. Es wurden dann Voraussagen getroffen, wo diese Schlägel und auch Hirschgeweihhacken bei künftigen Grabungen zu finden sein würden. 2011 und 2013 wurden Abbau- und Golderzverhüttungsexperimente vom Deutschen Bergbaumuseum Bochum in einem Minendistrikt des 4. und 3. Jahrtausends v. Chr. von Sakdrissi in Georgien durchgeführt. Mit diesen Experimenten gelang es, nachzuweisen, wie das kaum sichtbare Gold geschürft, gemalen und durch Auswaschen gewonnen wurde und wie Golderzadern unter Nutzung dieser Probeentnahmetechnik kontinuierlich aufgespürt wurden. Inzwischen erbrachte die Rekonstruktion der Kupferschmelzvorgänge mit einfachsten, nur schwach reduzierenden Schmelzherden während der frühen Bronzezeit Erklärungsansätze für das mögliche Nichtvorhandensein von Nachweisen. Nicht erklärt werden konnte dagegen die Abwesenheit früher Schmelzplätze in Großbritannien. Mit dieser Arbeit wird es möglich sein, genauer vorauszusagen, wonach wir eigentlich suchen müssen.*

Introduction

The UK has a good tradition in practical experimental archaeology, and an academically principled approach to this study which has its historic roots in the work of John Coles' Archaeology by Experiment (Coles 1973). Indeed it could be said that both Coles and Peter Reynolds (the first director of the Butser Iron Age Farm project; see Reynolds 1979) were the two great proponents of experimental archaeology in Britain. Both helped to define the standards we employ today. In fact it was Coles who referred to the need to 'faithfully reconstruct and repeatedly test technological processes suggested through archaeology by means of a programme of controlled experiments'. More specifically his eight-fold principled basis for carrying out experimental archaeology was based on the following premises:

(1) All materials used should be those locally available to the society under study.
(2) All the methods used in experimentation should remain within the bounds of the possible (thus a thorough knowledge of the procedures under study were essential).
(3) Modern technology should not interfere with the experiment, but should only be used in the analysis of results.
(4) Both the scope and appropriate scale of work should be properly assessed in advance, but also in the light of the experiment itself (i.e. one should always factor in the sourcing, collection and transport of the materials used, as well as the time and manpower entailed).
(5) Archaeological experiment(s) should be repeatable.
(6) A desired end result should be considered at the outset of each experiment.
(7) The results of such experiments should consist of observations that lead to suggested conclusions (in other words, the fact that something was possible does not necessarily mean that it was done that way).
(8) Every experiment should be honestly assessed and the errors openly stated.

Cole's additional proviso to this approach was that "experimental archaeology cannot and does not intend to prove anything…it is simply a tool whereby we can gain insights that might lead to further discovery" (Coles 1973, 15ff.).
However, it is these insights which can sometimes prove so valuable, particularly in those cases where little or no archaeological evidence of a process survives. Yet such an approach based just on hypothetical ideas would appear ride in the face of one of the most fundamentally stated principles of experimental archaeology i.e. that all experiments should be evidence based, and should seek to reconstruct what is already known from the archaeological record (Reynolds 1999). But how strictly should we interpret this? For doesn't the process of engagement in experimentation bring new levels of understanding to a subject, and through this the means to predict the nature of the missing evidence?
The current paper seeks to demonstrate the value and importance of predictive experimental archaeology as a tool to understand ancient technology and craft; both through anticipating new evidence, and developing new ways of looking at things.

Experimental archaeology in the study of ancient mining and metallurgy

The predictive experimental archaeological approach has been used successfully by the author to investigate ancient mining as well as some of the earliest smelting and metalworking technologies. Both of these activities can be difficult to interpret from the archaeological record, since often we are dealing with absent, confusing, or indeed negative evidence concerning the identity of the material being extracted and the stages of the 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 that might be found; the route these experiments take invariably being guided subjectively, and by attempting the simplest or minimalist approach, the only pre-condition being a considerable familiarity in handling both the materials and original tools, and also a 'closeness' to the relevant archaeology – preferably as a researcher and excavator. Such an approach is neither processual nor post-processual (Hodder 1982); since at the same time it is both an 'immersed' activity and objectively predictive.
It might be useful at this point to consider some of the particular issues associated

with the interpretation of ancient mining and smelting sites.

