Archaeometallurgy 1962-2013: The establishment of a discipline

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ABSTRACT: This paper charts the development of archaeometallurgy through the last fifty years. The situation existing in the 1950s is described, followed by the principal developments through the succeeding half century, with some achievements, continuing problems and future directions outlined. The paper is mainly focussed on early mining and extractive metallurgy in the British Isles and Europe, and covers topics such as excavation, scientific examination, provenance studies, ethnographic recording and experimental replication. Much has been achieved through the life time of the Historical Metallurgy Society, but there are still plenty of challenges ahead!

Introduction[1]

The last half century has seen remarkable progress in archaeometallurgy, comprising the integration of history, archaeology and scientific investigation with metallurgy. As reflected in the title of this article it is an account not just of progress but of the establishment of archaeometallurgy as a discipline. It is salutatory to reflect on the state of the study of early extractive metallurgy and metalworking as it existed up to end of the 1950s and in some cases beyond.

With few exceptions there was a general perception that there was little to be learnt from the study of the surviving physical remains of early mining and smelting operations[2]. For example the great historian of science, George Sarton, in his authoritive history of classical science and technology regretted the lack of contemporary written sources on Greek and Roman smelting, expressing with some exasperation that the surviving physical evidence was impenetrable: 'The history of ancient mining is almost dateless; slag heaps are the best evidence but it is impossible to say when they were built' (Sarton 1959, 377). This seems to have been at least the unconscious attitude of those archaeologists given the apparently thankless task of excavating old mine sites. Buildings and burials tended to have been excavated and complex structures such as defences and the bath house reported in detail, but evidence of the actual processes – those slag heaps – were generally ignored. Indeed shapeless, formless heaps that were often of very considerable extent, and in this author's experience, usually remarkably devoid of artefacts in the usual archaeological understanding; what was the point of investigating them further (Fig 1)?

The received wisdom for prehistoric extractive metallurgy was even more bleak, it was commonly believed that later mining operations were likely to have destroyed all evidence of any prehistoric workings (Fig 2) (Slater 1985), and thus with just a few exceptions little investigation was carried out on prehistoric workings[3]. In the British Isles this belief had become so engrained that it was treated as an unchallengeable axiom. Thus

Figure 1: Typical Roman copper-smelting slag heap at Be Ora, Wadi Timna, Israel, in 1976, with Beno Rothenberg in the left foreground. These slag heaps are the surviving physical remains of the smelting process, but before the involvement of scientific investigation it was not clear what information was to be obtained by excavating such obviously formless structures.

when Oliver Davies carried out his excavations at a number of ancient copper mining sites in Wales in the 1930s and 1940s (Davies 1939; 1947) he automatically assumed they were of Roman date, although even in his initial reports he had difficulty explaining the apparent exclusive use of stone mining tools. Subsequently the Roman date of these mines was challenged, it was pointed out that the mines did not fit in at all with the known system of roads and forts and even more problematically the excavations had failed to produce a single sherd of Roman pottery. Thus they were assigned to the Dark Ages and later. No one in the mid 20th century seems to have considered the possibility that they could have been earlier[4]. Indeed, when it was first suggested in the 1970s that some of the mines with stone hammers could belong to the Bronze Age, this was initially quite widely and vigorously contested[5].

Figure 2: The 18th and early 19th century opencasts at Parys Mountain, Anglesey, North Wales. A classic example of complete degradation and destruction of the previous landscape, yet extensive underground workings of Bronze Age date have survived there.

The first European copper mine to be scientifically excavated and shown to be of great antiquity was Rudna Glava in the former Yugoslavia, excavated by Boris Jovanovic, first reported in 1971 (Fig 3), closely followed by the mines at Ai Bunar in Bulgaria (Černych 1978). The first to establish the true antiquity of the mines worked with stone hammers in the British Isles was John Jackson at Mount Gabriel (Fig 4) in Ireland (Jackson 1968; O'Brien 1994), although this was not universally accepted[6].

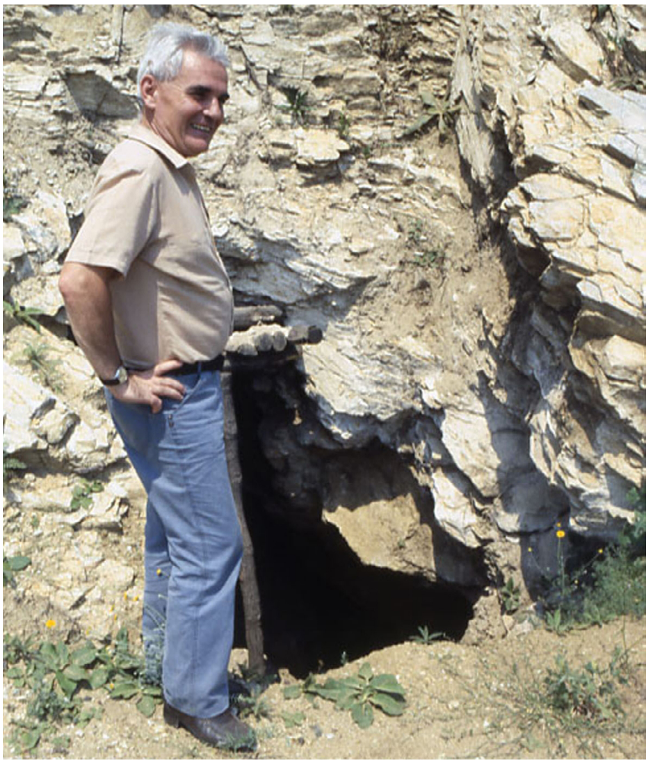

Figure 3: Boris Jovanovic at Rudna Glava in 1985.

