Early Metal Mining and Production

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Introduction, History and Methodological Approaches

The study of the history of mining and metallurgy has an excellent and comprehensive literature both in terms of thriving journals and standard texts. Any new book on the subject has to be carefully targeted if it is to be of any value; fortunately, current, flourishing, research is constantly raising new vistas and challenging old ideas.

There is a wealth of published information, particularly on the processes used in later periods, and there are many excellent general surveys of the subject, of which the works of the late R. F. Tylecote are pre-eminent (see Bibliography). However, archaometallurgy is currently evolving very swiftly and our perception of many aspects of the development of metal production in antiquity, as well as the methods used to study the subject, have changed considerably, even in the short time that has elapsed since Tylecote's last works were published shortly before his death in 1990.

This book aims to emphasise some of the more significant recent advances within the framework of a more general world-wide coverage. The exploration and excavation of early mine and smelting sites reinforced by the scientific investigation of the production debris excavated from them, the continued publication and study of the contemporary technical texts, and experimental reconstructions of early processes are all currently providing new insights into the technical processes behind metal production and the overall development of metallurgy through almost ten millennia. Some of these new approaches are considered later in this chapter.

The book sticks very firmly to an understanding of the various processes used in the past based on the surviving material evidence, which is augmented where applicable by relevant documentary or ethnographic evidence. There is little attempt here to integrate the metal technologies into the overall social or economic life of the communities that used them. This is in part due to the purely pragmatic limitations on the size of the book and of the author's knowledge and experience.

The work seeks to confine the discussion to the level of information that can be obtained directly from the surviving material evidence. The composition of the materials can give far more unambiguous information on the technology of the process that produced them than on the society that made and used them. This is not to say that these are more certain or any less speculative than those in other areas of archaeology, but they are grounded on the immutable chemical properties of matter rather than on the much less perfectly formulated theories of the workings of human society.

History of Research into Early Metallurgy

There seems to have always been a strong interest in the history of metallurgy; it was only natural that miners should be curious about the 'old men' who had worked the ore bodies before them and left such tangible evidence of their presence. By the Renaissance this interest has permeated the first texts on mining and metallurgy. Thus, for example, Biringuccio, in the *Pyrotechnia* (Smith and Gnudi, 1942), and Agricola, in both the *De re Metallica* (Hoover and Hoover, 1912) and the *Bermannus* (Halleux and Yans, 1990), discuss and interpret the classical texts that deal with minerals and metals, principally, Pliny's *Natural History* (Rackham, 1952). Furthermore, this was often done in the spirit of academic inquiry rather than for any useful practical information that the ancient texts might still contain. This scholarly interest continued to flourish, and in the eighteenth century, for example, the metallurgy sections of Bishop Watson's *Chemical Essays* (1786) contained some very perceptive and informed comments on those books of the *Natural History* that dealt with metals. Thus, the strong historical bias so evident in the first modern scientific metallurgical texts such as Percy's great works (Percy, 1861, 1864, 1870 and 1880) can be seen as continuing this tradition. Percy's innovation was to include descriptions of a wide range of contemporary traditional metallurgical processes, and from these ethnographic examples he made the first attempt to construct a tentative history of the development of smelting technology (p. 171). His descriptions were based principally on reports he had garnered from within the British Empire, particularly from India and south Asia, and he could be surprisingly demanding and censorious of his sources. Thus after quoting the detailed and apparently excellent account of lead mining and beneficiation (given in Chapter 5, p. 163) and smelting (given in Chapter 6, p. 210) in India by Captain Dixon (1831), Percy caustically notes that

> Capt. Dixon was neither a mineralogist, geologist, miner, nor metallurgist; for otherwise his description would have differed much from what he has

> communicated. This is another illustration of the difficulty, not to say impossibility, of describing from personal observation a simple metallurgical process with necessary detail and accuracy in the absence of previous special education on the part of the observer. (Percy, 1870, p. 294)

His comments do have a certain relevance for later recording of metallurgical processes by some non-specialists, but in this instance one cannot help feeling he was being a little hard on Captain Dixon!

The sequence postulated by Percy for the development of metallurgy, based on surviving modern traditions, was necessarily simplistic. The whole study of cultural change was in its infancy, moreover only a very limited amount of ethnographic information was available to Percy when he wrote in the 1850s to 1870s, with little or nothing from Africa (see Chapters 5 and 7 for putative furnace typologies).

Accounts were published of some of the great early mines of antiquity reopened in the nineteenth century, notably Laurion (Cordellas, 1869; Ardaillon, 1897) and Rio Tinto (Nash, 1904), where the enormous scale of the early workings could not fail to impress those engaged in reworking them. These accounts were written by the mine managers and engineers rather than archaeologists. Archaeological survey of early mines had to wait until the twentieth century. Of these, the field survey of Roman mines and smelting sites carried out by Davies (1935) remains a classic, both in the thoroughness of the survey and the erudition of the interpretation of the sites.

In the later nineteenth century metallurgists such as Godfrey and Tookey (see Percy, 1880, pp. 340–3), Gowland (1915a) and Roberts-Austen (1888) who had all been working in Japan published details of the traditional methods of mining and metallurgy practised there. The work of Gowland was of especial importance as on his return to Britain he took a strong interest in archaeology and applied his knowledge of Japanese practices to interpret the remains of ancient metallurgy found in the west; hence the prevalence of Japanese woodcuts illustrating his excellent papers on Roman non-ferrous metallugy (Gowland, 1899, 1900, 1901 and 1917/18)!

Gowland's papers are probably the first major series of papers in English devoted to the technical study of ancient metallurgical processes, both on specific sites and more generally. His work integrates archaeology, ethnographic parallel and scientific analysis very successfully.

The analysis of ancient metalwork also has a long history. From the inception of real chemical analysis in the eighteenth century, antiquities were subjected to analysis. Thus in 1774, Alchorn, George III's assay master, was reporting the analysis of two Bronze Age swords from Ireland (Pownall, 1786), and Martin Klaproth, 'the father of analytical chemistry', included the analysis of Roman coins and mirrors in many of his publications of the late eighteenth and early nineteenth centuries (Klaproth, 1798, 1795–1815). Other early analyses of Bronze Age metalwork from Britain and Ireland were published by Mallet (1852). This interest in the scientific study of antiquities continued amongst famous scientists such as Davy, and eminent archaeologists such as Schliemann, who had analyses carried out on some of the bronze and silver artifacts from his excavations at Mycenae and Troy.

The development of physical analytical techniques in the twentieth century enabled analyses to be carried out much more quickly and with very much smaller samples than had hitherto been the case with wet chemical methods, enabling large-scale analytical projects to become feasible. Although some of these had simple descriptive or technical objectives, the most prestigious and largest sought to link the trace element composition of the metal with the typology of the artifact and to identify the provenance of the metal sources used. The first of these was the work of the Sumerian Copper Committee of the British Association for the Advancement of Science on Middle Eastern copper (reported annually in the *British Association* from the 1920s through to the 1930s). By far the largest were the projects that Otto and Witter undertook (1952), which were continued and much amplified by the SAM project (Junghans *et al* [1960, 1968 and 1974] for copper, Hartmann [1970] for gold) on the metalwork of the European Bronze Age. These projects inspired others such as Culberg (1968) for Scandinavia, and the Russians have carried through an immense programme of analyses on some 60,000 bronzes from the Eurasian land mass (Chernykh, 1992). These projects detached the composition of the metal from its primary direct link with the metallurgy of the artifact and made it no more than an adjunct of the typology. This move towards more indirect interpretative uses seems to be one of the reasons why projects like these have, overall, met with little convincing success.

During the nineteenth century academic interest in the textual evidence expanded enormously, including studies of early science and alchemy, culminating in the great works of Marcelin Berthelot (1888 and 1893) on classical and medieval alchemy. (These works seem strangely neglected as a source for early metallurgy, at least amongst English-speaking scholars.) Appreciation and understanding of other classical sources for early metallurgy also developed enormously during the late nineteenth century as exemplified by the extensive and generally excellent footnotes by Hoover and Hoover in their superb edition of the *De re Metallica* published in 1912, where the ancient sources are discussed at length. This continued into the twentieth century, exemplified by Bailey's work (1929, 1932) on the chemical subjects in Pliny's *Natural History*, and by C. S. Smith in edited translations of various European medieval and Renaissance metallurgical texts. This interest has also extended outside Europe, in works of translation and discussion such as Ray (1956) for India, Lo Bue (1981) for Tibet, Allan (1979) for Iran, Toll (1968) for the Yemen and Arabia, and above all Needham for China (see Needham, 1958, 1965 and 1974 for volumes which have a significant metallurgical content). More recently, significant new advances have been made by applying the knowledge obtained by the scientific examination of artifacts, or the excavation and study of the production sites, to the descriptions given in the contemporary early literature. The first can be exemplified by the specific identification of some exotic alloys of antiquity such as the much prized Corinthian bronze or the Egyptian *hśmn-km* by a combination of directed scientific analysis and careful literary study (Craddock and Giumlia-Mair, 1993). The case of *hśmn-km* (literally black copper) is especially instructive; it had been previously studied with great perception by the Egyptologist Cooney (1966) who was able to say a great deal about it, everything in fact except what it was! In the absence of any scientific input he went badly astray on the composition and thereby missed the all-important connections with other related copper alloys from around the world.

Site examination may be exemplified by the production of zinc in India. There are many contemporary references to the early occurrence of zinc and its production, all of which had been translated and published, but it took both a major analytical programme on early brasses and field work at the production site at Zawar in Rajasthan to bring out the real meaning and significance of the early commentaries, and together the two sources of information have reinforced and amplified our knowledge of the early process. (This is described in some detail in Chapter 8, partly as an illustration of the use of historical sources.)

Ethnographic descriptions of surviving traditional processes became much more detailed and fieldwork-based, notably in Africa as exemplified by Monsignor Hemptinne (1926, reported in Herbert, 1984, pp. 51–5) for copper smelting, and by Cline (1937) for iron smelting. Through the twentieth century this fieldwork has revealed a much greater diversity of smelting practice than was hitherto conceived of, the significance of which has still to be fully digested (Killick, 1992, and later on p. 261).

Metallurgists such as France-Lanord (Salin and France-Lanord, 1943) and Maréchal (1963) in France, Panseri (1963) in Italy and Smythe in Britain (see Tylecote, 1986 for many references to his work) began the serious metallographic study of early metal artifacts, and from this developed the work of Coghlan (1951, 1956, and Allen *et al*, 1970) and then of Tylecote. The publication of *Metallurgy in Archaeology* in 1962 and the establishment soon after of the Historical Metallurgy Group with its *Bulletin*, latterly the *Journal*, put the whole subject of archaeometallurgy on a serious footing, deeply grounded in archaeology, metallurgy and the physical sciences. This approach is exemplified in recently-published syntheses such as those presented by Tylecote (1962, 1976 and 1987), Moesta (1986), Maréchal (1983), Mohen (1990) or of compilations such as those edited by Craddock (1980), Craddock and Hughes (1985), Maddin (1988), Hauptmann *et al* (1989), Domergue (1989b), Crew and Crew (1990), Éluère and Mohen (1991) and Steuer and Zimmermann (1993).

The involvement with field archaeology continued, and the next developments were the major long-term campaigns of excavations at early mining and smelting sites. These were firmly focussed on the technology of the processes, based on the investigation of the mines and the contents of the slag heaps. These investigations required a new approach and methodology for the excavation and sampling of sites. In this the work of Rothenberg and his teams at the Bronze and Iron Age copper production site of Timna in Israel (Rothenberg, 1972, 1988, 1990b; Conrad and Rothenberg, 1980) and latterly the classical silver and copper production site of Rio Tinto in the south of Spain (Rothenberg and Blanco-Freijeiro, 1981) were of great importance in establishing the new approaches. The work of these teams and others demonstrate that many technologies first recorded in the post-medieval period in fact go back much earlier (see Chapters 2 and 5).

The investigation of early mine systems was pioneered by the Deutsches Bergbau Museum, Bochum, initially using a team of ex-coal miners from the Ruhr together with archaeologists and geologists at sites such as Timna (see the Bergbau Museum's journal *Der Anschnitt* for their work and that of other groups in Germany). Elsewhere teams such as the Early Mines Research Group's work in the ancient mines of Wales, and a team based on the Peak District Mines Historical Society, Derbyshire, now regularly investigate sites around the world (see the *Bulletin* of that society for reports on their work).

This specialisation has been reflected in the establishment of specific courses in archaeometallurgy and also of research groups engaged in the scientific study and replication of early metallurgical processes at a number of universities and museums around the world, from Beijing to Bradford, as part of the more general application of the physical sciences to the study of the past (Bowman, 1991). Institutions such as the British Museum and the Deutsches Bergbau Museum are now establishing collections of production debris documenting the development of extractive metallurgy and refining processes from around the world, from the ore through to the ingots (Craddock and Hook, 1987).

The establishment of archaeometallurgy as a distinct discipline with full-time specialist practitioners able to embark on long-term research has had major implications. The range of techniques applied to archaeology continues to expand as does their sophistication, such that it now requires scientists dedicated to the study of the material past to fully realise the potential of these techniques (see Tite, 1972, and journals such as *Archaeometry*, published by the Research Laboratory for Archaeology and the History of Art, Oxford, for descriptions of some of these techniques).

Through the majority of the twentieth century the trend in analytical technology generally was towards ever-increasing analytical precision and sensitivity over an ever-widening range of elements and even isotopes. This has opened up new possibilities of research in archaometallurgy. Developments in stable-isotope measurements have, for example, provided fresh impetus into the provenancing of metals (Stos-Gale, 1989, but see Budd *et al*, 1993 for a cautionary counterview). In the latter twentieth century the significant advances have been in revealing the structure of the metals, both radiographically and at very high magnification (see Cahn and Lifshin, 1993, for a comprehensive survey of the full range of analytical and examinational techniques currently available). In radiography the application of techniques developed for medical uses (such as xeroradiography) have made the whole process much quicker and cheaper than hitherto experienced. Major developments with image intensification (which allows continuous virtual real-time viewing) coupled with the flexibility and improved resolution of image enhancement admits the possibility, for example, of recording a video exploration around the inside of an object.

The techniques of electron microscopy have also undergone important developments, incorporating ever more sophisticated software to enhance the image produced. Scanning electron microscope systems have been particularly valuable in elucidating the structure of metals and of their production debris. Coupled with this have been advances in the associated micro-analytical systems that now allow compositions to be determined spatially, either as line traces across a surface or full analytical mapping, allowing the precise compositional and structural determination and identification of specific features at whatever magnification is required. New developments in the spectrometers attached to microscopes are enabling light elements to be determined with ever greater sensitivity, with important applications to the study of slags and refractories as well as to ferrous metallurgy. Thus overall as analytical systems continue to improve, the most significant recent advances for the study of early metals and metallurgy would seem to be in the ability to see structure and to relate this directly to composition.

Finally, the replication of early metallurgical processes has grown both in scope and sophistication of the recording, from the first recorded experiments on ancient Indian copper working technology, published in America in the late nineteenth century (Cushing, 1894), on through the twentieth century smelting replications with pioneering work on copper by Coghlan (1939–40) and iron by Richardson (1934). The later history of smelting experimentation has been summarised by Tylecote and Merkel (1985).

As in many other areas of research new technology has proved of great assistance, especially the lightweight and robust solid state monitoring devices. The advent of video systems has transformed the recording of these processes.

Problems and Potentials in Archaeometallurgical Studies

For this section, reference can be made to Craddock (1989).

Mines

The investigation of early mine workings requires very special skills, above all else practical experience in working underground, and it is very noticeable how many of those engaged in mine exploration have considerable experience caving or potholing. It must be stressed here that old mines can be extremely dangerous and parties entering old workings must include experts in the safe exploration of old mines, and of course all the safety procedures must be followed. Old workings are very often on the property of mines that are still operational and in these cases the company will normally insist that members of their staff accompany the party underground. In the author's experience, both in India and Spain it proved invaluable to have the experience and local knowledge of the geologists and mining engineers assigned to our team, as well as the logistical assistance the companies provided.