Mining

Both mining and smelting are inherently destructive operations. In the case of metal mining, whatever was being sought in terms of ore will in most instances have been extracted, then processed, and finally removed from site. In the case of 'primitive mining', this might involve quite time-consuming careful selection of ore, followed by hand-crushing, hand-picking and piecemeal separation of mineral. Ironically, in terms of modern mining, the latter approach may prove to be an altogether more efficient (or at least thorough) process, so much so in fact, that what at first sight might seem to be a perfectly straightforward question, i.e. 'is this a copper or lead mine ', might not be an easy one to answer, since both ores commonly occur together (Bick 1999; Mighall et al. 2000). Even if we could confirm that it was a copper mine, we would still need to ask ourselves whether it was the sulphide minerals or the oxidized minerals that were being extracted, or for that matter a combination of the two (see Craddock 1995, 11; 32; Timberlake 2003, 100-102; Timberlake, Marshall 2013b, 80).

Mine spoil as an artefact of the mining process does normally survive the test of time, but at the same time this may have a history of re-deposition and mixing, including contamination with later infill. Because of this the archaeology of these deposits can be both complex and difficult to interpret. Some mining tools, particularly stone ones, have a good record of survival, yet these implements are frequently re-cycled, then re-deposited, with fragments of these then ending up scattered across the site. Our own experience of looking at these early mines suggests that little in the way of a ritual importance was ever attached to the use of practical mining tools, although there are occasional exceptions to this (see Timberlake, Prag 2005, 5).

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-preserving environment of the waste heaps, where there was little chance of survival. On yet other occasions these tools would have ended up being re-cycled and consumed as fuel within the next fireset hearth (Timberlake 2003, 71). Because of this much less than expected 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.

Smelting

As regards metallurgy, the preservation of the various stages of a smelting operation is an even a rarer occurrence within the archaeological record. Furnaces are broken down to extract metal from incomplete smelts, components of the furnace walls and tuyeres are recycled, whilst slags produced in earlier smelting operations may have been broken up and crushed in order to release entrapped prills of metal for re-melting; with the ground residue then being used as temper within ceramics and 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 of smelting hearths (Craddock, P. 1994, 75). Paul

Craddock has succinctly summarised the situation: "…at best the evidence is enigmatic and at worst non-existent" (Craddock, P. 2003, 8).
These uncertainties as to the nature of the earliest smelting processes (particularly in Britain where we have no furnaces pre-dating the Early-Middle Iron Age; Young 2010) makes this one of the most interesting new challenges for investigation.
Of course in hindsight we might be asking ourselves whether greater care taken in the excavation of sites possessing prehistoric metallurgical remains could have afforded us a much better picture of what was going on in prehistory. If this had been the case, we might now be in the position to accurately reconstruct and test these processes by means of a programme of controlled experiments. This is exactly what Coles and Reynolds would have considered to be the ideal. Unfortunately, the necessary starting point in terms of examples to copy would simply have been impossible to achieve in the current instance. For this reason, the partial or even complete absence of archaeological evidence should not be seen as a reason to invalidate the use of experiment, it just requires a different approach.
The good experimenter will try and enter into the mindset of the miner and smelter, in order to discover just those sorts of improvements and practical solutions they might themselves have come up with given the limitations of materials to hand, and the simple technology available. To take this one step further, predictive experimental archaeology may help us to recognize what we have already found, as well as showing us what to look for.
The following are just a few examples of how this has been put into practice.

Experimenting 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, Timberlake 1988).
Handles made of hazel sticks or twisted willow withies were first used by us in mining experiments a year later (Craddock, B. 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

Abb. 1: Stone mining hammer with bound stick handle from Chuquicamata, Chile. – *Steinerner Abbauschlägel mit gebundener Stockschäftung aus Chuquicamata, Chile.*

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 raw-hide strips were used for binding and knotting the cobbles in position. These were loosely modelled upon 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 at Chuquicamatain 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 when this item turned up on loan at the British Museum in 2000 (Craddock, B. et al. 2003) (*Fig. 1*). 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, this partly based upon 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 criteria we subsequently adopted for continuing to use these hafting techniques in our reconstructions was the universal similarity we noted in the shape and modifications present in 'prehistoric' stone mining tools (Craddock, B. et al. 2003, 63); naturally it seemed to follow from this that the hafting of these cobble tools 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 (*Fig. 2*)! 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 (Timberlake 2003, 94).