The recognition of the survival of the remains of early extractive metallurgy all over Europe was immensely aided by the widespread application of radiocarbon dating from the 1950s on[7]. This was only the most conspicuous of a range of scientific techniques that began to be applied to archaeological investigations from the mid 20th century. In particular developments in analytical techniques such as X-ray fluorescence, atomic absorption spectrometry and induced coupled plasma spectroscopy to determine composition, X-ray diffraction and Raman spectrometry to determine molecular structure, and above all, scanning electron microscopy with micro analytical facilities, have together revolutionised our ability to extract information from the previously formless debris of the slag heaps. Following the initial work of Michael Tite on ceramic bodies it is now possible to determine the maximum temperature attained on furnace

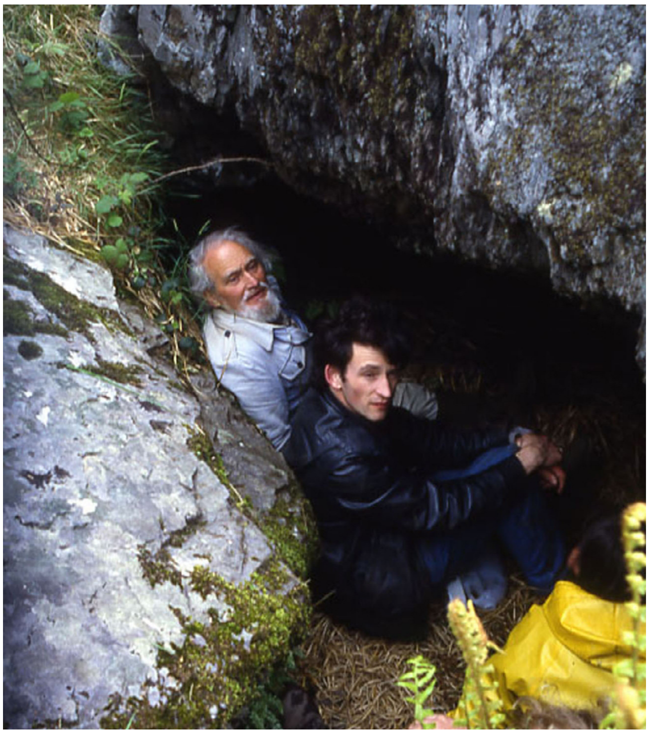

Figure 4: John Jackson (left) and Billy O'Brien (right) together down an old working at Mount Gabriel in 1986.

linings, crucibles etc by the degree of vitrification. The extent of the penetration of the vitrification into the clay body from the surface gives information on the duration of the process at high temperature (Fig 5) (Freestone and Tite 1986). The slags (Fig 6a) which clearly had set just moments away from the actual process would be a record of that process if only they could be read (Morton and Wingrove 1969; 1972; Bachmann 1982). Thin sections and SEM micrographs revealed the slags as being made up of complex mixtures of both amorphous and crystalline minerals, together with remains of unreacted ore, fluxes and entrapped blebs of the

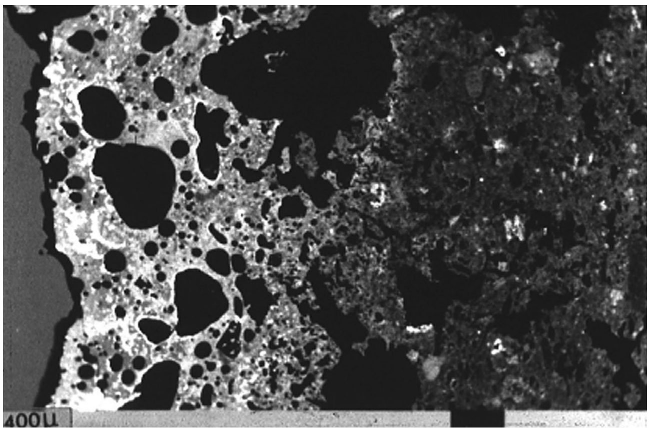

Figure 5: Backscattered SEM image of furnace lining from Timna, exposed side on left. The degree of vitrification and its penetration can give information on the maximum temperature attained and on its duration.