A very considerable expertise has now been built up by the specialist teams of early-mine investigators in the excavation and recording of early mines, often in extremely cramped conditions in old workings packed with waste material (*deads*). Note that the filling of the worked-out galleries with deads was often done very carefully in order to channel air to the working face or to direct the exit of fumes from firesetting etc, and thus the topography of the waste stacked underground should be fully recorded. Often little survives of the tools and

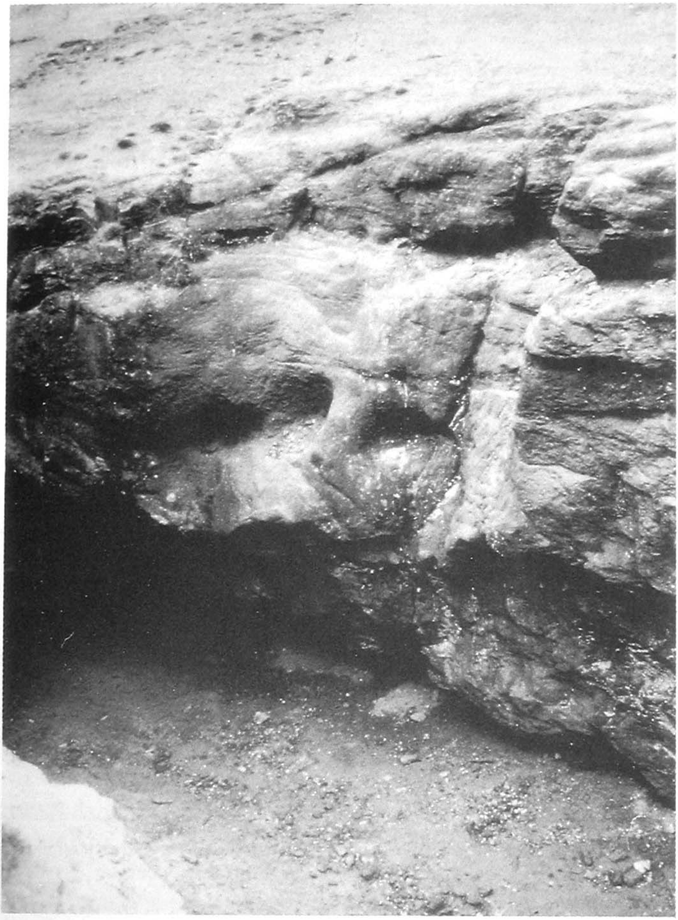


FIGURE 1.1 Four thousand years of mining history in one rock face, Engine House Lode, Alderley Edge, Cheshire. The diffuse pecking in the centre made by stone hammers in the Bronze Age, a small shaft to the right cut with steel stools, probably post medieval, and the jagged edges of the main trench caused by blasting in the nineteenth century.

supports within the mines, but the mining methods and the structures that once existed can be recognised from the often ephemeral marks that survive on the walls (Figure 1.1, Table 1.1 and Chapter 2). Underground workings are rarely of a single period, and with experience evidence for various campaigns of reworking can be recognised on the walls and related to the stratigraphy of the floor deposits by judiciously-positioned excavations (Willies, 1987 and 1992a; Weisgerber, 1989 and 1990 for example).

TABLE 1.1 Principal mine dating indicators.

Mining technique	**Evidence**	**Date range**	**Examples**
Battering with stone hammers	The stone hammers themselves, usually present in quantity. Often with pecked indentation or full groove (see Fig. 2.10)	Chalcolithic – end of Bronze Age	Alderley Edge, England (Carlon, 1979) Mt Gabriel, Ireland (Jackson, 1980) Rudna Glava, former Yugoslavia (Jovanovic, 1980)
	Diffuse bruising on mine walls (see Fig. 2.9)		Alderley Edge (Craddock and Gale, 1988) Timna, Israel (Conrad and Rothenberg, 1980)
Firesetting	Smooth walls with continuous curve, often coated with soot, thick layers of ash, charcoal and burnt rock	Chalcolithic – recent	Mt Gabriel, Ireland (O'Brien, 1980) Zawar, India (Willies, 1987)
Metal tools	Long thin scratches. Often parallel (see Fig. 2.9) Wedge-shaped pick marks	Late Bronze Age – recent	Timna, Israel (Conrad and Rothenberg, 1980) Rio Tinto
Blasting	Remains of drilled shot holes, very ragged appearance of mine wall	Late seventeenth century – present	Every modern mine

As well as revealing the technology and chronology of the workings, one of the primary aims is to obtain representative samples of the ore that was mined which is essential both for understanding the smelting technology and for provenance studies. However this is not always as straightforward as it would at first seem, especially in very early workings. Ore deposits are very heterogeneous, both in terms of the metals and their mineralogy (Thompson, 1958; Leese *et al*, 1986). The remaining ore is in a sense almost by definition the ore the old miners did not want. Thus at the Early Bronze Age copper mines at Cwmystwyth in central Wales, lead ore, galena and cerussite is abundant in both the mine wall and spoil tips, but hardly a trace of copper survives, the metal that was in fact being mined in antiquity. However, the real problems are both more subtle and serious than this simple example would suggest. It is reasonably certain that copper was the metal sought at mines such as Cwmystwyth, but it is much more difficult to try and establish which copper minerals were mined from a deposit in which virtually all the mineralisation has been removed. The remaining copper ore below the ancient workings is chalcopyrite, $CuFeS_2$; was it left because it was too difficult to mine or too difficult to smelt (see Chapter 2)? The Bronze Age mines at Mount Gabriel in County Cork, Ireland, give another example of this problem. The first reports claimed the ore mined in antiquity was a tetrahedrite or *fahl* ore from the secondary enrichment zone (Jackson, 1968). Further work, based on the very minimal mineral left behind, showed the only ore remaining was very finely disseminated chalcocite, Cu_2S from the primary sulphidic deposits, but it is now believed that the original deposit was likely to have been principally made up of oxidised minerals such as malachite from the secondary oxidised zones (O'Brien, 1990).

The same problems also exist in much later periods of exploitation as exemplified by silver ores (see Chapter 6). Many of the ore bodies worked in antiquity are now mainly composed of deposits of argentiferous lead sulphide, galena, PbS. However it seems likely that the principal mineral mined in antiquity from many of these deposits was argentiferous cerussite, lead carbonate, $PbCO_3$ (see Chapter 6, p. 213).

However, where it has been established which minerals were exploited then the ore remaining in the ancient galleries can give an indication of the minimum grade of ore that was considered worth processing. For example, at Rio Tinto (Craddock *et al*, 1985 and later on p. 216), a heap of argentiferous jarosite ore, assaying at about 100 ppm of silver was found in a Roman gallery. Studies on the contemporary slags from the mine suggested the Romans could not easily recover silver from ore below about 150 ppm. Thus the heap of mined ore is likely to have been abandoned after a trial assay had shown that the silver levels were just too low for economic recovery.

After mining the ore the mineral was concentrated by a variety of methods (see Chapter 5). These *beneficiation* treatments produce large quantities of regular-sized debris that is very recognisable and quite distinct from the coarse mine waste found in the immediate vicinity of the mine entrance. Samples of this should be taken as it gives information on the methods of beneficiation used and on the efficiency of the separation process, a vital stage in the overall production of the metal (see Chapter 5, p. 156 later, and Merkel, 1985 and 1990).

Collection and Study of the Debris of Smelting and Refining

The furnaces and other structures associated with metal production were in general fairly ephemeral and normally few intact structures survive. This can be both disappointing and difficult to interpret for the non-specialist archaeologist (see Chapter 5, p. 169 for the problems in reconstructing the shape of a furnace from the surviving fragments). However, the smelting and refining processes did produce large quantities of distinctive and durable debris and from the study of this material the principal process parameters can be established (Table 1.2). From the Bronze Age onwards the smelting processes produced quantities of slag which only very rarely will have been reprocessed or moved, thus the presence of slag in quantity on a site is usually to be taken as evidence of metallurgical activity of some kind, and metal smelting on any scale at all will result in quite substantial deposits of slag. Contained within the slag heaps there will be fragments of the furnaces together with other refractories such as the tuyeres and crucibles as well as remains of the ores, fluxes, fuel and even occasionally the smelted metal itself.

Until the very recent past information on early mine and smelting sites was obtained mainly from chance finds both below and above ground. However, many ore deposits have long and complex histories of exploitation, thus the remains of structures and various refractories lacking any archaeological context are undateable and consequently of little value. There has been a natural tendency to link remains of earlier activity to the known history, and archaeology is currently revealing the unexpected antiquity of many mine sites around the world as being in prehistory, long before any written record. Even the slag heaps are likely to have built up over long periods at some mines; the slag heaps at the Corta Lago area of Rio Tinto have built up over a period of three thousand years (Figure 1.2). These major heaps contain the material evidence of the production technologies stratified within the usually well-defined slag layers. These heaps can sometimes cover many square kilometres to a depth of several metres, and clearly archaeologists in the past have found them a rather daunting prospect and so instead have opted for excavation of the archaeologically more familiar burial grounds, road systems, ritual, military or domestic structures (the bath house is always a favourite on Roman sites), anything in fact which had some sort of deliberate recordable structure and offered the prospect of some recognisable artifacts. This reluctance to tackle the processes head on was understandable as until the advent of systematic scientific study it was not obvious what information could be got from the rather anonymous and shapeless debris that comprised the heaps.

TABLE 1.2 Potential information to be derived from excavated metallurgical samples.

Material	Information	Technique	Pitfalls
Raw materials ores, fluxes, clay	Nature of raw materials in furnace charge. Concentration of metal in beneficated ore. Identity of metal smelted	Quantitative analysis (AAS or ICP etc)	Are samples representative? Take samples from contexts such as pits where material was stored for use after preparation. Other ore fragments etc found on site were probably discarded
Fuel	Size of pieces; important parameter of furnace operation	Physical measurement	As above, try to obtain a sample that has not been crushed since burial
	Composition, as source of elements in the furnace charge	Analysis (AAS, ICP)	
Refractories	Temperature and duration of process	SEM study of vitrification	Identification of the refractory fragment and its location on the structure Important to ensure the fragment comes from the vicinity of the reaction zone. Possibility of confusing slagging/glazing with vitrification
	Nature of ceramic body	Petrographic study of unbloated thin section	
	Metal processed	XRF or spectroscopic qualitative analysis of contact surface	
Slags	Reducing conditions of process	Full quantitative analysis (AAS. ICP etc)	Obtaining dating material can be difficult, dateable artifacts rare
	Chemistry of process	XRD analysis, SEM study	
	Metal smelted, efficiency of separation	XRF or spectroscopic analysis	
Metal	Efficiency of process Composition before refining/alloying, important for provenance studies	Full quantitative analysis (AAS or XRF)	Ensure the metal is freshly smelted, not scrap for resmelting etc Corroded metal may not be representative

FIGURE 1.2 Section of one of the main ancient slag tips at Corta Lago, Rio Tinto, Huelva, Spain, cut by nineteenth century opencast mining, and being cleaned up for recording and sampling. The heap built up from the Late Bronze Age through the Carthagenian and Roman periods, culminating in nineteenth century debris at the top.

With the realisation that the key parameters of the processes were quite literally frozen within the slags and refractories, and the rapid advance in the scientific techniques necessary to reveal them, interest began to focus on the heaps (Craddock, 1989). Clearly what was required was a representative sample of associated material, ores, fluxes, furnace fragments and other refractories and slags, together with some indication of their date. This is achieved by the careful selection of a number of sample points over the heaps as whole, followed by excavation to obtain the stratified material. On extensive sites it can be useful to cut a series of sections by machine to establish the basic stratigraphy. This is then followed either by extensive sampling from the recorded sections or, ideally, area excavation down through the heap to obtain the sample that should be statistically representative of the various materials. It is necessary to resist the natural tendency to select the apparently interesting or unusual as part of the general sample. An unusual piece is unlikely to be a good candidate to represent the usual process. However, sometimes happy accident or unusual preservation can preserve a detail of the process. At Zawar in India, for example, many hundreds of the zinc smelting retorts were examined, some with the charge still inside revealing a small central channel. One retained not only the central channel, but the charred remains of the stick which had made it, showing that the retorts were charged into the furnace with the stick still in place to act as a stopper (Chapter 8, p. 313). This can apply to whole heaps as well, thus although the heaps tend to be fairly uniform there are sometimes concentrations of especially interesting materials, as exemplified by the small layer of silver smelting debris, including a small ingot of silver, at site 19a at Rio Tinto (p. 216), or the debris from the mine assay office dating from the fourth century BC at Agucha in India (p. 223). Thus it can be very rewarding to study carefully the contents of exposed sections.

Many of the most interesting and potentially informative materials such as *matte*, *speiss* or even the metal itself will be present as shapeless lumps and are very difficult to recognise in a slag heap. However, these are usually distinguishable by their density, thus one should try and handle as much material as possible, although this is not always easy on major sites.

Because the furnaces tend to be located away from the immediate vicinity of domestic occupation, and because the heaps grew so rapidly compared to ordinary archaeological deposits, pottery and other dateable artifacts tend to be rare, and thus the most prized find on a metallurgical excavation can sometimes be the few shards of pottery which provide a date. Very often physical dating techniques have to be relied on exclusively; carbon 14 dating is the most usual first choice given the quantities of charcoal that are found in the heaps from the smelting processes. The age of the timber selected for making charcoal should be borne in mind when taking charcoal samples for radio carbon dating. Most organised production from large smelting sites will have favoured quick-growing coppice wood, which is unlikely to be more than about twenty years old at the time it was burnt. However earlier, smaller operations were quite likely to have used whatever timber resources were to hand, and some could have been centuries old when burnt (note the massive root depicted in Figure 5.29). In general one should try and avoid featureless charcoal, selecting instead twigs or small-diameter round wood charcoal.

Archaeomagnetic dating has also been employed with some success, for example on some Romano-British iron smelting sites in the south-east of England (Clark *et al*, 1988). Prerequisites for this technique are some undisturbed baked clay and a knowledge of the history of earth's magnetic field for the region. Another approach has been to date the slags directly, either extracting small quantities of charcoal for accelerator mass spectrometry (AMS) radio carbon dating (Gillespie *et al*, 1984) or by fission track dating using alpha recoil, and thermoluminescence (although the latter techniques have not been widely applied) (Carriveau, 1974; Elitzsch *et al*, 1983).

Scientific Study of the Remains of Extractive Metallurgy

The study of the refractories and slags has been dealt with in detail elsewhere (refractories: Tite *et al*, 1982a and b, 1985 and 1990; Freestone, 1989; Freestone and Tite, 1986; slags: Bachmann, 1980, 1982a; Sperl, 1980; general: Freestone and Middleton, 1987 and Freestone *et al*, 1991), and here only an outline will be given of some of the main methods by which the principal parameters of the smelting processes are determined (Table 1.2 and Figure 1.3), concentrating on some of the practical difficulties of interpretation.

The various refractories, furnace linings, tuyeres and crucibles are often of quite distinct ceremic bodies, and the various clays and fillers used can be determined petrologically and compared to the local domestic coarse wares, collected for that purpose. In general, local resources were used with no obvious preference for more refractory clays, but a wide range of fillers were added. These are typically more coarse, and in greater amounts than is found in the bodies of the ordinary domestic ceramics, and were added to give increased resistance to thermal stress (Chapter 5, p. 172).

The principal parameters of most metallurgical processes are the temperature, the duration, the reducing conditions and the overall chemistry of the process. The vitrification of the refractories can give indications of the first two parameters, and the slags contain evidence of the latter.

Most ceramic bodies used in antiquity begin to soften and melt as the temperature rises above about 900 °C, becoming completely molten by about 1250 °C. This is the relatively low range of temperature attained by most early smelting installations, and in fact it is quite likely that the inability of the refractories to withstand high temperature was the real limiting factor of early furnaces. The degree of vitrification of the furnace wall can give an indication of the furnace temperature at that point. This can be quantified by taking a portion of the unvitrified refractory, usually from the outer regions, and heating it under approximately the same reducing conditions through a known range of temperatures until a similar degree of vitrification is observed on the test piece. Note that this only records the temperatures at the furnace wall, the temperature in the reaction zone before the tuyere might well have been several hundred degrees hotter.