Abb. 2: Using an experimentally-hafted cobble stone hammer during a mining experiment at Sakdrissi, Georgia in 2011. – Nutzung eines experimentell geschäfteten Feldsteinhammers während des Bergbauexperiments in Sakdrissi, Georgien, 2011.

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 (*Fig. 3*). As a result the strength and efficiency

Abb. 3: Bruising the fibres of hazel sticks in preparation for twisting these and bending to form coiled handles for hammerstones. – Aufspalten von Haselspänen, um sie gezwirnt zum Wickeln einer Steinhammerschäftung zu nutzen.

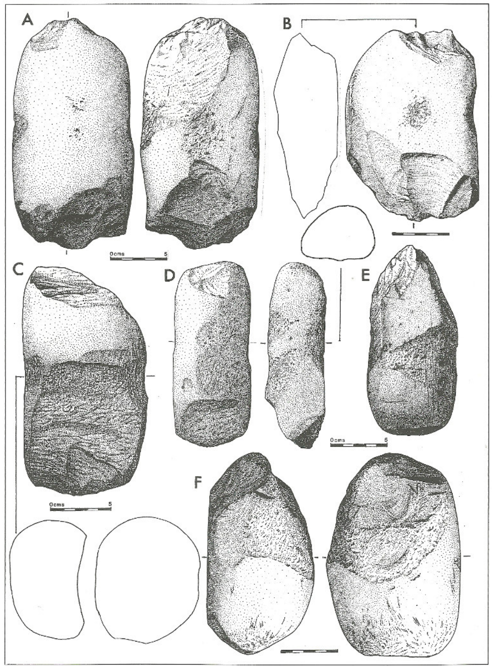

Abb. 4: Hammerstones from the Bronze Age mine on Copa Hill, Cwmystwyth NB. These show modification notches for hafting as well as bruising from use. – Schlagsteine aus der bronzezeitlichen Mine auf dem Copa Hill, Cwmystwyth NB. Sie zeigen Modifikationskerben für die Schäftung, ebenso wie Schrammen vom Gebrauch.

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, 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 bilateral notches pecked or ground into the sides of the experimental cobbles for hafting have now been recognized within excavated examples (*Fig. 4*), as have the facets on the flat surfaces of pebbles for the insertion of wedges to secure this, alongside wear marks from 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 (*Fig. 5*). We then found evidence for this tool use within the Bronze Age mine (TIMBERLAKE, CRADDOCK 2013, 45), the wear on the flake edges resulting from this use 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

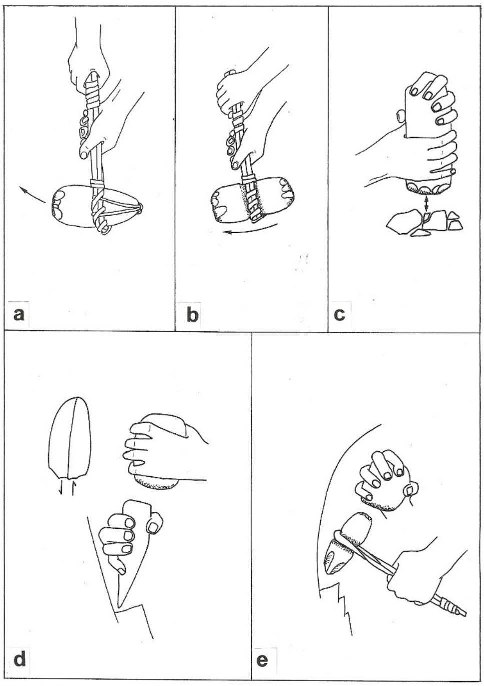

Abb. 5: Diagrams showing method of using and re-using hammerstones as different function mining tools. – Die Schaubilder zeigen die Art des Gebrauchs und der Wiederverwendung von Schlagsteinen als Abbaugeräte unterschiedlichster Funktion.

Abb. 6: Excavation reveals one half of a broken hazel withy handle discarded whilst mining in the Bronze Age, Comet Lode Opencast, Copa Hill. – Die Ausgrabung erbrachte die Hälfte einer gebrochenen Haselschäftung, die in der Bronzezeit in der Mine weggeworden worden war; Comet Lode Tagebau, Copa Hill.