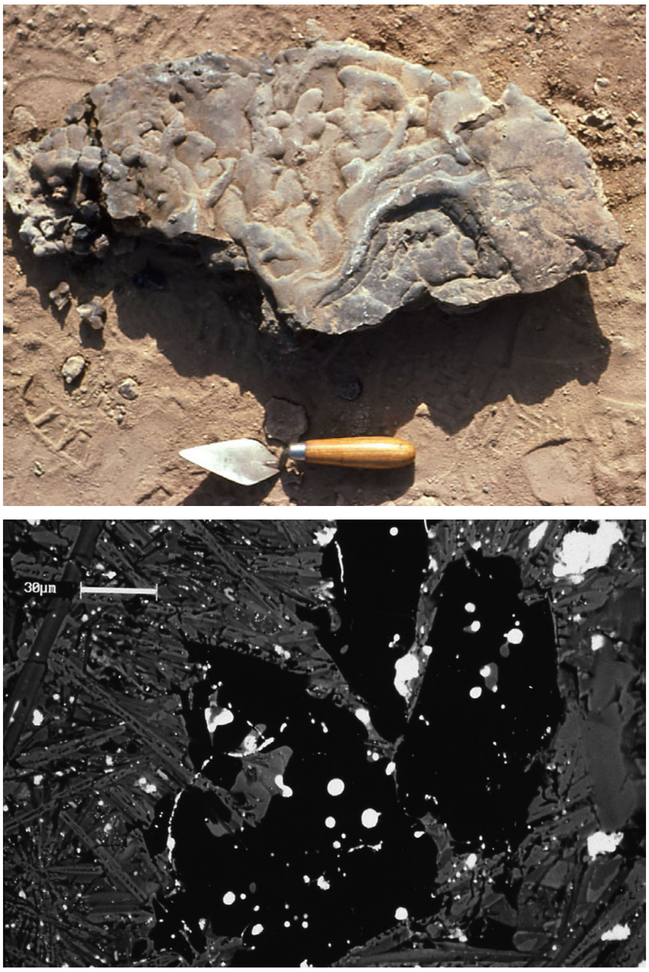

Figure 6: a) Tap slag from Mauryan period silver smelting operations at Site 7, Dariba, Rajasthan. Slags such as this were so obviously formed close to the process, yet without detailed scientific analysis are frustratingly mute. b) Backscattered SEM image of the slag showing large relict potassium feldspar (dark) with Zn-Fe-S and PbS inclusions (light) surrounded by dendritic olivine and hyalophane (grey), all indicative of the materials charged and the smelting conditions.

freshly smelted metal (Fig 6b). The overall composition gave information on the ores and fluxes charged, the blebs of metal gave some insight into the purity of the smelted metal, and their quantity remaining in the slag provided an indication of the efficiency of the process. The mineral species present gave information on the reducing conditions as well as the temperatures prevalent in the furnace, and thus the scientific study of material properly excavated and sampled from the slag heaps now routinely provides the evidence for the main operating parameters of the smelting processes.

Perhaps the first and certainly the most influential scientific programme of archaeological research on early extractive metallurgy was that initiated by Beno Rothenberg at the copper mines in the Wadi Timna in southern Israel (Fig 1), where the excavations were fully integrated with an extensive scientific research programme, with the scientists actually being present on site coordinating sample collection and excavation strategy (Rothenberg 1972; 1988; 1990; Conrad and Rothenberg 1980). Initially scientists such as Alexandru Lupu, Hans-Gerd Bachmann and Ronnie Tylecote were involved, but this expanded to include institutions, notably the Deutsches Bergbau Museum, Bochum, the British Museum Research Laboratory and the Institute of Archaeology, London, developing novel research programmes based around the debris of the mining and smelting processes[8]. From these beginnings coordinated archaeological-scientific projects have proliferated, initially in Europe, but rapidly spreading, such that the smelting processes used to produce a wide variety of metals all over the world have been established.

It is clear that many of the very earliest smelting processes everywhere produced little permanent debris, and may well have been carried out in crucibles (Craddock 1995, 126-44; see also some of the following papers in this volume). A broad trend that has become clear in investigations everywhere is the prevalence of wind-blown smelting operations. Back in the mid 20th century it was recognised that wind-blown bole furnaces had operated in remote locations across medieval Europe to smelt lead, and this was perceived as a primitive and wasteful process only suited to smelt a metal whose ore was very plentiful and cheap. Since then the remains of wind-blown smelting operations have been located globally from at least the Early Bronze Age onwards (Craddock 2001). They are usually sited on the prows of hills and pointing into the wind, exemplified at copper smelting sites such those at Chrysokamino, Crete (Betancourt 2006), Feinan, Jordan (Hauptmann 2000) and at the Wadi Dara, Egypt (Castel *et al* 1998), all at the inception of metallurgy, as well as to much larger and later operations such as the quite major iron smelting operations at Balangoda in Sri Lanka, which flourished at the end of the first millennium AD (Juleff 1998) and the pre-Hispanic copper smelting operations in the Atacama Deserts of Chile (Mille *et al* 2013).

Provenance studies

Before the advent of true archaeometallurgical studies, the one area of scientific involvement with metals had been the vexed subject of provenancing the sources of metals used in copper alloy artefacts of the Bronze Age, and to a lesser extent those of gold. To this end tens of thousands of artefacts were chemically analysed to determine their trace element content in the expectation that this would enable the artefacts to be grouped compositionally and the metal located to source[9]. The first objective may have had some success (*eg* Northover 1980), but the actual provenancing to source was hobbled from the very start by the almost total lack of information on early mines, their geology and mineralogy; even their locations were unknown. Even more worrying, in retrospect, was that this was not perceived as a major drawback, rather it was believed that somehow ever increasing numbers of analyses and ever more sophisticated statistical treatments would eventually bring success. The projects were widely criticised from the 1970s on (Waterbolk and Butler 1965; Craddock 1976; Tylecote *et al* 1977; Pernicka 1999), where it was argued that local variations in an ore body coupled with the effects of beneficiation (Merkel 1985), recycling (Bray and Pollard 2012), and variations in smelting processes would make attempts to obtain a unique fingerprint for a given source difficult if not impossible. Subsequent detailed investigations of Bronze Age mines have revealed the complexity of the ore bodies worked as exemplified by the copper mines on the Great Orme, North Wales (Dutton and Fasham 1994; Ixer 1999; Williams, this volume).