During the process heat penetrates the furnace walls raising the interior temperature and causing changes in the ceramic. The longer the process continues, the further the heat will penetrate into the ceramic wall. Eventually an equilibrium will be reached, but this is likely to take much longer than the duration of any early smelting process. Thus the penetration of vitrification into the clay body as observed on sections of the ceramic can give an estimate on the duration of the process at maximum temperature. Note that the penetration is not additive, but represents the duration of the single longest heating cycle, so reuse of the furnace will not affect the result. A more serious problem arises from the erosion of the surface of the furnace lining through vitrification or by slagging.

The apparently featureless slags are in fact made up of complex mixtures of crystalline and amorphous minerals (Bachmann, 1982a). The crystalline components can be identified by petrology and by X ray diffraction; Moesta *et al* (1984 and 1989) have used Mossbauer spectroscopy. The bulk composition can be determined by the usual analytical methods, and the composition of specific phases, minerals or inclusions can be determined by micro-analytical systems in association with the scanning electron microscope or electron probe microanalysis. As noted above, continuing improvements in the determination of light elements by these analytical systems is having a considerable impact on the study of slags. Many of the minerals occur only within quite narrow ranges of reducing conditions, and they are likely to have formed quickly in the first few moments after the slag left the furnace and before the onset of any oxidation, thus they can give a good indication of the smelting conditions within the furnace (Bachmann, 1980; Moesta *et al*, 1984 and Craddock *et al*, 1985). For example, the relative amounts of magnetite, Fe_3O_4, wustite, FeO, and free iron in a slag give a good indication of the reducing conditions. There is a danger of long-term corrosion of the slags leading to the partial oxidation of some of the minerals, thus samples near the surface should be avoided.

The combined study of the carefully-excavated refractories and slags from the same process can, then, establish the conditions within the furnaces (Figure 1.3). The chemistry of the process can be reconstructed from the bulk composition of the slags using the appropriate phase diagram (Bachmann, 1980).

In most early smelting systems the metal drained through the slag, thus it was important that the slag not only melted at a low temperature, but had a low viscosity just above its melting point. As all the components of the slag would have been in solution whilst molten inside the furnace, the present bulk composition can be used to determine the original viscosity at any given temperature (Bachmann, 1980; Craddock *et al*, 1985), using data calculated by Bottinga and Weill (1972), Bottinga *et al* (1982) and others. The size of the entrapped blobs of metal can also give a practical estimate of how easily the metal drained through the slag.

Even in the most efficient process some of the metal was retained in

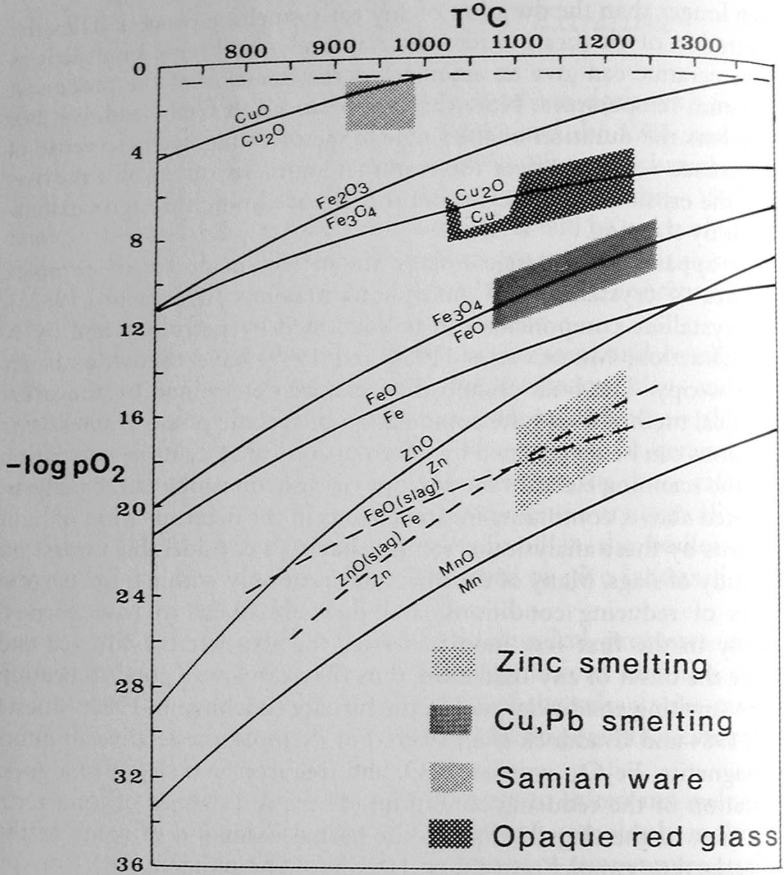


FIGURE 1.3 Plot of partial oxygen pressure against temperature. From study of the associated refractories and slags, the principal parameters of most metallurgical processes can be determined and represented as shown here.

the slag and thus a quickly-performed qualitative XRF (X-ray fluorescence) analysis will usually identify the metal smelted. If only iron is detected then it is likely that the slag was associated with iron production. The shaping of iron by smithing also produces slags (McDonnell, 1991). To determine whether an iron slag came from primary smelting or from smithing is much more difficult and requires more background information on the context and the quantities and nature of other associated materials and debris (McDonnell, 1983 and *nd*). The recognition and identification of the corresponding debris from the production and refining of blast furnace iron also requires careful examination (Morton and Wingrove, 1969a and 1971).

The determination of the activity which produced the slags is not always straightforward (Table 1.3). Processes other than metallurgy such as glass making and accidental fires can produce material that is very like metallurgical slag in appearance; burning hayricks produce a good slag (Evans and Tylecote, 1967; Biek, 1970; Bachmann, 1982a). Even the slag found at old mines may have nothing to do with smelting; boiler clinker can resemble metallurgical slag, at least visually. Almost all mines from the Iron Age to the very recent past would have maintained a smithy where the miners' tools were repaired and sometimes made. This of course does produce a real metallurgical slag. The remote mine of Nantyreira, high in the mountains of central Wales, was worked for copper in the Early Bronze Age and again, briefly, in the late nineteenth century for lead (see Chapter 2 and Timberlake, 1990a). It had a small slag heap which on investigation turned out to be an iron processing slag which could have been a potential source of confusion until it was realised that it belonged to the smithy. The ore was sent away for smelting in the nineteenth century, thus there were no slags at all directly associated with the mined ore.

Metal refining and alloying also produce quantities of slag (Tylecote, 1986, pp. 100–2). These so-called crucible slags tend to be lighter and more heterogeneous with much more entrapped gas in comparison with true smelting slags, and their analysis shows they usually formed under much more oxidising conditions (the problems of differentiating between crucible *smelting* and crucible *refining* slags is discussed in Chapter 4). The crucible slags tend to contain more metal, and this is very often an alloy, showing beyond doubt that they belong to a secondary process rather than the primary smelting process. The survey of Berthoud *et al* (1980) of metallurgical debris from the ancient Middle East showed that mine sites had primary smelting slags, whereas the slags associated with the processes of refining and alloying, containing tin and arsenic as well as copper, were concentrated in the larger settlements away from the mines.

The composition of the droplets of metal found in the slag heaps or retained on the crucible sides can be used to estimate the purity, or otherwise, of the metal produced. This is another very important parameter of the whole operation. However, caution is necessary in using these analyses. Small droplets or residues in a crucible will tend to have come from the periphery of the main melt and consequently will be richer in impurities and the more volatile elements, especially arsenic, than the metal overall. Another factor is the inevitable differential corrosion of the metal and this too will distort the overall composition.

It is also natural to analyse the surfaces of the furnaces, crucibles and moulds to determine the metal produced. Once again caution is

TABLE 1.3 Guide to the identification of possible metallurgical debris.

Nature of material	Category	Evidence
Slags	Non-metallurgical	Usually much lighter in colour and density, and less homogeneous Glass slags are more problematic, but are much more obviously glassy than most metallurgical slags NB Boiler clinker on mine sites
	Non-local (hard core, road metal etc)	Unusual distribution over the site, no evidence of other metallurgical debris. Mining/smelting in general vicinity of site
	Metallurgical (smelting)	Large quantities (many kg) of hard, dense tap slags, relatively uniform in structure and dark in colour Ore fragments Proximity to ore sources
	Metallurgical (non-smelting)	Less homogeneous, more gassy and lighter than tap slags, possibility of macroscopic metal inclusions. Associated material such as crucibles, mould fragments etc. Iron forging produces hammer scale, smithing bottoms Proximity to market NB Smithing slags from blacksmith's forges on mine sites
Refractories (crucibles, moulds, furnace fragments etc)	Smelting	Furnace fragments, tuyeres, crucibles, all heavily-vitrified and slagged. Tap slag should be much in evidence, possibly ore/flux fragments
	Non-smelting	Mould, crucible, furnace tuyere fragments. Possibly some vitrification and slagging or ash-glazing. Some slags usually rather gassy and unhomogeneous, often with metal inclusions. Proximity to markets
Installations (furnace etc)	Non-metallurgical (pottery, domestic etc)	May be quite large (>60 cm diameter) and be associated with ash, if not smelting. Structure and fragments tend to be unvitrified, although may be ash-glazed. Little evidence of associated slag or ore/flux fragments
	Metallurgical (smelting)	No ash, diameter <60 cm, heavy vitrification and slagging of refractories. Usually fairly poor preservation. Abundant associated slag Proximity to ore source. Abundant associated slag in vicinity
	Metallurgical (non-smelting)	Furnaces tend to be heavily vitrified, some slagging, usually fairly poor preservation especially for iron. Associated remains of crucibles, moulds etc. For iron forging presence of smithing bottoms and hammer scale. Proximity to market

necessary in interpreting the results. Volatile metals such as arsenic, lead and, above all, zinc, are extremely penetrative and many refractories that were not in direct contact with the metal, or have subsequently suffered from over-zealous cleaning following excavation, now contain quite substantial traces of zinc and nothing else, even though neither zinc or brass were originally present. The origin of this zinc is something of a mystery, but may come from the charcoal. Similarly, analysis of the upper parts of the copper smelting furnaces from Timna picked up considerable quantities of lead as well as the ubiquitous zinc, but no trace of the less volatile copper that was in fact the only metal smelted there (Tite *et al*, 1990).

Experimental Replications

The various approaches to discovering the technologies by which metal was mined and produced in antiquity have produced a mass of often very impressive data, but this still needs to be tested, and there is some information that can only be established by carrying out the processes. Some thermochemical parameters can be established by small-scale laboratory experiments such as the approach advocated by Moesta (1986) and practised by Rostoker *et al* (1989a), for example, in their experiments establishing the viability of some copper smelting reaction mechanisms under carefully controlled conditions. However, the true feasibility can only be established by full-scale simulation, preferably in the same environment as the original. Actual experience of a process at full scale often brings to light hitherto unsuspected problems, the appreciation of which can throw light on the whole process, as exemplified by the problems Merkel (1989 and 1990) encountered with the erosion of the furnace linings by the slag. Sometimes carrying out one process can reveal how another must have been performed, as exemplified by Cushing's experiments on working copper which unintentionally recreated the methods by which the metal was cut by North American Indians (see Chapter 3, p. 100).

The technology of metal production is especially amenable to this approach because there is not only a durable product, the metal, but also durable production debris in the slags and refractories to act as guides or indicators throughout the various stages of the operation. For example, much of John Merkel's work on recreating the Bronze Age copper smelting process was to produce a slag similar to that found on the ancient tips. Once that had been achieved he knew the experimental process was basically correct.

Experimentation has taken place in the recent past on almost all stages of extractive metallurgy from the firesetting of the ore deposits before mining (Craddock, 1992a) to the smithing of iron blooms at the conclusion of the smelt (Crew, 1991; Crew and Salter, 1991 and Sim, 1994). Some techniques such as firesetting were very poorly recorded whilst they were still in use such that almost all that is known of the technique has had to be relearnt from modern experimentation (see Chapter 2). In other instances where the processes were described contemporaneously, the record could not include data such as the furnace temperature and gas composition that can now be measured during the replication. In previous ages the experienced operator had to gauge the conditions from the colour of the flame issuing from the top. Many parameters such as how much air a man-powered bellows system can supply, not just in the laboratory for ten minutes, but in front of real furnaces for many hours with frequent blockages to contend with, can only be obtained from the reality of performing the process. This raises the question of the validity of comparing the efforts of inexperienced practitioners with the professionals of old. Failures are (and were) of course common, but too often it is not certain whether this was due to a lack of skill on the part of the modern practitioners or to flaws in the proposed technology. In this respect the establishment of dedicated research centres has enabled experience and expertise to develop to the point where it is comparable to the smiths of old. The extended experiments of Merkel on various aspects of copper smelting (Merkel, 1990), and of Crew (1991) on bloomery iron smelting, have in both cases built up a very considerable practical experience and skill. To exemplify the importance of their work in just two areas, Merkel has shown the significance of the different methods of blowing air into the furnace for the development of the whole process (see Chapter 5), and the work of Crew has emphasised the tremendous loss of iron between the smelted bloom and the finished artifact (see Chapter 7). Both have added a new dimension of reality to the processes they now work as experienced smiths.

It is important to note, however, that no matter how versed in the old technology the practitioners become, they remain essentially experimenters recreating a technology in the modern world rather than continuing a tradition. Peter Reynolds, of the Butser Iron Age Farm project in Hampshire, when asked how it felt to be an Iron Age farmer, replied that he had absolutely no idea, he was conducting a scientific experiment according to the precepts of the twentieth century.

Attempts to understand the ancient miner or smith at a social level through replication of his task are probably ultimately as illusory as by any other means, but as a means of answering more direct questions experimentation has had considerably more success.

2

The Development of Early Mining Technology

Mining Geology

To understand something of the problems faced by early prospectors and miners in locating and extracting metal ores, it is necessary to have at least a minimal understanding of how mineral deposits form, how they subsequently weather and how they are related to the environments in which they are found (Healy, 1978, Ch. 1; Barnes, 1988). These factors largely dictated that the mining strategies, and thus the metallurgical processes used, developed distinct regional characteristics. Many aspects of metal production in, for example, the mountains of Wales was of necessity going to be very different from those employed in the deserts of the Middle East. These factors will now be discussed.

Formation of the Deposits

Most exploitable deposits of the minerals of non-ferrous metals occur either as the primary veins or, where these have eroded and then reconcentrated in beds elsewhere. Often these are deposited by *hydrothermal* processes, when fissures and fractures in the main strata (the country rock) become filled with the deposits from saline mineral-bearing aqueous solutions. Thus the vein minerals are formed later than the country rock (known as an *epigenetic* deposit). Hydrothermal solutions are very hot, varying between 100 and 500 °C, slightly alkaline and under great pressure. Under these conditions silica and carbonates would be in solution together with the metallic minerals.

As the pressure and temperature drops, the silica or carbonates come out of solution variously as quartz, calcite etc, followed by such metal salts as are present. Compounds of iron tend to be the predominant metalliferous mineral in many ore deposits (although manganese was present in the veins of some of the more important early copper mines, with profound effects on the smelting technology, see Chapter 4, p. 130). Thus the vein material tends to be primarily composed of varying amounts of silica or carbonates and iron minerals, together with whatever non-ferrous minerals are present, usually in the form of sulphides. Where the iron sulphides had weathered to oxides and were not contaminated with other metals, notably arsenic, they were sometimes mined for iron ore, although usually at a different period than the minerals of the non-ferrous metals. Thus the chalcolithic copper mines of Rudna Glava, in Yugoslavia, were reworked by the Romans for iron (Jovanović, 1982, p. 109), and at some of the Etruscan mines in Campiglia, Tuscany, it is not at all clear whether they were being mined for tin, iron or for both (Craddock, 1986; Stella, 1927).

The salts which were deposited first, at high temperature and pressure, within or around the magmatic or igneous intrusions such as granites, where these were the source of the emanating solutions, are known as *hyperthermal* minerals. They include cassiterite, gold, chalcopyrite and galena along with pyrites, arsenopyrites and bismuthite, in a vein material consisting largely of quartz. The intermediate or *mesothermal* minerals include chalcopyrites, galena, sphalerite, tetrahedrite and gold in vein material consisting largely of quartz, pyrite, arsenopyrite and some carbonate rocks such as calcite, goethite and siderite. The suite of lower temperature minerals can include native gold, cinnabar, argentiferous galena and stibnite with vein material of quartz, pyrite and marcasite, with opal, chalcedony, calcite, fluorite or baryte.