Abb. 7: Mining experiment using an antler pick at the experimental site on Copa Hill, Cwmystwyth in the 1990s. – Abbauexperiment unter Verwendung einer Geweihhacke auf dem Versuchsgelände von Copa Hill, Cwmystwyth, in den 1990er-Jahren.

able to predict how, why and where such handles might break, and more importantly, what this fragments might look like if we found them preserved within archaeological deposits. This familiarity with the material enabled Brenda 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. 6*). At the same time she was able 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 some 4000 years ago (Timberlake 2002, 345; Timberlake 2003, 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.

Experimental archaeology and antler picks

Picks of red deer antler were first used in mining experiments at Cwmystwyth in 1990 (*Fig. 7*), primarily 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 was removed using the pick tool shown in *figure 8*. 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 1990). 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 (Eh/pH values and waterlogging of the mining sediments). Convinced by our experimental method and the broad understanding of the 'mindset' and practical thinking of the prehistoric copper miner, we had adapted our excavation technique to work much more slowly and carefully within the most pro-

Abb. 8: One of the experimentally-used antler pick tools from Cwmystwyth, showing the degree and position of wear. – Eine der experimentell genutzten Geweihhacken von Cwmystwyth zeigt das Ausmaß und die Lage der Abnutzung.

Abb. 9: Antler tool being excavated within the Bronze Age mine on Copa Hill in 1995. – In der bronzezeitlichen Mine auf dem Copa Hill im Jahr 1995 ausgegrabenes Geweihgerät.

mising areas. 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 (*Fig. 9*). The latter implement had been roughly prepared (with the end of the shaft broken off and the second tine removed by an axe cut), then used firstly as a prising pick, then as a percussive pick till the first tine had been worn down to a stub, turned round, then used on the hardest part of the antler (the crown) as a mallet. This type of secondary use and wear was exactly what we had 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, 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).

Experiments in gold extraction (2011 & 2013)

These experiments were carried out at the site of a late 4th- early 3rd millennium BC gold mine of the Kura-Axes culture, a site currently being excavated by a joint German-Georgian archaeological team of as part of the 2007-2014 Bochum Caucasus project (STÖLLNER, GAMBASCHIDZE, HAUPTMANN 2008). Our role in this project was to try and reconstruct the gold mining, milling and washing process as suggested by the archaeological evidence.
Sakridissi Mine has been claimed, with some justification, as being the earliest

example of (hard-rock) gold mining in the ancient world. 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 (<0.5mm) 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 Maschawera 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?

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

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, 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

Abb. 10: Milling down gold-bearing hematite and quartz samples within a multiple-hollowed mortar stone at Sakdrissi, Georgia (2013). The grindstone is in the background. – Zermahlen von goldführenden Hämatit- und Quartzproben in einem mehrfach ausgehöhlten Mörserstein in Sakdrissi, Georgien (2013). Im Hintergrund befindet sich der Mahlstein.