Provenance studies were given a major boost from the 1970s by the introduction of isotope analysis, initially and still mainly based on the isotopes of lead, but now joined by the isotopes of copper, osmium and tin. Studies began with lead and silver but rapidly spread to copper (Gale and Stos-Gale1982) and overall most programmes have been carried out to determine provenance of early copper alloys based on a combination of lead isotope and trace element analysis. The ratios of the lead isotopes should be much less susceptible to changes caused by weathering of the ore body whilst still in the ground or by the smelting procedures than the trace elements. Also, with the increasing recognition and study of the early mines that would have provided the metals used in prehistory, provenancing began to have some form of reality. A notable success was the attribution of many of the very earliest copper alloy artefacts from Ireland and the rest of the British Isles to the mine at Ross Island in the south west of Ireland, confirming previous hypotheses based on typology and trace element analysis suggesting south west Ireland as a likely source (O'Brien 2004). Other sources in the British Isles proved to have less distinctive lead isotope ratios and the work of Brenda Rohl on British copper and lead mines showed the care that had to be taken in the surveying and sampling the potential sources (Rohl and Needham 1998). Unfortunately many lead isotope projects have gone ahead without such reliable and necessary source data. In addition many copper sources have radiogenic ores, among them Mount Gabriel, Great Orme and some

Cornish deposits, to mention just a few sources from the British Isles. This could result in wide variation in the lead isotope ratios from within one deposit. However, such divergent lead isotope ratios are not apparent in the copper alloys used in the British Bronze Age so far analysed.

As with any new and developing methodology there have been controversies and disagreements (*eg* Budd *et al* 1993, replies and counter replies; Scaife *et al* 1999) and the results of some projects have been surprising, and controversial in themselves. Thus for example a large hoard of copper ingots from the Bronze Age mine at El Maysar in Oman have a lead isotope signature that is not only totally different from the ores lying in the ground a few metres away, but are unlike those of any known source from within Oman (Prange *et al* 1999; Prange 2001; Weeks 2007). A more widely discussed case is the Bronze Age copper ingots of Mycenaean oxhide type from Sardinia (Sanna *et al* 2004). These have been known for many years and were always assumed to have been smelted from the local ores by or for the Mycenaeans to trade back to the east Mediterranean. Lead isotope analysis showed that on the contrary the oxhide ingots were of Cypriot copper, and even more strangely this copper was apparently not used in the local copper alloy artefacts which were of Sardinian copper (Gale 1999). These results, at variance with expectations, could be taken as reasons doubt the validity of the method as whole, but a more positive approach is to see lead isotope provenancing studies as revealing something of the hitherto unsuspected complexity of Bronze Age distribution networks.

Ethnographic recording

Ethnographic parallels have always been important in the study of all aspects of early technology. The accurate recording of processes, postulated for past societies but still being carried out in remote locations by traditional craftsmen or women who are expert in them can provide invaluable information both in assessing the validity of the reconstruction of the ancient process concerned as well as aspects such as their productivity etc. Thus, for example, the weight losses encountered during the modern replication bloom smithing operations seem extraordinarily high (Crew 1991), but accurate records made in India in the mid 19th century of the traditional *Agaria* iron smelters showed that losses of approximately 50% were usual during the smithing operation to convert the freshly smelted iron bloom into bar iron (Percy 1864, 266).

Figure 7: Traditional copper smith at Fez, Morocco in 1985, but the vessel was made from sheet copper bought in from a stockist, not raised or sunk in a traditional manner.

Ethnographic recording faced increasing problems through the 20th century as traditional practices ceased or became infiltrated by modern materials and methods. For example, the smith photographed making a copper vessel in the 1980s at Fez, Morocco (Fig 7) was most certainly a traditional craftsman, but equally certainly he was not using traditional methods. His predecessors would have made a vessel by sinking or raising a disc of metal by hammering. The introduction of power-rolled sheet metal in the relatively recent past now means that all that the smith has to do is cut and bend the sheet, acquired from a stockholder, to the required shape and solder or braze the joins. Some extra hammering may be done as shown in the photograph to give a traditional appearance to the piece and to stiffen the metal by work hardening.

Not only have new materials and methods become disseminated but even ideas on the history of the processes concerned. Thus the author was discussing the origins of the Indian patinated zinc-alloy *bidri* wares with the proprietor of a long established workshop at Hyderabad in India in 1994, and was pleased and gratified that their ideas on the origins of the process coincided with those held by scholars in London. This gratification was tempered when Susan Stronge's (1985) book on *bidri*, published by the Victoria and Albert Museum, was spotted on the shelf above the proprietor's head. This raises concerns especially as increasingly the ethnographic record is not of the living technology, but rather the memories of the last practitioners, or even of elderly people who witnessed the processes as children, often after considerable lengths of time (Juleff 1998; Schmidt 1997).