Vein Deposits

Some vein filling mineralisation was the direct result of volcanic activity and in this case would have been contemporary, or deposited shortly after the formation of the fissures. These deposits are known as *syngenic*, exemplified by the copper deposits at Parys Mountain on Anglesey (Cockshutt, 1965; Timberlake, 1990a). Note that in some cases the minerals may have been metamorphosed later and could now be mistaken for epigenic hydrothermal deposits.

The morphology of the veins varies enormously and is principally governed by the nature of the country rock in which they have formed. In hard strong volcanic rocks such as granite the veins are likely to be found completely within the original fissures, which usually preserves well-defined sides and are relatively narrow but often deep. This is frequently the case in some of the deep Cornish tin mines (Burrow and Thomas, 1893) (Figure 2.1). In metamorphic schists or slates which are easily fractured, it is usual for veins to form in a broad zone of minor interconnecting fissures of the fracture regions. In soluble rocks such as limestone the original fissures are likely to have been enlarged by ground water, or dissolved away by the mineralising solutions, with new

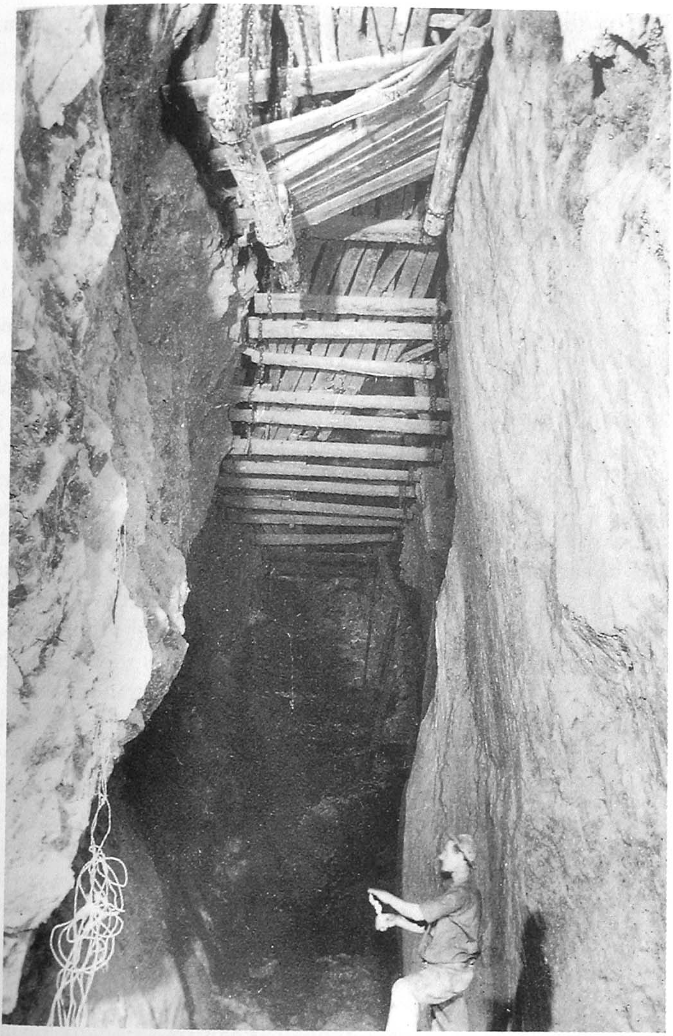


FIGURE 2.1 Well-defined vein in a strong country rock of granite, 375 level at Dolcoath Mine, Cornwall.

minerals deposited subsequently in them as exemplified by the Great Orme (p. 60). These are known as *replacement deposits*. Where the ground waters or mineralising solutions are able to permeate the country rock and saturate it with mineral solutions they form *disseminated deposits*. Sometimes rich ore bodies known as *pipes* or even *flats* form, which are concordant with the bedding of the rock (exemplified by some of the Derbyshire lead mines). Disseminated deposits can also occur in loosely-bonded sandstone or gravels such as are found at the copper mines at Alderley Edge in Cheshire (Warrington, 1965; Carlon, 1979, Ch. 2 and Fig. 1.1). The ore bodies here were enriched by mineral-charged ground waters percolating downwards through faults and fissures.

Since their formation, the veins are likely to have been subjected to many forms of further geological activity (Shepherd, 1980, Ch. 2). The veins could have been badly *faulted* where the country rock has dislocated, thereby breaking up a continuous vein into segments which are often displaced by many metres. Losing the vein at a fault was one of the chief worries of early miners, and there was nothing for it but to stop or send out exploratory workings into the surrounding country rock to try and locate a continuation. It was also possible that in the distant past entire strata, country rock, vein and all could have been exposed at the surface and eroded, by a river for example, only to become buried again, leaving only fragments of the vein with no continuation. The main ore body at Cwmystwyth in central Wales is cut by the present valley of the Ystwyth; the early workings are all on the north-east side and only in the nineteenth century was the southern continuation discovered, albeit worked with no success (Hughes, 1981). A more usual occurrence was for folding and uplifting to form domes which have long since eroded down leaving the remnants of the country rock and mineralised veins exposed as ridges. The ore bodies at Zawar in Rajasthan, are excellent examples of this type of erosion and all the early mines there follow the veins down from where they have been exposed on the tops of the ridges (see Chapter 8, p. 312).

Placer or Stream Deposits

Where a vein has been eroded considerable quantities of ore will have been carried away and may well have become reconcentrated in the alluvium. These *placer* or *stream* deposits have traditionally been the main source of certain metals, notably gold and tin, the latter in the form of its oxide, cassiterite (Penhallurick, 1986). Indeed these two metals are often associated, hence most prehistoric gold artifacts contain traces of tin (Hartmann, 1970) and Cornish tin miners, for example, traditionally carried a goose quill in which to deposit any flecks of gold they found (Penhallurick, 1986, p. 160). The form of the alluvial deposits depends on the distance from the original deposit (the *primary* or *reef deposit*), and the age of the deposit.

Forms of Deposit

Eluvial deposits occur in the immediate vicinity of the primary deposit, typically on the original hill slope below the vein. These deposits are very poorly sorted and dispersed. If the slope was sufficient then it could be successfully worked by *hushing* and ground sluicing (see p. 87). Some of the deposits at the Roman gold mines in north-west Spain (Lewis and Jones, 1970) and also some of the early tin workings in the Erzgebirge of Bohemia were of this type (Manes, 1823/4). Pliny gives a graphic account of the use of water at the gold mines in Spain (see p. 89). Even where eluvial deposits were not rich in themselves they could still be important as indicators of a primary deposit nearby, as in Devon and Cornwall where the eluvial or *shode* tin as it was known locally was followed to its source (Penhallurick, 1986, p. 77). Other heavy minerals, such as galena, PbS, which are not strong enough to survive to become incorporated in alluvial deposits are found in eluvial deposits.

The main placer deposits occur in the sands and gravels of the river valleys below the primary veins. Here the dense minerals will have been sorted from the gangue by the flowing water and reconcentrated according to density. Many of the famous gold deposits of antiquity were of this type, including the gold-bearing gravels of the river Pactolus at Sardis in Turkey, which for a short period provided King Croesus and the Lydian state with enormous wealth (see Chapter 3, p. 116 and Shear, 1924). The heavy minerals such as gold and cassiterite are often associated with dense black magnetite sand, which itself has been used as an iron ore. Iron sands were worked by the Etruscans at Elba and Populonia, and by the Chalybes near Amis on the Black Sea coast of Asia Minor (Forbes, 1964b, p. 202), as well as by the Japanese for the direct production of steel by the *tatara* process (Rostoker *et al*, 1989b and Chapter 7, p. 249). These deposits could also be effectively worked by ground sluicing (see below). Tylecote (1981a) and Richardson (1934) discuss some of the problems in using these ores.

Some of the placer deposits are of course now raised well above any river valley (for example the tin deposits of the Jos plateau in Nigeria (Fawns, *nd*), or buried deep below later strata, as exemplified by the quartz conglomerate gold 'reefs' of Witwatersrand and Johannesburg in South Africa (Adamson, 1972). Some placer deposits can be found in gravels not obviously now associated with any recognisable river valley. Similarly, primary deposits can also be eroded by the sea, and the minerals sorted and redeposited by wave action. Once again the sea in question may well have retreated and disappeared in the remote geological past, as is the case with the South African gold fields.

Weathering of the Ore Bodies

Where an ore body is exposed at the surface it will gradually weather due to the chemical action of the air and percolating water. Taking copper as an example, the sulphidic minerals will typically oxidise to form complex mixtures of oxides, hydroxides and above all hydroxy-carbonates, including the familiar green and blue copper minerals, malachite and azurite, respectively, together with some remaining unchanged sulphidic copper ore. It is in this weathered horizon that native copper is formed by the reduction of copper salts in the aqueous solutions that permeate the upper levels of an ore body (Chapter 3, p. 94 and Maddin *et al*, 1980). The intimate association of the native metal with the oxidised copper minerals must have given the hint of a possible connection to the first metallurgists.

Any gold in the deposit will remain behind in these upper oxidised levels. At Rio Tinto these are currently worked for gold, although there is no evidence that this was done in antiquity. The gold is usually extremely finely dispersed, and thus early man was probably unaware of its existence. The remaining minerals in the upper, oxidised or altered zone will be chiefly iron oxides, principally hydrated iron minerals, goethite and limonite, with the oxides hematite (Fe_2O_3) and magnetite (Fe_3O_4), residual pyrite and clay. This forms a rather weak fissured or vesicular rock, variegated over a wide range of colour from yellow to black, but predominantly red and purple. This very characteristic rock, known as the *gossan* or *iron hat*, would have attracted the attention of any prospector (Figure 2.2). Some minerals will dissolve and either run off or percolate down into the ore body and together with clay fill up minor voids and fissures (*vugs*). Alternatively they will carry on down to the base of the weathered horizon where the metallic salts will precipitate forming distinctive, rather clayey ores. In the case of copper ores these are usually known by the German name *Fahlerze*, literally faded or pale, discoloured ore, and as they are rich and easy to mine they have attracted miners since the inception of metallurgy. The principal minerals encountered here are chalcocite and other complex sulphides such as tetrahedrites. Typically fahl ores have a very wide range of composition as the minor and trace metals in a deposit tend to concentrate here, and these impurities will frequently carry through into the smelted metal. Thus the copper from such a deposit will tend to be enriched in a range of trace metals, especially arsenic, antimony, bismuth, silver, lead and nickel, potentially in a pattern of concentration characteristic of the deposit. The high levels of metals such as arsenic and antimony in some of the chalcolithic copper from Palestine, notably the Nahal Mishmar hoard (see Chapter 8, p. 291 and Shalev and Northover, 1993), and antimony-

FIGURE 2.2 Corta Lago opencast mine at Rio Tinto, Huelva, Spain, showing the massive red weathered gossan deposits sat on the primary sulphidic ore body. The rich jarosite silver ore was found at the junction and the ancient workings are concentrated at this level. Note the small gallery, which leads to a complex system of workings (indicated).

arsenic-silver-cobalt-nickel in the Bronze Age metals from the Alps and central Europe (Northover, 1982), attest the early use of fahl ores. Although these distinctive compositions have formed the basis for provenance studies in the past, it has hitherto proved difficult to move from broad overall trends in composition to create specific groupings assigned to specific regions. Recently, however, the long overdue recognition and investigation of the appropriate early mine sites, coupled with advances in analytical techniques, notably lead isotope analysis, have revitalised provenance studies (see Chapter 1, p. 4 and 7).

The lead-silver ores equivalent to the fahl ores are the *jarosites*, which only form to any extent in arid climates from the degradation of pyrite in a silica-rich environment. They are clayey ores predominantly of mixed iron potassium sulphates with a wide range of other metals, depending on what was present in the original vein (Dutrizac *et al*, 1983). At silver mines such as Rio Tinto where jarosites occur, the early workings are concentrated in the enriched jarosite zone between the junction of the weathered gossans and the primary unchanged pyrites (Figure 2.2 and p. 216).

Beneath the weathered horizon a zone of secondary, supergene, enrichment of sulphidic minerals has often formed, lying over the unchanged primary deposits of sulphides, principally pyrite and chalcopyrite.

Finally one very important point must be made. In the temperate and northern lands the whole of the weathered horizons will often have been planed off by glaciation during the ice ages. Evidence of ice action is very apparent at mines such at Mt Gabriel, or Cwmystwyth, which are set in classic glaciated landscapes. Thus both the topography and even the nature of the minerals exposed at the surface of mines over much of central and western Europe are totally different from those found in the Mediterranean and the Middle East, so that the development of extractive metallurgy often necessarily proceeded along very different paths. This should always be appreciated when considering the origins and degree of independent development of European metallurgy (see Chapter 4, p. 144).

Prospection

Many rich metal ores could be distinguished immediately from barren country rock either by their bright colours or by their density. For example, cassiterite, the most common ore of tin, usually occurs in stream deposits as rather nondescript black pebbles or sands, but its density of 6.8 to 7 would immediately indicate that this was something different and worth investigating further. Almost all metal ores are relatively dense, and panning for ore must have been practised since the inception of metallurgy (Figure 3.7). A simple flame test would reveal the presence of many metals such as copper, and even the smell of the burning mineral could be informative: the smell of garlic would indicate the presence of arsenic for example (Charles, 1985).

Deposits of metallic minerals were detected where the ores or the gossans outcropped at the surface. In arid, thinly-vegetated landscapes such as much of the Middle East, most surface deposits would have been conspicuous, but much less so further north where the brightly-coloured oxidised ores and gossans had often been glacially removed, and the ground was usually under dense vegetation. The anonymous *Bergwerk* compiled in the early sixteenth century (Sisco and Smith, 1949) and Gabriel Plattes' *A Discovery of Subterraneall Treasure* published in 1639, give excellent reviews of the prospection methods then in use, and these are likely to be broadly similar to those used in the more remote past. The vegetation could be a valuable indicator in itself. Some plants can tolerate high concentrations of heavy metals, such as lead and copper, and may even flourish in soils contaminated with these metals where other plants would die. Notable examples are *Saxifraga hypnoides*, *Thlaspi alpestre*, and *Minvatia verna*, the sandwort, known as lead wort in the mining areas of Britain, which are all specifically lead tolerant (Buchanan, 1992); *Viola lutea* is specific for zinc and *Silene Rupestris* for copper. In China the plant *Elshotzia splendens* which flourishes at the copper mine of Tonglushan was used as an indicator of copper (Anon, 1980). Agricola (Hoover and Hoover, 1912, pp. 37–8) comments on some specific plants as indicators, and also on the poor condition of the vegetation generally (with blackened foliage etc) above the vein. The method is still used, but the earth-bound prospector has now been replaced by aerial photography with infra-red film and satellite imaging.

Agricola, in common with other early writers such as Plattes devoted considerable attention to divining, which he treated in a quite matter of fact manner, although finally advising the reader to avoid 'the enchanted stick' (Hoover and Hoover, 1912, p. 41). This technique has probably fallen further from scientific respectability than any other 'traditional' technique, yet it was clearly an important method until quite recently (Bailey *et al*, 1988).

In well-wooded territory rocky outcrops and stream beds provided the best access to the underlying mineralisation, and ore found in a stream bed could be followed back to the primary mineral vein, usually in a lode of quartz or calcite.

Once the ore was located mining could begin in earnest.

Mining

The Form of the Mines

Early miners simply dug out the ore from where it outcropped, following it in until it was lost by faulting or mining was checked by water, rock instability or ventilation problems. In any case, narrow workings or pits rarely penetrated below about 10 metres from the surface. The reluctance of early miners to dig exploratory, development or drainage channels in the country rock outside of the vein is a very noticeable feature of ancient mines. Thus the forms of the first mines are very much dictated by the ore body; discontinuous concentrations would be worked by a series of small pits as at Mt Gabriel, Ireland (see later on p. 51, Figure 2.20, and O'Brien, 1990 and 1994), while more continuous veins would have trenches dug along them, as exemplified by Chinflon in the south of Spain (Figure 2.3) (Rothenberg and Blanco-Freijeiro, 1980). Sometimes the size and width of the ore body enabled the mine to develop into a sizeable opencast as at Cwmystywth in central Wales (see later on p. 55, Figure 2.23 and Timberlake, 1990b).