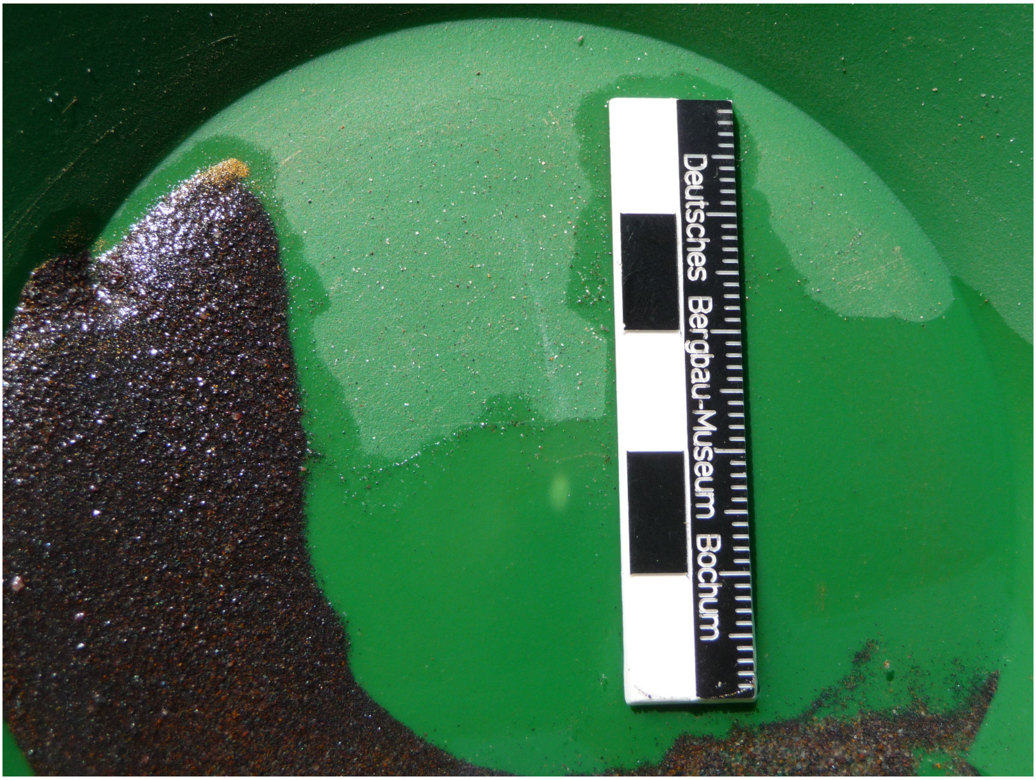

Abb. 11: A fine-grained gold 'head' lying adjacent to the remnant hematite and heavy minerals within a gold washing pan. Sakdrissi, Georgia 2011. – Feinkörniger bei Hämatit-resten liegender „Goldkopf" sowie schwerere Goldkörner in einer Waschpfanne. Sakdrissi, Georgien, 2011.

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 multiple-hole mortar stones (recovered from the Bronze Age mine) 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 (*Fig. 10*).

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. 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 Kuru-Axian settlement of Dzedzvebi.

Gold washing and recovery

Samples of pulverised ore weighing between 0.5-1 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 the best heads of gold (*Fig. 11*).

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 be 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.

The analyses of some of the ore samples remaining within the 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 may 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 2014, 91-92), with a minimum of cut-off of about 1 ppm Au (Stöllner 2014, 86-87). Our experimental work suggests that a realistically achievable cut-off grade is more likely to have been

Abb. 12: The water-filled 'assaying cistern' cut into a rock platform lying in between the ancient opencast mine openings, Sakdrissi, Georgia 2011. – Die wassergefüllte Prüfzisterne in einer Felsplatte zwischen zwei Öffnungen des bronzezeitlichen Tagebaus. Sakdrissi, Georgien, 2011.

around 5 ppm (Timberlake 2014, 53). Nevertheless, we should always remember that in such situations we are dealing for the most part with the evidence of 'negative evidence'. We are always therefore making some assumption as to the richness of an anciently worked-out mine; all our experiments show is that this was practically possible, and how they might have done this.

Our engagement in the totality of this mining process confirmed to us the probability that 'continuous assaying' was an essential part of this labour-intensive prehistoric mining operation to extract the fine-grained (and macro-invisible) gold. Because of this we recognized the importance of there being an 'assay place' located within the very heart of the mining complex, perhaps one from which future directions in the mining operation could be dictated. Experimental prediction in this case was conveniently answered by the recognition of a working area (the same one used by us for milling and assaying ore during our experiments), together with the discovery of a neatly cut oval-shaped cistern within the rock outcrop adjacent to Mine no.1 (*Fig. 12*). 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 to pan with in buckets from this naturally rain-filled cistern. It seemed obvious to us that through undertaking these experiments on-site, we were able to understand the processes that we were investigating, and more easily predict the sorts of materials and features that we should be using.

Reconstructing the earliest smelting processes

The nature of copper ores

Some 10 years of experiments attempting to smelt Welsh chalcopyrite (the mineral assumed until now to be the main ore won at most Early-Middle Bronze Age

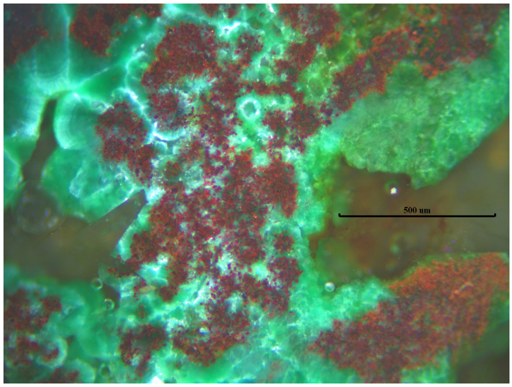

Abb. 13: A Bronze Age ore? Microscope view (under X-polars) of malachite surrounding cuprite and native copper, from the Comet Lode Opencast tips. – Bronzezeitliches Erz? Mikroskopansicht von malachitumgebendem Cuprit und nativem Kupfer, von der Comet Lode Tagebau-Halde.