From the forgoing it might be thought that there was no point in continuing ethnographic recording of traditional processes and the local knowledge of them in a world where modern materials and information are so invasive. The answer must in the affirmative, both for information on past processes, but now mainly to record the ongoing reactions of the traditional processes in a world of rapidly changing technologies. In extractive metallurgy very often this led to the termination of the traditional processes (Craddock 2009), but in some instances adaptation has taken place[10]. Just occasionally, traditionally processes have survived apparently in isolation, as exemplified by the distinctive copper smelting technology practised by Nepalese smiths of Sikkim and Bhutan in the foothills of the Himalayas, recorded by Blandford in the mid 19th century and included in Percy's *Metallurgy* (1861, 389-90; Fig 8a). This was a *matte* smelting process for the extraction of copper from chalcopyrite ores in distinctive furnaces/hearths. Seemingly nothing more was heard of the process until the early 21st century when it was discovered still in operation by the Norwegian archaeologist and anthropologist, Nils Anfinset, smelting locally mined copper ores at Okhabot in Western Nepal (Anfinset 2011; Fig 8b)[11].

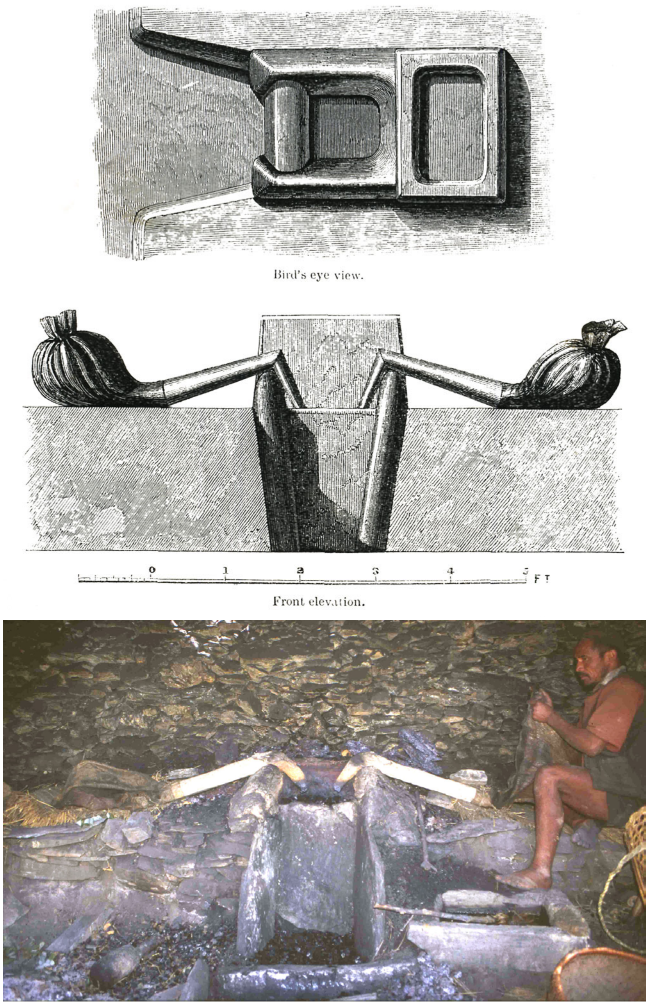

Figure 8: a) Copper matte smelting process of chalcopyrite ores by Nepalese smiths in Sikkim as recorded in the 1850s by Blandford and reported in Percy's Metallurgy. B) The process that continued at the village of Okharbot in western Nepal until the 21st century.

Experimental archaeology

Through the last sixty years replication experiments have become an integral part of the research into ancient technologies (Dungworth and Doonan 2013). Within the framework of archaeometallurgical research this is both to demonstrate that the postulated processes actually work and to establish many parameters such as fuel consumption, labour requirements, blowing arrangements etc that can only be determined by recording a working process.

Experimental archaeology was certainly around in the 1950s, but could be fairly amateurish, fun to play at, but often not sustained, poorly recorded and rarely properly reported[12]. Amongst the first to recognise the importance of carefully conducted and recorded smelting experiments was R F Tylecote on both ferrous and non-ferrous metals (Tylecote and Boydell 1978; Tylecote and Merkel 1985; Merkel 2013; Doonan and Dungworth 2013). Much of the work on non-ferrous smelting was inspired by, or part of, the Timna project (Merkel 1990; Fig 9).

Figure 9: Smelting experiments conducted by John Merkel (left) with bellows slave Brenda Craddock (right), to replicate the LBA copper smelting at Timna.

Other experiments were carried on to investigate the fate of minor and trace elements in copper ores during their smelting to determine which elements were likely to be the most useful in provenance studies, as mentioned above (Tylecote *et al* 1977).

Many projects from the last half century could be mentioned but the sustained research programmes of Peter Crew (1991; 2013) has placed our understanding of the early bloomery iron smelting processes on a much firmer basis. The experiments have demonstrated the immense labour expended to convert ore to artefact (see also Ethnographic recording, above) and have also suggested very different reconstructions from those proposed previously for the often sparse remains of excavated iron smelting furnaces of the European Iron Age.