Some European Bronze Age mines established extensive underground mining systems such as the mines at the Mitterberg (Pittioni, 1948 and

FIGURE 2.3 Small Bronze Age trench mine at Chinflon, Huelva, Spain. Malachite copper ore was extracted from a vein material of quartz.

1951), and the Great Orme's Head (Lewis, 1990a) described later (Figure 2.26).

Even with the primitive tools described below, the Bronze Age miners seem to have removed every last morsel of ore before a working was abandoned. One is always struck by the virtual absence of any usable ore surviving in any of the ancient workings, and the waste tips are similarly barren. With the exception of Alderley Edge and Great Orme the principal copper ore now present at most of the early mines in the British Isles is chalcopyrite, but it is quite probable that weathered oxides and hydroxy-carbonates once existed in greater quantity and would have been the principal ores taken by the first miners (see Chapter 1, p. 11).

Mining Technology

Some vein and country rock was soft enough to be mined directly with the primitive tools available, but usually the rock had to be weakened by burning a fire against the rock face, the technique known as firesetting (Craddock, 1992a; Timberlake, 1990c and d; Simonin, 1869, pp. 410–2). Although this technique was in use right up to the end of the last century, there are few detailed contemporary accounts of the practice (Collins, 1892/3; Hoover and Hoover, 1912, p. 120; Manes 1823/4, 9, pp. 292–4). Thus the probable mode of operation has had to be reconstructed from the few descriptions and illustrations that exist (Figure 2.4a and b) and from experiments (Holman, 1927, and more recently those recorded in Crew and Crew, 1990). In the experiment of Timberlake (1990b), a fire of substantial logs was set alight against the face to be worked and left to burn for some hours, most conveniently overnight (Figure 2.5). Most early underground mines were systems of small galleries and once the fire took hold it would be impossible to approach because of the choking smoke and poisonous fumes of sulphur dioxide and carbon monoxide. (Note that the figures shown in 2.4b are suspect, Simonin specifically states that the mine was evacuated during firesetting.) In some nineteenth century mines with large straight galleries, shuttering was erected to confine the smoke and fumes to the roof enabling miners to approach underneath to tend to the fire. From the author's own experience of firesetting the rock begins to shatter and spall almost immediately the fire takes hold. This goes on with some violence for about an hour, and after that the heat continues to slowly penetrate into the rock causing further fracture and shattering for up to about 30 cm behind the rock face if the fire is left overnight. Next morning the burnt out remains of the fire can be approached and doused with water if necessary.

If water was ever thrown over the fireset areas its only function would have been to cool the shattered rock and extinguish the fire so that work could commence, the dousing could play no part in the fracture of the rock as the exposed rock was already deeply shattered. In one experiment a fierce fire of brushwood was burnt against a rock face for about an hour and then doused whilst the rock face still at red heat. This caused violent but shallow fracture and very little rock could be mined subsequently, suggesting that this was not a feasible way of proceeding quite apart from the near impossibility of approaching a fire whilst it was burning in the constricted space of a primitive mine. Pliny, in the *Natural History* (33.71), describes how hard, flinty rock was attacked with fire and vinegar, which some have interpreted as meaning that the fire was actually doused with vinegar, or equally unlikely that the burnt rock was chemically treated with vinegar (Healey, 1978, p. 85). The suggestion of

(a)

A—Kindled logs. B—Sticks shaved down fan-shaped. C—Tunnel.

(b)

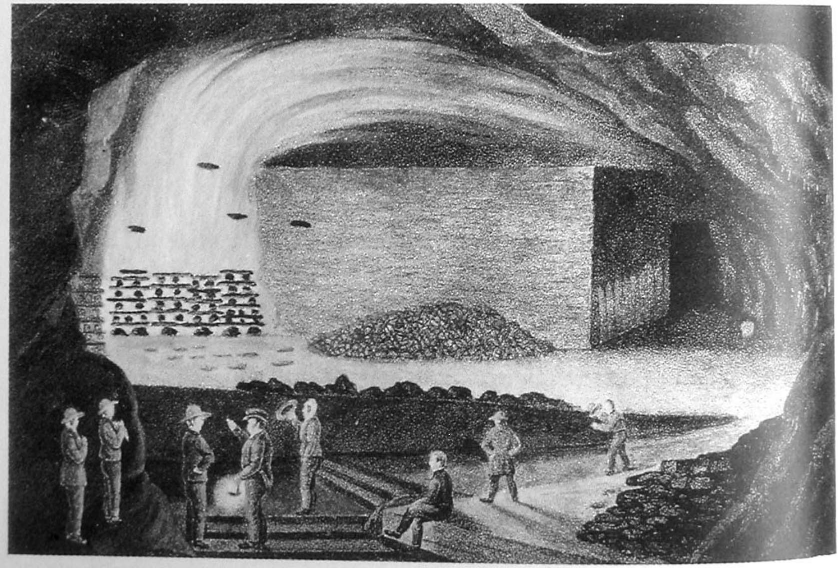


FIGURE 2.4 Firesetting as practised in Germany in the sixteenth and nineteenth centuries; (a) woodcut from *De re Metallica*; (b) lithograph dated 1837, one of a series of the Rammelsbreg mine at Goslar.

FIGURE 2.5 Firesetting experiment in progress at Cwmystwyth, central Wales. A fire of substantial logs was left to burn for many hours against the face to be mined.

Hoover and Hoover (1912, p. 118) that the text is corrupt superficially seems the most likely explanation. Possibly *ascia*, an axe, was meant not *aceto*, although this change is linguistically suspect and the use of vinegar for cracking rocks is mentioned unambiguously elsewhere by Pliny (23.57), and by Livy (21.37), and even by the Chinese. Recent experiments have shown that a variety of different rocks heated to 900 °C broke up more completely when doused even with dilute vinegar than with water, and limestone disintegrated completely (Shepherd, 1992). Even so, it still seems improbable that vinegar was ever used extensively in mining.

The fire-weakened rock yields easily to the primitive stone and antler tools used by the first miners; in recent experiments after burning about three quarters of a ton of wood against a rock face, about twice that amount of rock was detached in a morning by one person using stone hammers and antler picks, although it is very probable that the use of fuel was extravagant (Timberlake, 1990d).

Firesetting could be used both for very precise targeted work (Figure 2.6) as well as for wholesale rock removal (Figure 2.7), for which fires on the scale of Figure 2.4b must be envisaged. Fireset workings are very distinctive, the mine walls tend to follow shallow curves with no sharp angles, giving a continuous, rather sinuous appearance to the workings

FIGURE 2.6 Complex fireset working at the Kestel tin mine dating from the third millennium BC. Note the smooth continuous contours of the walls, and the very precise nature of the work quite typical of firesetting.

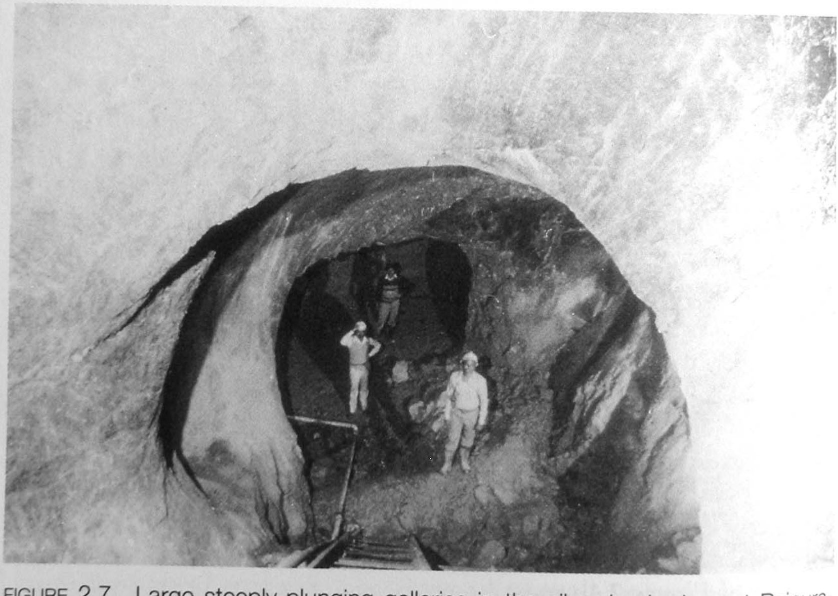


FIGURE 2.7 Large steeply-plunging galleries in the silver lead mines at Rajpura-Dariba, Rajasthan, India, dating to the later first millennium BC. The smooth sinuous profile of the rock face is very typical of firesetting.

(Figures 2.6, 2.7 and 2.21). As the rock tends to fracture parallel to the face and to almost peel away, the surfaces are generally very smooth. In many mines the roofs are still blackened with soot and the floors buried deeply in ash, burnt rock and partially burnt wood. The latter is a very valuable source of material for radiocarbon dating, usually being made up of small brushwood timbers, and also directly associated with a specific mining event. The rock to be attacked by the fire was often very specifically targeted and the fire would be positioned on platforms, which in large chambers could be many metres tall (Figure 2.8).

Mining Tools

Stone hammers are by far the most obvious and plentiful indication of early mining and as such will be considered in some detail here

Stone Hammers as Indicators of Early Mining

Stone hammers have been recovered in large numbers from primitive mines all over the world and quite clearly they were important mining tools. Their numbers and distinctive apearance make them good indicators of early working. Unfortunately until recently there has been some uncertainty, in Britain at least, as to both their age and use; this has only been finally resolved by a series of excavations in Wales and Ireland. Over two centuries ago Lewis Morris, the King's Surveyor of Mines noted the stone hammers at the Twll y Mwyn mine in central Wales and argued that they must date from before the time when man had the use of iron, on the simple grounds that if iron had been available surely it would have used in preference to stone (Pickin, 1990). This was eminently sensible reasoning from an experienced mining surveyor. When other ancient mine workings were encountered in the nineteenth century in Wales and elsewhere the miners recognised that the primitive mining technology was very different from anything they knew from the recent past, and also noted the considerable thickness of calcite flowstone covering some of the tools and waste heaps underground in some mines, notably on the Great Orme (James, 1988 and 1990; Lewis, 1990a), drawing the obvious conclusion that the mines were of great antiquity. The confusion only came much later in Britain when archaeologists became involved. In the 1930s and '40s Oliver Davies trenched a number of sites in central and north Wales that had produced stone hammers (Davies, 1937a, 1939, 1947 and 1948). He clearly felt that the mines should be Roman, but as author of the standard work on Roman mining (Davies, 1935) he knew enough about classical mining to recognise that the stone hammers were not Roman, so suggested that they had been used by the local population forced to labour for their Roman masters.

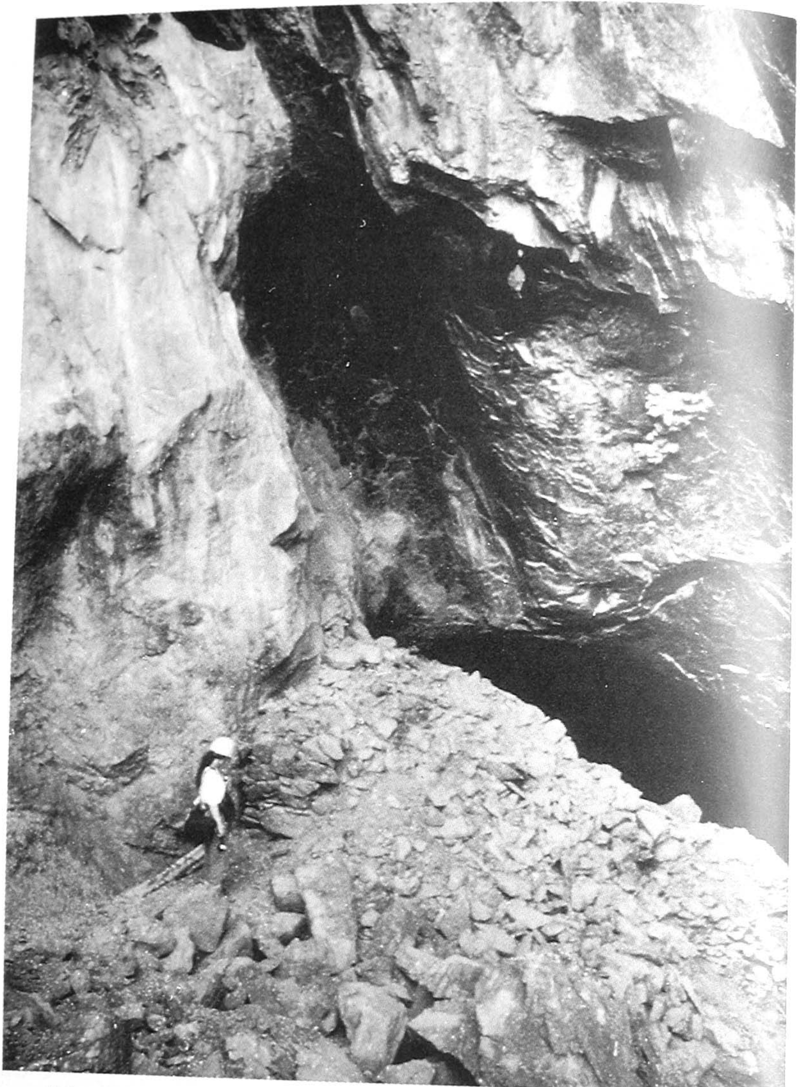


FIGURE 2.8 Entrance to a huge chamber at the copper mines of Singhana-Khetri, Rajasthan, India, worked by firesetting. Note the rounded profile of the working and the platform built against the face on which the last fires were placed. This is probably post medieval.

Subsequently, other archaeologists pointed out quite rightly that there was a total absence of Roman material, and moreover there were no Roman roads, forts or any Roman activity near any of the sites, and stone hammers became discredited, in Britain at least, both as indicators of early mining and even as mining tools (Briggs, 1983). The recent excavations on mine sites have completely rehabilitated them, but it may be useful to give some of the general reasons for believing them to be primitive mining tools.

Grooved stone hammers are known from a number of European flint mines (Schmid, 1981) and at early copper mines such as Ai Bunar in Bulgaria (Černych, 1978), Rudna Glava and Rudnik in the former Yugoslavia (Jovanović, 1988), Chinflon etc in Huelva province of Spain (Rothenberg and Blanco-Freijeiro, 1981), the Mitterberg in Austria (Pittioni, 1948 and 1951), Cabrières in Herault, France (Ambert *et al*, 1983), and at many other early copper mining sites around the world, but nowhere does the use of heavy, hafted stone hammers persist after iron became available locally. At the few multi-period sites which have been carefully surveyed, the use of the hammers as mining tools is confined to the chalcolithic or Bronze Age phases of working. In this respect it is instructive to compare the adjacent mines of Chinflon and Rio Tinto in Spain. The small Bronze Age mine of Chinflon yielded hundreds of hammerstones (Rothenberg and Blanco-Freijeiro, 1980), yet detailed exploration of the huge mines at Rio Tinto only 20 km to the north have not produced a single hammerstone from any of the Phoenician, Iberian or later workings.

It has been suggested that the hammers could have been for a variety of uses, including ore crushing. However it is clear from both the hafting of the hammers and their fractured ends that they were intended to deliver a massive blow resulting in considerable shock, commensurate with a mining tool, but not with the more controlled action needed for crushing and grinding. Their use as mining tools is further attested by the very distinctive marks left by the hammerstones on the walls of many of the mines where they have been found (see later and Figure 2.9). Much smaller unhafted stone pebble tools were used for ore crushing, although the hammerstones were sometimes reused as anvils.

The hammers are typically river or beach cobbles of whatever hard rock was available in the vicinity, although sometimes the cobbles were brought some distance. For example, the many hundreds of hammerstones littering the hillside at Cwmystwyth in central Wales may well include many beach pebbles, most probably from the vicinity of Aberystwyth some 30 km distant (Timberlake, 1990b). The hammers typically weigh 1–3 kg, but with a considerable spread on both sides, there being both small examples of only a few hundred gms and monsters of up to 30 kg. Although generally not extensively modified, most hammerstones show some evidence of hafting. At some sites such as Chinflon (Rothenberg and Blanco-Freijeiro, 1980), Ross Island, Co Kerry (Jackson, 1980), or Alderley Edge (Gale, 1990) many of the hammers have a continuous groove pecked around their midriff (Figure 2.10). It is more common, in the British Isles at least, for the hammer to

FIGURE 2.9 Gallery in the Bronze Age copper mines at Timna, southern Israel. The diffuse peck marks on the left are very characteristic of mining with stone hammers. Note the very different scratch marks made by later metal tools on the right.