copper mines in Wales; (Craddock, P. 1995; Timberlake 2007, 33; Timberlake 2009), using the simplest furnaces and various combinations of roasting and co-smelting reduction, has led to something of a re-assessment of the ores mined, and the nature of the mineral deposits they worked. 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, 34; Craddock, Meeks, Timberlake 2007), the much greater likelihood is that the ores they used were carefully selected samples rich in oxidised copper minerals (and perhaps sometimes native metal; see *Fig. 13*) removed from the surface outcrops and immediately sub-surface deposits of partially weathered low-grade chalcopyrite (Timberlake, Marshall 2013b, 85). The ability to do this using even poorly oxidised ores has been shown in recent experiments carried out on 'rotted chalcopyrite'/malachite mixtures, smelting this ore within simple 'hole in the ground' furnaces to produce copper prills within 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 process had already been suggested (Timberlake 2010, 291), whilst the current experimental results predicting this as a strategy for exploitation alongside the selective hand-picking of rich oxide or supergene minerals during mining.

Experimentation and the simplest smelting furnaces

Since 2004 experiments have been carried out at Butser Ancient Farm (UK) in an attempt to gain some idea of the evidence and processes associated with the earliest production of metal (Timberlake 2005; Timberlake 2007; Timberlake 2013). Hand-picked malachite, or crushed mixtures of malachite, gangue minerals and rock (containing a minimum 50% copper) can be successfully smelted within an open wood or charcoal fire (so long as marginally reducing conditions can be maintained) at temperatures of between 850-900ºC. Such roasting/reduction to copper oxide, then to copper metal will take place in the solid state, but for this to melt and coalesce into copper prills, a temperature of 1100ºC would be needed. Our experiments using different-sized pits have demonstrated that 500 g of malachite can be smelted easily within a shallow pit or posthole just 20 cm diameter and 10 cm deep, under 15 cm of burning charcoal, and in less than 25 minutes. Such a hearth becomes more effectively reducing for smelting if it is then clamped using a piece of turf to form an oven (*Fig. 14*). The digging of a pit can be avoided completely if the charcoal pile is large enough, and the ore lies towards the bottom. Yet 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 (i.e. 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 ore being smelted. This can be done using a clay tuyere or organic pipe linked to a pair of bag bellows, or perhaps under optimal conditions through a constant directed wind. The position of the tuyere is critical, but in other respects the nature of these furnaces is simple, with little in the way of any recognisable features (*Fig. 16*).

A successful smelt may be carried out if attention is paid to maintaining the temperature within a fire (i.e. a bright yellow-orange colour seen beneath a dark surface indicates an interior temperature of between 1050 and 1100ºC; see *Fig. 17*),

Abb. 14: Smelting copper ore using bag bellows within a simple pit furnace clamped with a turf 'lid'. – Aufschmelzen von Kupfererz mit Blasebälgen in einer einfachen mit Torfsoden ausgekleideten und abgedeckten Schmelzgrube.

Abb. 15: Smelting copper ore within the embers of a large wood fire at Pločnik, Serbia in 2013. – Aufschmelzen von Kupfererz in der Glut eines großen Holzfeuers in Pločnik, Serbien, im Jahr 2013.

Abb. 16: The surviving evidence of smelting within a simple unlined pit furnace, Cambridge 2012. – Überrest des Schmelzvorganges in einem einfachen, nicht ausgekleideten Grubenofen; Cambridge 2012.

Abb. 17: Looking down the clay tuyere into the furnace during a smelt. The flame colour indicates a temperature of about 1100ºC. – Blick durch die Lehmdüse in die Schmelzgrube während des Schmelzprozesses. Die Farbe der Flamme zeigt eine Temperatur von etwa 1100°C an.

by facilitating the presence of reducing conditions (a blue-mauve colour flame upon the surface), by allowing sufficient time for a smelting conversion to take place (indicated by a strong green colour to the flames; *Fig. 18*), and through the prevention of too much oxidation. A second green flame 'event' will almost certainly indicate that the smelted copper is already being re-oxidised, a cindery mass of red copper oxide being the end result. This re-oxidation process can be halted fairly immediately 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 simplest Bronze Age copper smelting furnace may just be a controlled fire, with or without a pit underneath, and perhaps also with the traces of a burnt turf surround or capping. We should be aware of this when trying to identify such activity within the archaeological record. For without slag, cinders, metal prills or ore being visibly associated with the charcoal and ash, the recognition of an early furnace may prove quite difficult. In fact some of these features may well have been identified as domestic hearths, and vice versa.