The experimental replication of the wind-blown iron-smelting furnaces excavated by Gill Juleff (1998) at Balangoda, Sri Lanka, showed that the postulated form of the very-unlikely-looking smelting structures not only worked but produced large quantities of iron with an appreciable carbon content, such that Juleff (1998, 218) speculated that this iron might have been the famed *sarandibi* from Sri Lanka in the later 1st millennium BC, rather than crucible steel as had been previously assumed.

Smelting experiments can also lead to unexpected discoveries. For example, tin metal is quite rare in Bronze Age founder's hoards that regularly include copper ingots along with the bronzes[13]. It has been frequently suggested that one reason for this is that the tin was transported from the mines in form of the beneficiated cassiterite mineral and thus easily missed, and that bronze might have been produced either by co-smelting copper and tin ores, or by the addition of cassiterite to the molten copper in a crucible under charcoal (Charles 1975). Experiments by the Early Mines Research Group found this was perfectly feasible (Timberlake 2007) and gave a good bronze that was identical to ancient bronzes in all but one rather important detail. British Bronze Age bronzes have very low iron contents, typically of the order of 0.05%, but the bronzes made by co-smelting malachite and tin ores contained approximately 0.2% iron, presumably introduced from the cassiterite (Craddock *et al* 2007, 41). This suggests that usual Bronze Age practice must have been to make bronze by mixing purified tin and copper metals.

Hypotheses and speculations

Through the last fifty years archaeological investigations dedicated to sites of metal production, together with detailed scientific examination of the associated debris as well as the metals, all backed up by serious replication work, has transformed our technical knowledge of early metallurgy – from mining and smelting through the alloying, fabrication and decoration of the artefacts of the various metals used in the past. However, some broader questions seem to generate hypotheses, perhaps less reliant on a hard factual basis, as Colin Renfrew has remarked (1967, 276): 'Ideas and theories in Prehistory seem to have a life of their own surviving and flourishing quite independently of the evidence upon which they might be supposed to rest'. Indeed some seem to be based more as a reaction to the ideas of the previous generation. This is perhaps nowhere more apparent than in the vexed question of diffusion versus independent discovery, especially when applied to ancient metallurgy (Craddock 2011). Did the use of metals spread out from a very limited number of centres or did metallurgy develop independently at many centres? The old diffusionist models, as first seriously formulated by Gordon Childe (1957) were challenged and brought down by a combination of RC and CR, that is, radiocarbon dating and Colin Renfrew! Through the 1960s it became widely accepted that metallurgy had developed independently of the Middle East at least in the Balkans (Renfrew 1969) and in the Iberian Peninsula (Renfrew 1967), and probably at other centres as well.

Even then, James Muhly (1986), writing about the move away from diffusion to independent discovery, presciently observed that 'opinion has swung from one extreme to the other and we are now at the far side of the swing of the pendulum.'. Now, thirty years on, diffusion is back in fashion with claims that the various skills needed for extractive metallurgy would have been beyond the capabilities of the indigenous Neolithic communities to have developed independently (Roberts *et al* 2009).

The role of the Beaker Culture in the dissemination of metallurgy through much of Western Europe in the latter part of the 3rd millennium BC exemplifies the changes in these paradigms very well. The Beaker peoples were originally perceived as nomadic tinker-pastoralists, exploiting metal deposits as they came across them on their travels and disseminating the resulting metals amongst the indigenous population (*eg* Case 1966). Then from the 1960s they became downgraded from a real people to a 'peer-polity interaction' (Renfrew 1987, 236). More recently however, the presence of Beaker activity at the late third millennium BC copper mines at Ross Island (O'Brien 2004), as represented by their distinctive pottery, seems to have reinstated the Beaker culture as being the first to exploit the metal resources of Ireland, in fact doing just what they were traditionally supposed to have done! Similarly the scientific tests on the bones and teeth of the Amesbury Archer, recently excavated from a Beaker grave near Stonehenge, suggested that he had been brought up far away, possibly in Central Europe before moving to Britain (Fitzpatrick 2011). Furthermore, amongst his beakers and other grave goods, he had a polished stone believed to have been used in some metalworking operation. Here again the Beaker folk are back as real travelling people, and involved with metalworking.

Forward

Irrespective of the perceived cyclic nature of some archaeometallugical speculation, as discussed above, it is possible to determine some of the present gaps in knowledge and how they may be addressed in the future.

There are major problems in understanding the very earliest processes not least because they apparently produced so very little durable debris, which makes the smelting sites difficult to locate as well as to study. It is challenging to attempt to reconstruct processes from negative evidence. Studies have been carried out on the tiny amounts of slag that have been recovered, from some sites, but given their scarcity, are they typical of the process being carried out at these sites as a whole? It is also difficult to understand why the so-called slagless processes were resorted to, especially as even the simplest smelting processes recorded in India and Africa in the last two centuries all routinely treated copper-iron-sulphide ores and produced slags without difficulty, as exemplified by the primitive but effective *matte* smelting process carried out in the southern Himalayas (see above and Fig 8).