FIGURE 2.10 Grooved stone mining hammer from the Bronze Age copper mines at Alderley Edge, Cheshire.

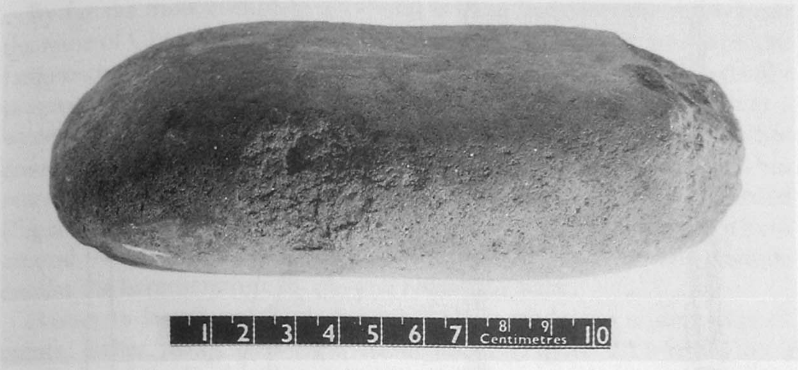


FIGURE 2.11 Mining hammer from Mt Gabriel, County Cork, Ireland. Note the small notches on the edge to accommodate the handle.

have notches pecked into the midriff edges (Figure 2.11) together with some roughening on the sides which it has been suggested provided a friction grip for wedges to hold the putative hafting in place (Pickin, 1990). In practice it is difficult to predict exactly where a wedge should be sited until the haft is made and these marks may be the result of hammering the wedges into place with a stone. Many hammerstones have no pecking at all, but their battered ends show they were clearly used for mining. In some instances the natural tapering shape of the cobble could have been easily wedged into a haft, but they often show evidence of having been used at both ends. It is possible that some were hand-held for driving in wedges, but experiment has shown that the shock of using them directly against the rock face is extremely tiring on the arms and damages the skin on the hands, leading to the conclusion that some haft was probably essential (Pickin and Timberlake, 1988). Pickin (1990) in a preliminary study has brought together some of the main types found in Britain. However, much more work is needed before the distribution of the types, and the reasons for the variation in hafting this implies, is understood.

The marks on the hammerstones together with a very limited number of surviving handles suggest three principal methods of hafting (B. R. Craddock, 1990). The deep continuous grooves presumably were made for some form of rope or withy handle that could be twisted tightly round in a tourniquet, although as yet no examples of grooved hammers still retaining their handles have been found. A handle of twisted hazel has been excavated from Mt Gabriel, where most of the hammerstones have only notches (O'Brien *et al*, 1990). A somewhat similar reconstruction was found to work quite well in mining experiments (Figure 2.12 left).

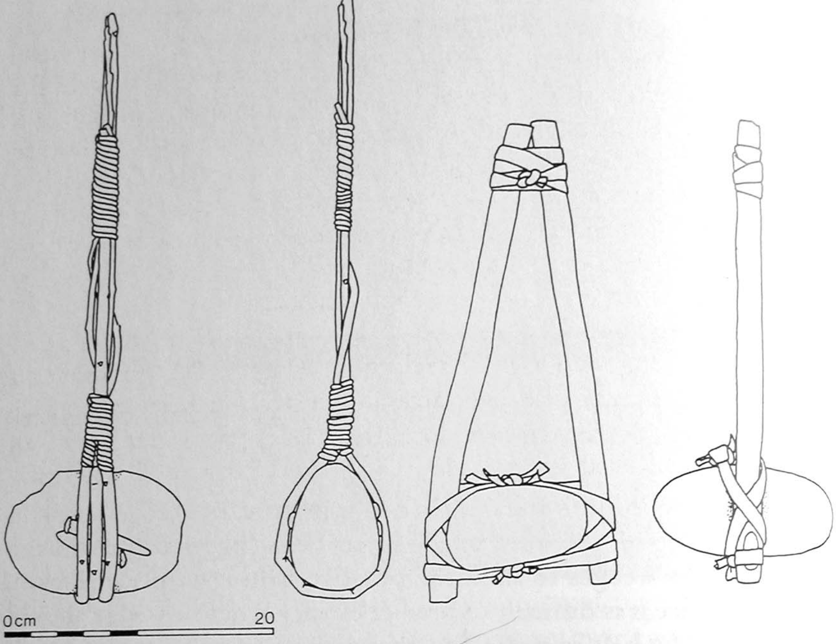


FIGURE 2.12 Stone hammers with handles of twisted withy (left), and of wood and sinew (right), made for mining experiments.

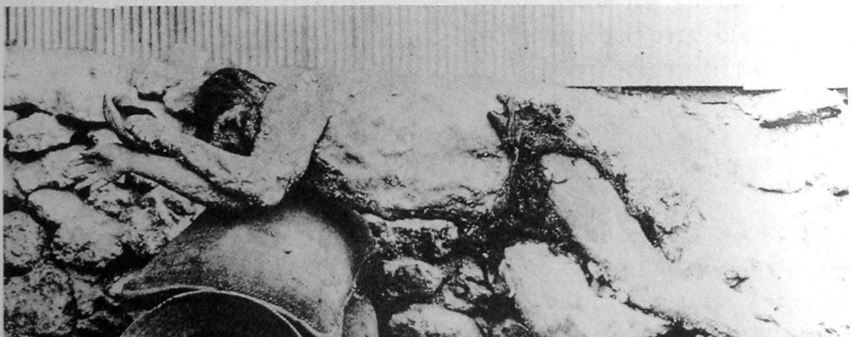


FIGURE 2.13 The 'copper man', immediately after discovery in the copper mine of Chuquicamata, Chile, in 1900, hence the rather poor quality of the photograph. Note the assortment of mining hammers, baskets of ore (cf Indian examples Figure 2.43), and the short-handled wooden shovel (cf Mt Gabriel, Figure 2.17).

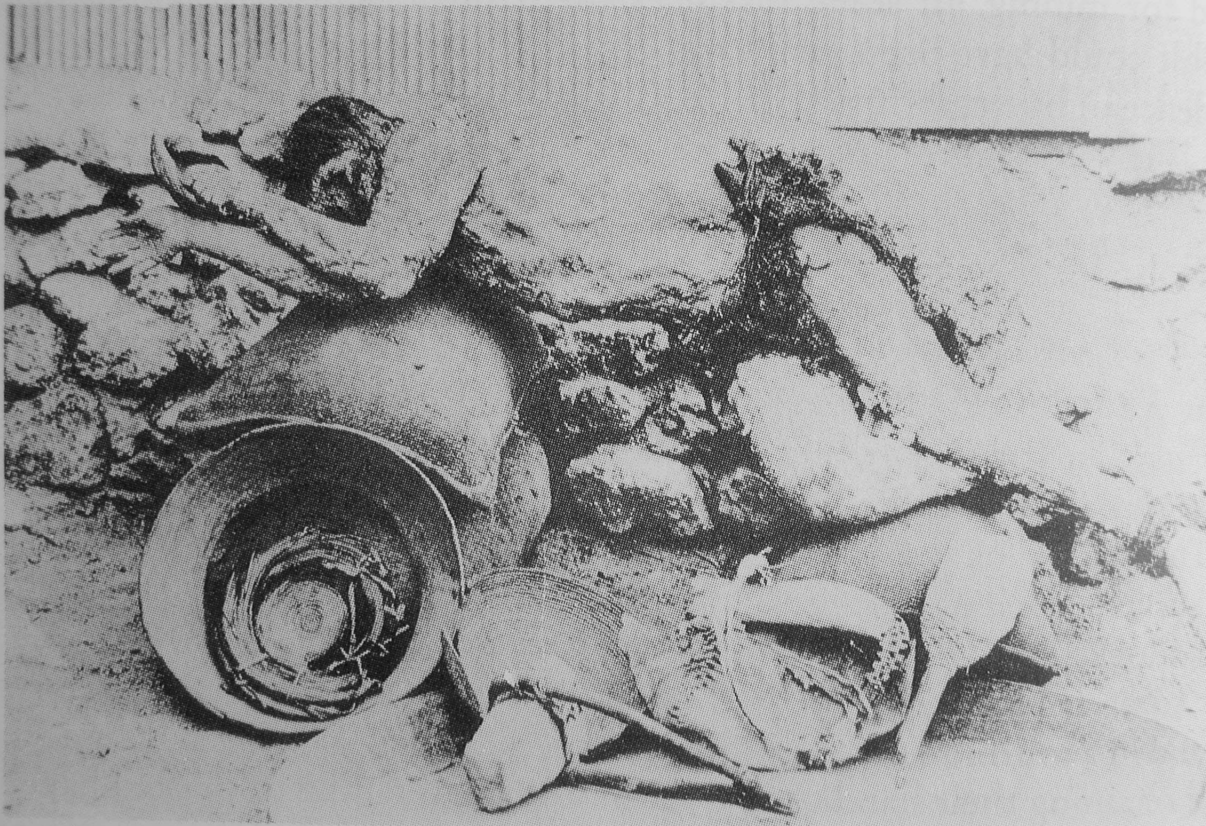


FIGURE 2.13 The 'copper man', immediately after discovery in the copper mine

By far the most complete surviving mining hammers are those from the mine of Chuquicamata in Chile. Four hammers were found with the famous copper man (Bird, 1979; Weisgerber, 1992; Figure 2.13) perfectly preserved together with the rest of his mining equipment, including a wooden shovel and baskets of ore, dated to about AD 600. Another complete hammer from the same level of the mine as the copper man has recently been examined in detail at the British Museum and recorded (Figures 2.14a and b). The handle was made of a single stick or root bent around the hammerstone and tightly bound with rawhide. The rawhide cradles the hammerstone by passing round the back.

Hammers based on these survivors were made for mining experiments, either using two rigid hazel sticks (Figure 2.12 right) or a continuous length of willow bent around the stone, held with rawhide and hemp string (Figures 2.15a and b). These both performed very well against rock weakened by firesetting, the small hammer has already mined over a ton of fireset rock in mining experiments.

The very large hammers from the Great Orme mine have no hafting marks, in common with most of the hammers from that mine, although most bear the typical batter marks, confirming that they had been used for mining. However, they are far too heavy for conventional use as hammers. They could have been held in a sling and swung from the shoulder, but trials have proved this to be unwieldy in practice and it is more likely that these heavy giants were held in a cradle and swung from a timber tripod or bipod against the rock face (Lewis, 1990b). (See p. 73, Figure 2.36 for later parallels.)

The very small hammers and reused flakes would have been useful for loosening rock and ore in small crevices and vugs, and some could have been hand-held.

If the rock was soft then firesetting could be dispensed with and the hammers could be used directly, leaving a distinctive pattern of diffuse peck marks on the unshattered rock face. Examples of these survive in a number of mines, notably at Alderley Edge (Figure 1.1) and from the earliest phase of work at Timna (Figure 2.9).

The enormous numbers of hammers found underground and in the spoil tips of the early mines show that they had only a short working life before they were discarded. Many are obviously fractured beyond repair (although notches and roughening are sometimes found on old fracture surfaces). On the other hand, many more are apparently undamaged yet have been found discarded on the tips, even at mines such as Cwmystwyth where the beach pebble hammers must have been carried a considerable distance. This may result from sporadic exploitation with each group bringing the tools they were likely to need, only to discard them later at the end of their visit whether they were worn out or not. A

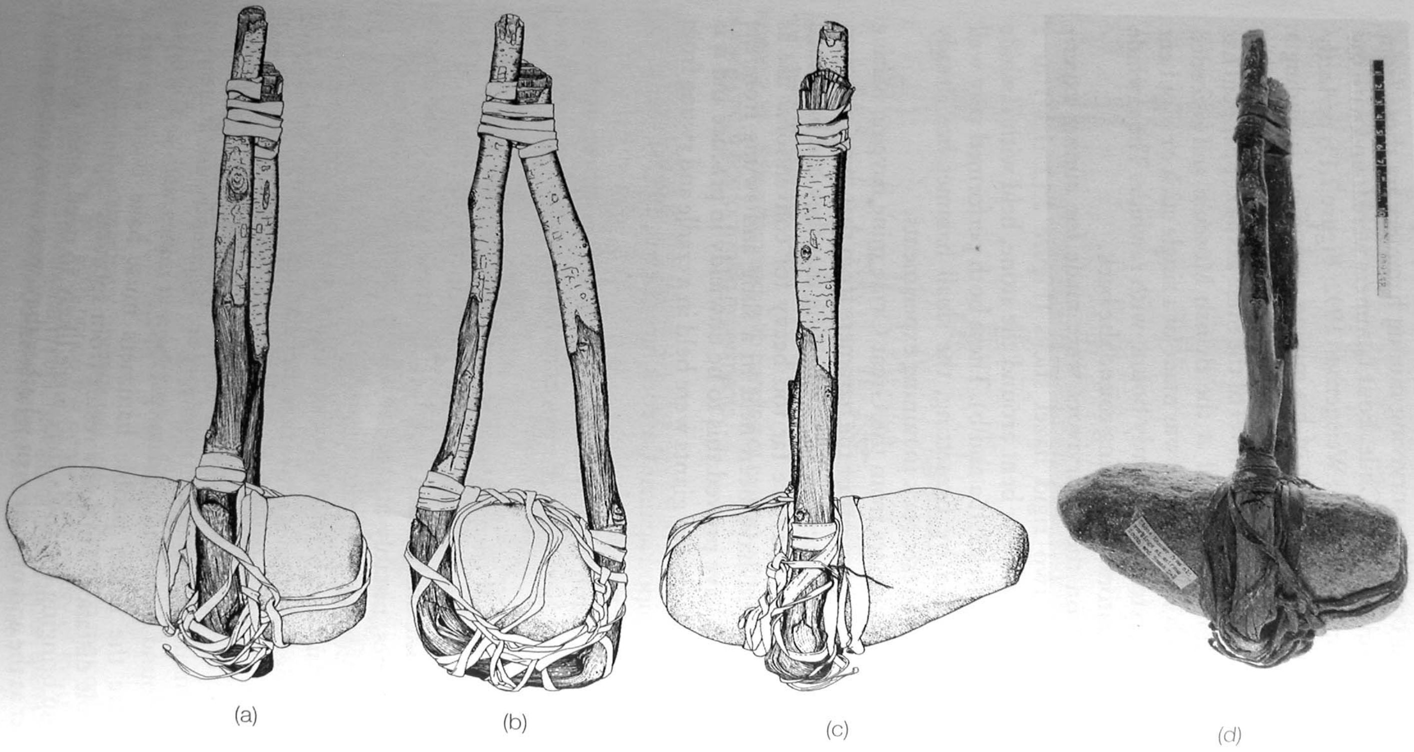


FIGURE 2.14 Drawings (a–c) and photograph (d) of a fully hafted stone hammer found at *Chuquicamata in the same levels as the copper man.* (I am grateful to Dr Wray for the opportunity to study this mining hammer.)