Our experimental experience of constructing 'Bronze Age type' furnaces enables

Abb. 18: Green and mauve coloured flames issuing from the top of a small pit furnace. This indicates reducing conditions as well as the commencement of copper smelting. – Grüne und fliederfarbene Flammen schlagen aus der Spitze eines kleinen Grubenofens heraus. Dies zeigt eine reduzierende Atmosphäre im Inneren der Grube sowie den Beginn der Kupferschmelze an.

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). Very careful examination of any sediments associated with potential hearths may be the deciding factor here. 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 (*Fig. 19*), may be all that remains of this process; most of the product having been removed in prehistory following careful sorting and picking (see Williams 2013 re. Pentrwyn, Great Orme). Charcoal, however, is a great adsorber of heavy metals, and because of this, geochemical soil sampling using a PXRF may be the best initial way to determine the likely metallurgical function of a burnt pit (Jenkins, Timberlake 1997,). Clearly there are always other possible explanations for pits or hearths associated with copper anomalies, yet this method does have potential in the search for the very earliest evidence of smelting and metallurgy (Timberlake 2007; Jenkins, Timberlake 1997).

Conclusions

The practice of predictive experimental archaeology might well be considered to

Abb. 19: A conglomeratic slag cake enclosing prills (droplets) of copper formed during the smelting of a self-fluxing oxidised copper ore. Pločnik, Serbia 2013. – „Schlackenkuchen"; Konglomerat mit eingeschlossenen Kupfertropfen, die sich während des Schmelzens eines selbstfließenden, oxydierenden Kupfererzes bilden, Pločnik, Serbien, 2013.

be an extension to normal experimental archaeological design, in that it is a logical step forward to using experimentation as a means to predict the nature of evidence present but not recognised within the archaeological record. As has been shown above, the mining and early smelting activities can be both difficult to interpret, and occasionally invisible. Yet the continuing search for the very first evidence of extractive metallurgy in Europe (particularly in Britain where the evidence for this remains slim) must be one of the challenges still facing archaeo-metallurgists. Therefore anything this approach can offer to the investigation should be welcomed.

Hopefully the case study evidence presented here alongside this discussion of the methodology and principles associated with predictive experimental archaeology will be useful in shaping the design of future work. Indeed, it is an interesting concept in itself that one can potentially understand things not yet discovered about the past, just as one can use this as a tool to guide the on-going process of archaeological excavation. In this case archaeologists undertake experimentation on-site during the course of archaeological excavation, whilst being fully 'immersed' in the activity of those who they are investigating from the past. However, there are dangers in this approach, and we should be aware of the potential pit-falls. In particular we cannot always be certain that we aren't sometimes just dealing with fortunate coincidences (or perhaps calculated guesses) when we predict the find of some artefact or evidence of tool use. For instance, there may be two or more different ways of doing something and producing the same residual evidence. Similarly we might make the false assumption that on finding one or two predicted artefacts we are looking at a truly representative selection of what was used. We might even convince ourselves that we are looking at something that we are not. The full and very careful subsequent excavation of a site(s) will prove whether this is the case, just as a measured response in announcing the findings will add certainty to the experimental results. Furthermore, one should try to adhere to Cole's principled basis on carrying out experimental archaeology i.e. that all experiments need to be repeatable, with broadly speaking the same sorts of results.

The experimental investigations described here are of value in themselves given the questions being tackled and some of the insights gained. This work has shown how hard rocks may be mined effectively using just unmodified cobbles held in twisted and bent hazel withy sticks, and also how antler picks may be used against hard quartz-veined rocks during the mining of metal (just as they are used upon chalk during the mining of flint). Similarly it has be shown that it is possible to mine fine-grained sub-visible gold from hard rocks using stone tools, processing this on stone mortars and grind-

stones, then washing away the lighter stuff to recover gold; this being a technique used on-site as a means of continual assay within a variable orebody composed of hematite veins with different gold concentrations. Experimental archaeology has also been crucial in the understanding and reconstruction of the earliest (and probably simplest) smelting furnaces, the archaeological footprint of which we can predict, yet have little evidence for.
Hopefully this approach to experimental archaeology, and the ideas behind it, will be field-tested in other areas of former craft and technology reconstruction.

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