There is still uncertainty over which copper minerals were smelted and when in the western European Bronze Age context, especially concerning the first use of the copper iron sulphide ores, chalcopyrite and bornite, as discussed in several of the other papers in this volume. It was once believed that the copper-iron-sulphides must have been exploited by the Bronze Age in the British Isles as exemplified by Ross Island (Ixer and Patrick 2003) and Cwmystwyth (Timberlake 2003a; 2003b). However there were always problems understanding the chemistry of the smelting process that somehow removed the iron from the molecule without forming a slag, or of a refining process that removed the iron from the copper to below the levels found in recent fire-refined copper but somehow left the arsenic and antimony contents intact (Craddock 1995, 136-7; 1999; 2011). More recent studies, as exemplified by the papers in this volume, have established that it is likely to have been the secondary oxide and tetrahedrite ores that were the first to be exploited rather than the primary copper iron sulphides. Experimental smelting will be of continuing use in resolving these problems (*eg* Bourgarit 2007; also several of the following papers in this volume).

The location of prehistoric mines is also still problematic. Hard rock deposits that were worked with stone hammers are now well documented but, taking the British Isles as an example, the stone hammer mines do seem to be concentrated in a band running across the centre, there seem to be no hammers in the south or in the north, yet it is difficult to believe that the ores of the south west and of the north of Britain were not exploited in prehistory[14]. More indirect techniques picking up the effects of mining activity on the surrounding environment may be of assistance, as exemplified by the recent work on speleothem analysis which recorded high levels of lead pollution in the vicinity of the lead mines at Charterhouse on Mendip, Somerset, in the late Bronze Age contemporary with the Wilburton phase bronzes which were often alloyed with lead (McFarlane *et al* 2013)[15]. Environmental studies, examining sediments laid down at the time of mining operations for heavy metals, such as those conducted by Tim Mighall (*eg* Mighall *et al* 2007) are also likely to locate previously unrecognised areas of early metal mining, as well as recording the overall environmental impact of those operations.

Identifying and dating early mines is not just a problem for prehistory. Many of the mines now recognised as belonging to the Bronze Age, at least in their inception, were formally ascribed to the Romans, as exemplified by Oliver Davies' 'Roman' mines (see above), such as Parys Mountain (Davies 1939), where the early working has now been shown to be of Bronze Age date (Jenkins 2003). It will be necessary to look for new evidence to establish Roman activity. This will be much more difficult than with the prehistoric mines, the latter's stone tools and characteristic rounded and bruised working faces are very distinctive, but the Roman workings are not dissimilar to post medieval workings as exemplified by those at Engine House Lode at Alderley Edge, once assumed to be post medieval, but now shown to be Roman (Timberlake and Prag 2005; Fig 10).

Moving from extractive metallurgy to metalworking, it was only during the last 60 years that mould fragments and other refractory materials were first recognised on

Figure 10: Engine House Lode, Alderley Edge. Note the narrow shaft with grooves made by a steel pick alongside the Bronze Age pit (left), both cut by the 19th-century trench working. The grooved shaft was considered to be post medieval until a Roman coin hoard was found in an adjacent shaft.

prehistoric sites, and now every other Late Bronze Age or Iron Age settlement seems to turn up some evidence for metal casting operations, for instance the tools and mould fragments for the lost wax casting of bronze horse terrets at Gussage All Saints, in Wiltshire (Wainwright 1979; Foster 1980). Similarly the excavations at major post-Roman urban sites have produced large quantities of metal working debris. Careful study backed up by detailed scientific examination in a number of cases has revealed a great deal of information of early medieval metalworking practices as exemplified by York (Bayley 1992) and Dublin (Bayley 2013). It is to be expected that much more evidence of this nature will be uncovered, recognised and studied at dedicated institutions such as English Heritage's laboratories to provide yet more information on metalworking processes of all dates.

Finally, the excellent initiative of English Heritage to record the remains of more recent industrial processes and to schedule exemplars of these, was both far sighted and very welcome (Palmer and Neaverson 1995). However, with the decline of manufacturing in Britain many 'modern' extractive and metalworking industries have either closed or radically changed their procedures in the very recent past. These processes should be recorded before they are lost, and their operatives interviewed too. In 1968 the Institute for Mining and Metallurgy carried out a major survey of the companies engaged in extractive metallurgy, covering no less than 20 metals at 46 plants from all over the United Kingdom (Ryan 1968). None of these is now operational; how many were recorded before they ceased operation and were demolished?[16]

Notes

1 This review of archaeometallurgy is heavily biased towards Western Europe and especially towards Great Britain at the expense of equally important field work and laboratory investigations undertaken elsewhere. This is partly due to space limitations, but also to the subject matter of the papers in this issue to which this paper is to some degree an introduction.

2 Oliver Davies' Roman Mines of Europe (1935) is a notable early exception where all types of evidence were considered. Coghlan's two works on copper and bronze (1951) and on iron (1956) are serious technical histories of metals technology; otherwise R F Tylecote's Metallurgy in Archaeology (1962) represents the first real archaeometallurgical publication, produced at the time when the HMS itself was forming (Belford 2010) with Tylecote as the editor of its Bulletin.

3 Richard Pittioni's investigations of the Bronze Age and Iron Age mines at the Mitterberg (1951) are a well-known exception.