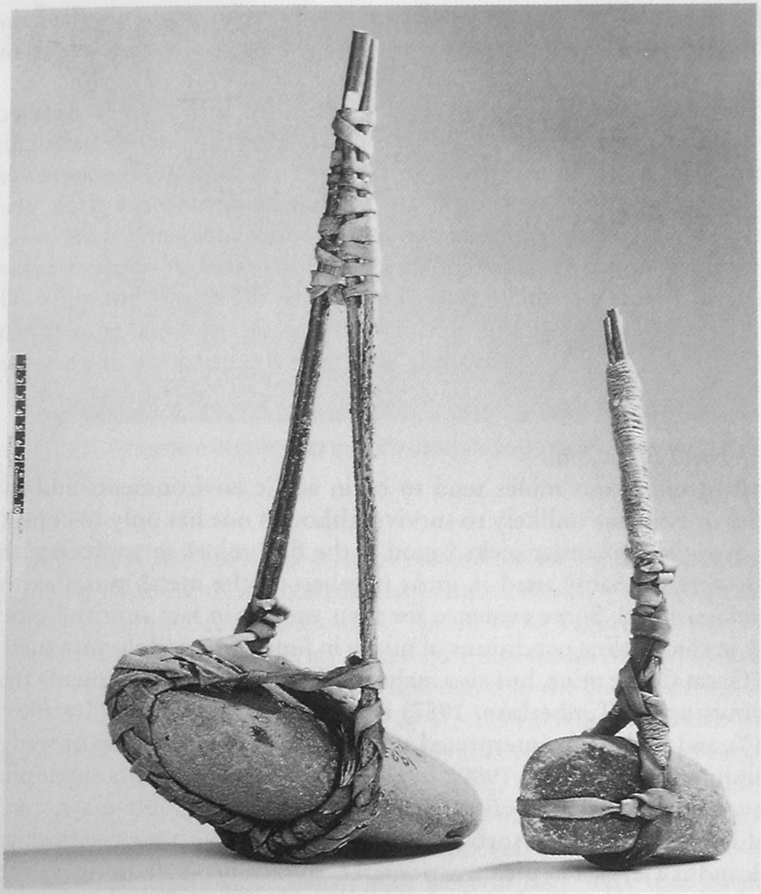


FIGURE 2.15 Stone mining hammers based on those shown in Figure 2.14. The heads are attached to the handles with strips of rawhide, note the cradle of rawhide holding the rear of the stone. The small hammer has already been used to mine over a ton of fireset rock in mining experiments.

good parallel is provided by the mounds of discarded basalt hammers surrounding the iron meteorites in the Canadian Arctic (Chapter 3, p. 107). Fresh hammers had been brought there, often from great distances by the Inuit each time they visited the meteorites.

It is also possible that the Bronze Age mining hammers had become blunted, reducing their efficiency, although if this is so then it is not immediately apparent; only further experimentation will resolve the problem.

Flakes which had spalled off the hammers in use abound at the sites and some bear clear evidence of reuse presumably hafted as small thin hammers suitable for use in small crevices. Experiments to use the flakes as wedges to open up cracks in the mine face were a failure; antler and even wood was much more successful.

The mining experiments carried out by the Early Mines Research Group showed that the hammerstones worked free from their hafts quite quickly, doubtless in part due to our inexperience, but it does seem very likely that rehafting and replacing broken hammerstones took place fairly frequently in antiquity. It was found expedient in the recent experiments to have one person designated to carry out repairs working with the miners and this may well have been the case in antiquity. The discovery of caches of unused hammerstones on the working platforms in the shafts at Rudna Glava might suggest the existence of an underground repair depot.

Antler and Bone Tools

Most metalliferous mines tend to be in acidic environments and thus antler or bone are unlikely to survive, although one has only to consider the quantities of antler picks found at the flint mines to appreciate that they were probably used in great numbers in the metal mines as well (Sandars, 1910). Some evidence for their use has in fact survived especially in the alkaline conditions of mines in limestone or dolomite such as the Great Orme mine, but also including badly-decayed fragments from Cwmystwyth (Timberlake, 1987) and from Rudna Glava (Jovanović, 1980), and tool marks interpreted as being made by antler picks or wedges at Siphnos (Wagner *et al*, 1980). In recent mining experiments antler picks proved surprisingly effective. The antler has considerable mass, a very useful springiness to absorb shock, and great strength for use both as a pick and as a lever. The pick was prepared by cutting off all the tines except one at the end, and the detached tines proved very useful as wedges.

Bone is less well attested probably due to its greater susceptibility in acid environments, but as with antler, at mines where the country rock is limestone or dolomite, the conditions are sufficiently alkaline for bone tools to have survived. At Great Orme's Head they are found underground in large numbers. They are mostly unfashioned fragments, and many must be food debris, but others show signs of heavy wear, probably from use as scoops to remove the copper ore from the soft dolomitised limestone that comprises the main ore bearing areas of that mine (Figure 2.16; Lewis, 1990a). Ox scapula shovels or rakes, similar to those found at the flint mines, have been recovered from the mines on Ross Island (O'Brien, personal communication).

Wooden Tools

Due to the frequently waterlogged conditions and generally poisonous environment wood survives surprisingly well in ancient mine systems,

FIGURE 2.16 Fragment of animal long bone used as a scoop from the Great Orme's Head mine.

although the major survivals seem to come from rather later mines (see below). In addition to the hammer hafts noted above, a shovel of alder has been excavated at Mt Gabriel (O'Brien, 1990; Figure 2.17) and the oak shovel excavated at Alderley Edge in the nineteenth century (Carlon, 1979, p. 40) has now been relocated and dated to the Early Bronze Age (3470±90 BP. Ox A-4050; Garner *et al*, 1994). Another much later example has been reported from the Anayatak copper mine at Murghul in Turkey, dated to about 300 BC (Kaptan, 1978), and at Laurion (Conophagos, 1980, p. 177). Mount Gabriel has also produced a large number of oak sticks about 30 cm in length and sharpened at one end, christened 'prickets' by O'Brien, who believes they were used to prise flakes of fire-shattered rock from the mine face.

Some form of container would have been essential for removing both ore and spoil from the mines, and the baskets preserved at Chuquicamata would seem ideal, very similar baskets being preserved in considerable numbers at the more advanced mines in India (see p. 81 and Figure 2.43).

Metal Tools

In the primitive mines metal tools are conspicuous by their absence. This is probably in part because the metal in any tools that were in use would have been too valuable to discard, and thus it is likely to be under-represented. Careful excavation at Great Orme resulted in the discovery of a small fragment of bronze which could have spalled off a chisel, and analysis showed the bronze was of a composition typical of the Middle Bronze Age, contemporary with the gallery in which it was found (Lewis, 1990a). Some very battered bronze flat axes etc. have been found in Bronze Age mines (Sandars, 1910), and some others seem to have been

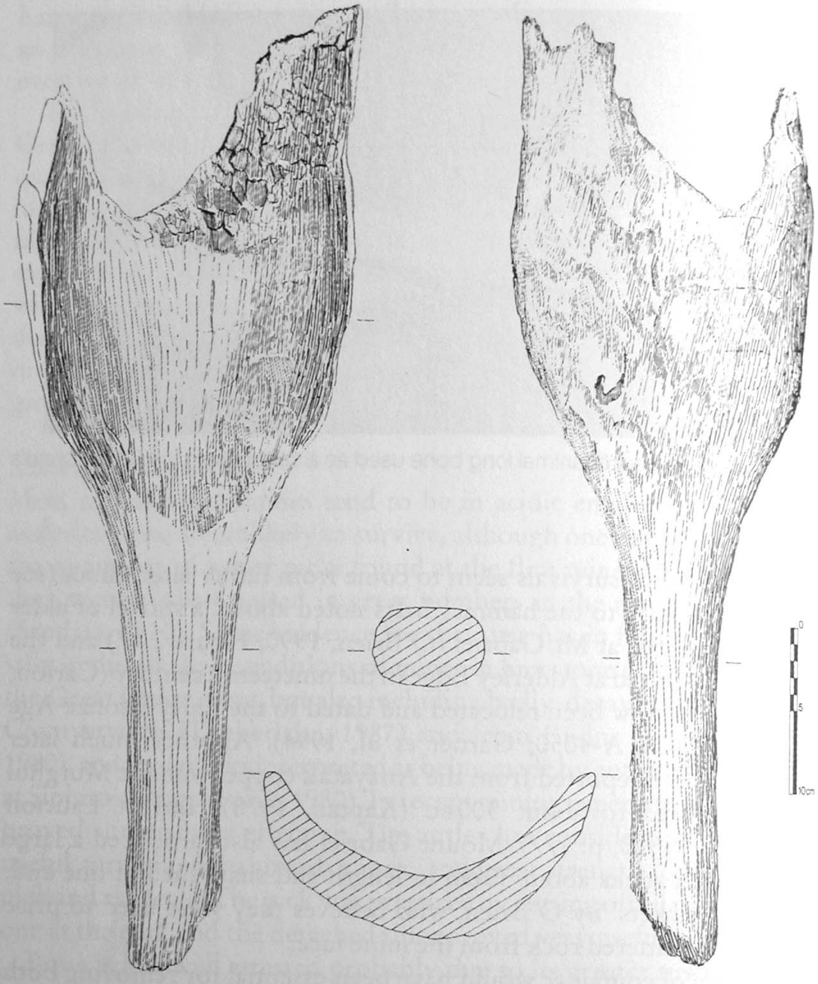


FIGURE 2.17 Short alder shovel from the Bronze Age copper mines at Mt Gabriel, Co. Cork, Ireland (cf the shovel in Figure 2.13).

reused as wedges. However, the absence of the distinctive marks made by metal picks or chisels on the walls of the early mines, coupled with the great scarcity of real purpose-made metal mining tools, does suggest that the use of metal underground was limited.

Some Early Mines

Figure 2.18 shows the distribution of the mines that we will be considering, while Table 2.1 shows radiocarbon dates for early mines.

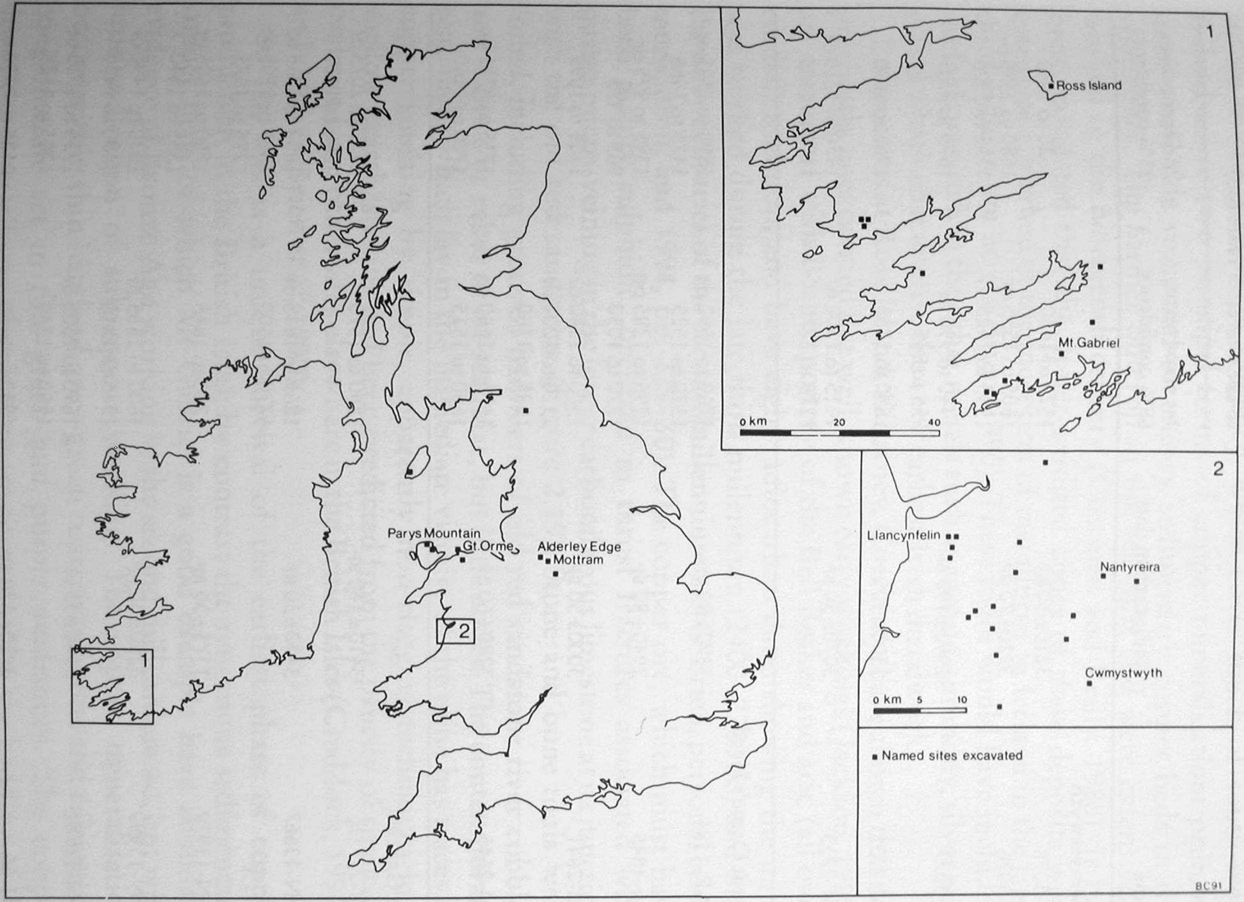


FIGURE 2.18 Locations of mine workings with stone mining hammers in the British Isles.

TABLE 2.1 A selection of radiocarbon dates for mines worked with stone hammers in the British Isles.

		Possible calibrated age range(s) by probability method, rounded outwards to the nearest 5 years (BC)	
Mine	**Radiocarbon date**	**1st error term, 68% confidence**	**2nd error term, 95% confidence**
Cwmystwyth			
Q-3078	3210±50 BP	1525 to 1430	1620 to 1410
Q-3076	3220±70 BP	1605 to 1555 or 1535 to 1425	1680 to 1385 or 1335 to 1325
Q-3077	2990±190 BP	1440 to 990 or 955 to 945	1675 to 810
BM-2732	3500±50 BP	1890 to 1755	1965 to 1690
BM-2733	3070±50 BP	1415 to 1300 or 1275 to 1270	1450 to 1210 or 1180 to 1165
Great Orme's Head			
CAR-1184	3370±80 BP	1760 to 1590 or 1570 to 1525	1890 to 1505 or 1475 to 1465
Har-4845	2940±80 BP	1295 to 1285 or 1270 to 1030	1395 to 975 or 965 to 935
BM-2641	3000±50 BP	1380 to 1340 or 1320 to 1200 or 1185 to 1160	1405 to 1095
BM-2645	3290±60 BP	1675 to 1660 or 1650 to 1515	1735 to 1715 or 1700 to 1440
Mt Gabriel			
BM-2271R	3410±140 BP	1890 to 1570	2130 to 2075 or 2040 to 1420
GrN-13667	3430±30 BP	1865 to 1845 or 1770 to 1690	1880 to 1835 or 1825 to 1795 or 1785 to 1675
GrN-13979	3375±30 BP	1740 to 1645	1750 to 1605 or 1555 to 1540
GrN-13980	3260±30 BP	1600 to 1555 or 1545 to 1510	1630 to 1490 or 1490 to 1455
GrN-13981	3340±35 BP	1690 to 1605 or 1560 to 1540	1735 to 1715 or 1705 to 1525
VRI-66	3450±120 BP	1930 to 1630	2135 to 2070 or 2050 to 1510

CALIBRATION: Pearson and Stuiver, 1986.

For this section it is useful to refer to the work of Jackson (1968, 1979 and 1980) and O'Brien (1987, 1990, 1994 and *et al*, 1990). The old red sandstones of the Hercynian Orgency, which cover much of south-west Ireland cover two principal forms of copper mineralisation: primary quartz sulphide veins and secondary sedimentary copper beds in the sandstones. The former outcrop in the sea cliffs and were extensively worked in the nineteenth century (Cowman and Reilly, 1988). It has been postulated that the upper oxidised zones of these deposits were extensively worked at the inception of metallurgy in Ireland in the later third millennium BC (O'Brien, 1990). These lodes would have included the fahl ores, rich in the other metals such as arsenic, antimony, silver and nickel which characterise the very earliest Irish metalwork.

Excavations at Ross Island, Killarney, Co. Kerry, have shown that the previously unexcavated but well-known early workings (Jackson, 1980) are associated with Beaker pottery of the Bell Beaker and AOC (all over corded) tradition, and have eight radiocarbon dates showing the mine was worked during the late third millennium (2400–2200 BC) and into the early centuries of the second millennium BC (O'Brien, personal communication, and 1994, pp. 229–30). The copper ore, which must have been mainly sulphidic, occurred in thrust fractures associated with quartz micro-veining in the lower carboniferous limestone at its junction with the old red sandstone (Figure 2.19). Stone and bone tools were found, including grooved hammers of old red sandstone river cobbles and shovels or rakes of ox scapulae, but little antler. The contemporary settlement which lay in the immediate vicinity of the mine has traces of copper smelting by simple, apparently non-slagging techniques in a shallow hearth, such as had been predicted from the paucity of smelting evidence from other sites elsewhere in the British Isles (Craddock, 1992b and 1993; O'Brien *et al*, 1990).