4 When considering the likely period when the stone hammers found at Cwmystwyth were likely to have been used, Hughes (1981, 6) vacillated between Roman and Dark Ages, but never considered the possibility that they could be of prehistoric usage. When the British mines were being reopened in the 18th and 19th centuries the miners had no problem assigning them to the pre-Roman Celtic world (Timberlake 2003a), and as the mine surveyor Lewis Morgan back in the 1740s so perceptively commented on the grooved stone hammers he encountered and illustrated from the Welsh mines, surely they must date from a period before the use of iron was known (Bick and Wyn Davies 1994). It was only later when archaeologists and historians became involved that problems started (see Note 7).

5 As exemplified by the following publications: Mount Gabriel (Briggs 1983; 2003; 2007), Alderley Edge(Worthington 1981) and Cwmystwyth (Hughes 1981; Briggs 2003; 2007). It was probably the conference at Plas Tan y Bwlch in 1989 and its publication (Crew and Crew 1990) that firmly established the reality of Bronze Age metal production in Great Britain.

6 The Bronze Age date was attacked in the premier British journal of prehistoric archaeology (Briggs 1983) with the truly bizarre alternative that the stone hammer usage was to be dated to the mid-19th century AD. Astonishingly this view is still being published (Briggs 2007). The development of the investigation of prehistoric metal mining in the British Isles has been summarised by Craddock (1994) and Timberlake (2003a).

7 Although Oliver Davies' assumption of Roman dates were considered unlikely in the 1950s or 1960s radiocarbon dating was not considered, possibly because no one contemplated that they could be prehistoric. When radiocarbon dating programmes of mines were finally initiated in Britain the first dates were obtained by amateur groups, eg by Duncan James at the Great Orme (James 1990) and the Early Mines Research Group at Parys' Mountain, Cwmystwyth and Nantyreira (Ambers 1990).

8 Following on from the experience gained at Timna other investigations of mines and extractive metallurgical process-

es were undertaken around the world, as exemplified by the ancient copper mines at Feinan, Jordan (Deutsches Bergbau Museum, Hauptmann 2000) and the Zawar zinc mines in India (British Museum, Craddock et al 1998). Much of Rothenberg's scientific research became based in the IAMS (Institute for Archaeometallurgical Studies) at the Institute of Archaeology, continuing the research work on the Timna material and replication of the smelting processes (Merkel 1990), together with new investigations, notably in Spain (Rothenberg and Blanco-Freijeiro 1981; Kassianidou et al 1995; Craddock 2013).

9 The earliest of these projects was that of the Sumerian Copper Committee of the British Society for the Advancement of Science back in the 1920s, but this achieved very little. Provenancing studies were revived in Germany after World War II when the usual analytical method was emission spectrography, with the first big projects published by Otto and Witter (1952), out of which developed the much larger Stuttgart project in which over 20,000 bronzes were analysed from all over Europe (Junghans, Sangmeister and Schröder 1960; 1968; 1974). Similar projects were set up in Sweden (Culberg 1968) and in the USSR where over 50,000 bronzes were analysed (Černych 1992, 16-18). A parallel project was established at Stuttgart to provenance Bronze Age gold (Hartmann 1970).

10 In India most of the traditional metal mining and extractive industries were discontinued by the early 19th century, despite some efforts to revive them, as exemplified by the zinc smelting processes (Craddock 2009). In the west of China, for a variety of technical and geo-political reasons the traditional zinc smelting process adapted and survived through the 20th century (Xu 1998; Craddock and Zhou 2003). Sometimes traditional processes can be preserved as heritage legacy as exemplified by the Japanese *Tatara* steel industry (Craddock and Zhou 1998).

11 Very recently Nils Anfinset returned to Nepal to record the process further, only to discover that production had ceased, although the smiths were able to conduct a smelt especially for him.

12 As Martin Bell (Bell *et al* 1996, xxv) trenchantly claimed for 1950s experimental archaeology generally: 'Certainly much that was subsequently claimed to be experimental field archaeology was qualitatively reduced to being what it actually so often was: weekend fun, uncontrolled, unrepeatable, short-term and scientifically nugatory.' Although things have greatly improved there can still be problems creating lasting and meaningful records of what was achieved, as discussed by Roger Doonan and David Dungworth (2013).

13 Before the discovery of the Salcombe Bay metal that includes both tin and copper ingots (Roberts and Veysey 2011).

14 The date when the elluvial and alluvial tin deposits on Dartmoor (Newman 2011) and the tin and gold deposits on the Mourne Mountains in Northern Ireland (Warner *et al* 2010) began to be exploited are all cases in point.

15 The possible prehistoric origin of the Charterhouse lead mines had already been suggested (Craddock 1994) and the lead isotope work of Brenda Rohl on Wilburton Phase bronzes had also suggested the Mendip Hills as likely sources of the lead (Rohl and Needham 1998).

16 In the introduction to the IMM survey (Ryan 1968) F D L Noakes, the then chairman of their metallurgical committee, justifying the need for a survey of the non-ferrous extractive metallurgical activities in the UK, stated that 'Most of us fail to look at things nearby, simply because they are nearby and will be there next week or next year'. As things were to turn out this warning against complacency was to be all too prescient.

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Figure 6b is by N D Meeks, Figure 8b by N Anfinset and Figure 9 by C Meredith; the other photographs are by the author.

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