So far, this is a unique survival of the earliest phase of copper production in the British Isles; by contrast the syngenous sedimentary copper beds of which Mt Gabriel is a good example have abundant evidence of Bronze Age working in the second millennium BC, but with little indication of subsequent working. The copper mineralisation occurs within thin bands of grey-green coarse sandstone and calcareous conglomerate set in fine green and purple mudstones. The copper deposits are stratiform, that is they are controlled by the bedding of the surrounding strata. However the copper-bearing beds are not continuous in the bands, which themselves are faulted. Thus the copper ore occurs as discreet concentrations rather than in long veins. This of course determined the mining strategy, the mines being a series of small pits rather than linked galleries following a continuous vein.

FIGURE 2.19 Copper workings on Ross Island, Killarney, associated with Beaker material and dated to the later third millennium BC. The site has produced many grooved stone hammers.

At Mt Gabriel about thirty pits have so far been discovered on the south side of the hill, driven into the green sandstone beds in the purple mudstones (Figure 2.20). The mines are generally just drifts following the strata, but in one instance (mine no. 3) investigated by O'Brien and his team, the Bronze Age miners after following the strata in for five or six metres then decided to work *across* the bedding and tunneled for a further five metres.

Glacial action has removed any weathered horizon and the rock is hard with few cracks or fissuring, thus firesetting was always necessary (Figure 2.21) before mining with stone hammers, and possibly antler and bone tools which would not have survived in the acid peats. The hammerstones which litter the hillside of Mt Gabriel in enormous numbers are beach cobbles brought from Schull Bay less than 5 km to the south. They have little hafting evidence beyond the nicks pecked onto the central midribs on approximately 30 per cent of them (Figure 2.11). A separate handle of twisted withy has been found together with the wooden 'prickets' discussed above (p. 47) and the short-handled shovel (Figure 2.17). (Note the similarity to the shovel found with the 'copper man' from Chile (Figure 2.13).) A number of partially burnt pine splint lights have also been recovered.

FIGURE 2.20 Typical mine entrances at Mt Gabriel.

The principal ore mined is now believed to have been malachite together with some adventious sulphides, and this would have required careful beneficiation. It has been suggested that the ore was crushed in the immediate vicinity of the mines and the ore removed by hand picking, leaving behind heaps of crushed rock and stone tools. Some stone slabs and concentrations of stone crushing tools suggest that some of the ore was more finely crushed in order to release the finely-dispersed primary ore for separation by washing, although no direct evidence of the latter process has been identified. As with most early mines the walls have been picked clean of mineral and the heaps of crushed debris are remarkably free of copper mineral; very little was missed or wasted.

Based on the surviving site evidence, Jackson (1980) suggested that at least 300–400 tons of copper were produced in the Early Bronze Age in the south-west of Ireland. However, continuing survey and excavation on Mt Gabriel suggest these estimates need to be considerably scaled down. Metal production over a 200-year period in the Early Bronze Age is now estimated to have been between 20 and 27 tonnes of copper, giving an annual production of about 133 kg at best, but still enough to make 400 or so flat axes (O'Brien, 1994). Even so this activity may have had some lasting effect on the environment, at least locally. The replacement

FIGURE 2.21 Small fireset trial at Mt Gabriel. Note the smooth continuous face, typical of fireset work.

of deciduous forest by blanket peat bogs over much of south-west Ireland during the first half of the second millennium BC is well attested, and although climatic deterioration was fundamentally responsible for this change, the persistent removal of very large quantities of wood from a fragile environment for the purposes of mining and smelting may have exacerbated the situation, and even contributed to further peat formation.

Whether through lack of ore or fuel, climatic deterioration or changed economic conditions, the mines of south-west Ireland seem to have passed out of use before the end of the second millennium BC, and remained so until they attracted renewed interest during the nineteenth century, when miners clearing out the old workings found and pondered on the tools of the ancients.

For this section it is useful to refer to the work of Ambers (1990), Hughes (1981) and Timberlake (1987, 1990b, 1990d, 1992a, 1992b and with Mighall, 1992). The mine has a long history, with continuous exploitation for silver and lead from at least the medieval period to become one of the largest and most successful producers of lead and zinc in Wales during the eighteenth and nineteenth centuries (Hughes, 1981). Copper is also found in the veins and this was the metal exploited in the second millennium BC. The country rock is of Silurian gritstones and shales, and the epigenic mineralisation occurs in lodes of quartz, with some iron carbonates. The main copper-bearing deposit was Comet Lode, which was probably the only one to be exploited in antiquity and is of considerable width, varying between 1 and 6 metres. The lode runs almost vertically down the side of a heavily-glaciated valley, and would only have been exposed at the top, from where it was mined in antiquity, the rest being buried under glacial scree. In the ancient tip running down the hillside are quite sizeable lumps of galena, discarded by the Bronze Age miners, but conversely the tip from a recent shaft which cuts through the ancient working contains considerable quantities of chalcopyrite. This shaft was sunk by prospectors who were looking for lead and zinc ore and were not interested in the relatively small amount of copper ore. Thus it is probable that chalcopyrite was also the predominant copper mineral present and mined in the Bronze Age. Due to the great width of the ore body the ancient workings take the form of an opencast which follows the ore down from the exposed top of the vein near the summit of Copa Hill (Figures 2.22 and 2.23). The opencast is about 25 metres long and recent excavations through the shale and mine debris followed the sides down for 7 metres below the present level of the fill with no sign that the bottom was near. A small gallery cut in one of the sides was encountered with the very well preserved marks characteristic of stone hammer mining (Figure 2.24). At the back of the gallery a natural fissure or *vug* continues on up for a further metre or so but is never more than a few centimetres wide. The gallery was probably following this vug out from the main vein and similar buried galleries may well exist elsewhere in the sides of the opencast. The remains of the spoil tip run down the steep side of Copa Hill for over 100 metres and stone hammers and debris can be picked up down the hillside below for several hundred metres. At some time in the past it appears that the old tip was partially removed, possibly to recover the discarded lead ore and to prospect the hillside beneath. This was done by hushing, damming up the front of the old opencast with a turf dam to form the reservoir (see p. 89). This makes it very difficult now to estimate the original scale of the workings.

FIGURE 2.22 Four thousand years of mining history at Copa hill, Cwmystwyth. Note the series of channels directing water from the dam (Figure 2.49) to remove the glacial debris covering Comet Lode (running vertically down the hillside). The Bronze Age workings are at the very top of Comet Lode.

FIGURE 2.23 Bronze Age copper mine at Copa Hill, Cwmystwyth. Because of the width of the lode the mine developed as an opencast.

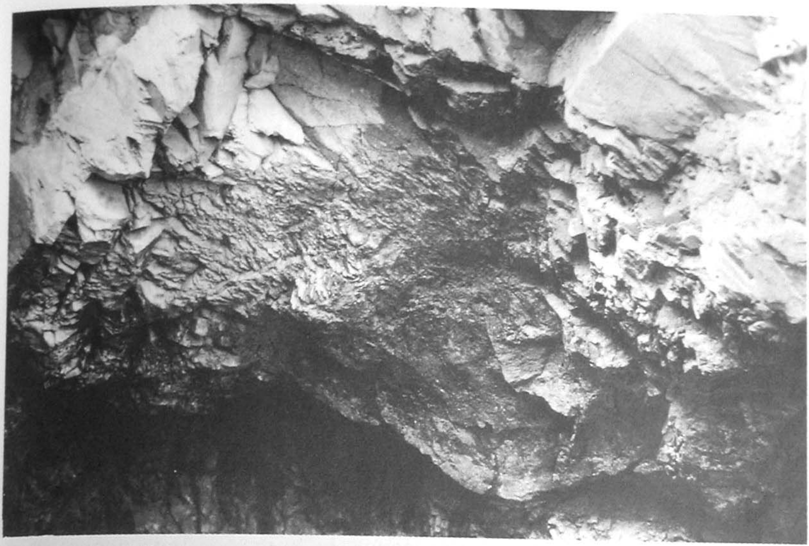


FIGURE 2.24 Well preserved batter marks made by stone hammers in the roof of a small gallery in the main opencast at Cwmystwyth. (The width of the rock shown is about 50 cm.)

The dumps contain an exceptional concentration of hammerstones. These are principally of local gritstones, sandstones and quartzitic sand stones and although some could come from the Ystwyth river, their smoothness and sphericity suggest that many were beach cobbles brought from the coast at Aberystwyth some 30 km away. They are typically between 12 and 30 cm in length, but include both larger and smaller examples, including flakes from the larger hammers that have been hafted to form small, thin hammers. Some of the hammerstones had been reused as anvils for grinding the ore. Only one small poorly-preserved fragment of antler has been recovered from the acidic environment of the heaps, but it is likely that antler could have been extensively used. The tip also contained quantities of charcoal from the firesetting operations; the majority seems to have been of oak (Timberlake and Mighall, 1992), as at the nearby site of Nantyreira, Hafron Forest, and also at Parys Mountain, Anglesey (Timberlake, 1990c), but some ash and hazel charcoal was also present. Radiocarbon dates from this charcoal show the mine was operating in the early and mid-second millennium BC (Table 2.1).

Cwmystwyth is just one of about twenty similar mines in central Wales where stone hammers have been found, usually in quantity. At most of these mines lead and zinc ore were the predominant minerals, but it seems that the stone hammers were located near those parts of the ore body where the copper mineralisation was concentrated. The lead ore discarded in the ancient tips suggests it was of little interest to the ancient miners. There is at present no evidence for lead mining in Britain coeval with the use of the stone hammers, although the smiths must have been aware that the dense, distinctive galena mineral could be easily smelted to lead and, significantly, Welsh bronzes of the Early Middle Bronze Age from the Acton Park phase do contain up to about 7 or 8 per cent of lead (Northover, 1980). It was not until the very end of the Middle Bronze Age that leaded bronzes began to be used in quantity in the rest of Britain (Brown and Blin-Stoyle, 1959), but the source of the lead is presently unknown.

Central Wales has one of the largest concentrations of stone hammer mine sites in Europe, and together with north Wales and south-west Ireland contains the majority of such mines found in the British Isles (Figure 2.18). The excavation work carried out to date at Cwmystwyth, Nantyreira (Timberlake, 1990a) and at Llancynfelin (Timberlake, 1992b) suggest the mines were worked in the Early and Middle Bronze Ages, when the region must have been of some economic significance. This is possibly reflected in the greater evidence for human activity generally in the central mountainous regions of Wales compared to that during the preceeding Neolithic period.

Rudna Glava

The prehistoric mines at Rudna Glava (Jovanović, 1971, 1979, 1980, 1982 and 1988) are a series of small closely-spaced pits following the malachite copper ore (Figure 2.25). The original extent of the prehistoric mining is difficult to estimate as recent opencast mining for the magnetite iron ore of the gossans has probably removed the majority of the original mines, leaving only those at the periphery. The country rocks are mainly of limestone and marble and the copper ore lodes contain quartz with some carbonate rocks associated with the iron and copper secondary minerals. About forty shafts have so far been discovered averaging about 15 to 20 metres in depth and 0.7 to 2 metres across, although as the excavator has emphasised, the size and shape was determined by the ore present; in no way should they be regarded as planned mines. The surface material was very loose and thus the sides of the shafts had to be battered, giving them a funnel-shaped profile in their upper parts, sometimes reinforced with drystone walling to minimise the danger of collapse. Below this, a step was normally cleared above the vein itself, to facilitate mining by creating an access platform and to stop any loose material that might roll down from above carrying on down into the shaft proper. Firesetting is claimed to have been practiced, but there is remarkably little charcoal in the waste material. Over 200 mining hammers of the

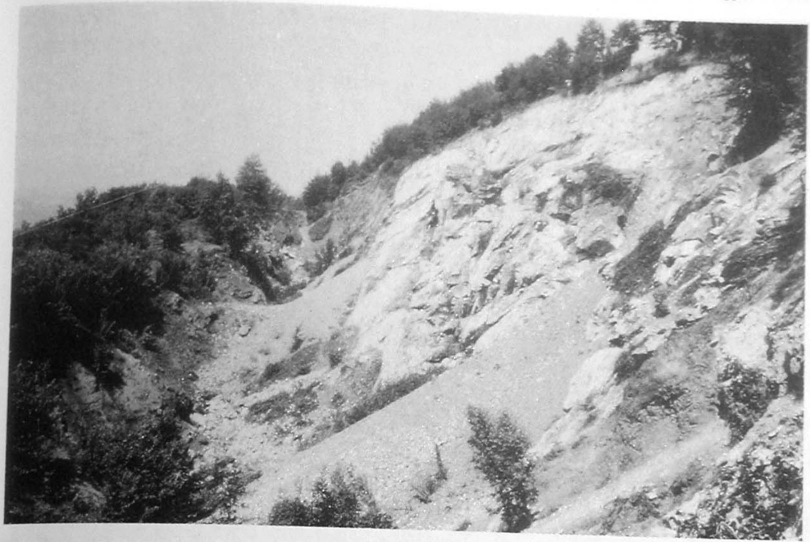


FIGURE 2.25 Mining operations at Rudna Glava, former Yugoslavia. Modern opencast mining for iron ore led to the discovery of Eneolithic copper mines. The mines lie exposed along the right side of the pit.

familiar hard rock river cobbles have been found. Most of these have a continuous groove pecked around the middle for a rope or withy handle, but some of the illustrations (Jovanović 1982, pp. 55, 57, figs 135–140) seem to show notching rather similar to that found on the Welsh hammers. Unused cobbles without any grooves were found on the access platforms suggesting that the miners carried out hafting on the spot as the need for new hammers arose. Because the deposits are calcareous, bone and antler survive, and the remains of ten antler picks have been reported so far. The mines contain a remarkable quantity of pottery including caches of high quality vessels. It is possible that they were used for carrying drinking water, but they do seem rather fine for such a mundane task, and the presence of an altar with one group suggests they could have had a more ritual function within the mines. Shrines within ancient mines are not well attested but should come as no suprise to anyone familiar with the shrines to St Barbara in the mines of Catholic countries or to Durga in Indian mines. The pottery is of the Early and Middle Vinca period, which should date the mines to the first part of the fourth millennium BC.

There must be many more mines similar to Rudna Glava in the Balkans. Stone hammers have been reported from other areas of Serbia such as at Jarmovac, where Davies (1937b) reported grooved stone hammers, and at Rudnik, where pits containing enormous numbers of

FIGURE 2.26 Major Bronze Age copper mining at Great Orme's Head, Llandudno, north Wales, showing part of the opencast exposed by removal of later mining debris.

grooved stone hammers have recently been investigated (Jovanović, 1988). The mine at Ai Bunar in Bulgaria from which malachite was also obtained probably began in the fourth millennium BC and with Rudna Glava represents the earliest mines in Europe (Černych, 1978).

Great Orme's Head, Llandudno

For this section it is useful to refer to the work of Davies (1948), James (1988), Jenkins and Lewis (1991), Lewis (1990a and 1990b) and Smith (1989). The Great Orme is a prominent headland of Carboniferous limestone jutting out into the Irish Sea. Extensive dolomitisation has provided the host areas for the primary epigenic sulphidic mineralisation, principally of chalcopyrite. In this soft fracture rock firesetting was probably not usually necessary, except perhaps at depth. The ancient workings are very extensive as recent underground exploration, and the removal of thousands of tons of nineteenth century mine debris from the original surface and ancient workings, has revealed (Figure 2.26). Indeed this is the largest prehistoric mine in Britain, and must be amongst the largest in Europe. So far only limited exploration of the ancient mine has taken place, working out from the nineteenth century shafts and galleries into the earlier underground workings that are often choked with stacked mine waste, now cemented together with calcite flow stone deposited by the calcareous mine waters. Extensive study of the mines now suggests that the Middle Bronze Age miners dug out the ore from where it outcropped at the surface creating a series of extensive opencasts possibly extending over 100 m and then following the ore down into the hillside to a depth of at least 40 m in a system of complex and tortuous workings following the ore-filled veins and fissures (Figure 2.27), rather than by working in and down from the side of the valley into the hillside and penetrating for a very considerable distance from the entrance as was tentatively suggested previously (James, 1988, fig. 1).

Stone hammers have been recovered, but not in enormous quantities, and few of them seem to show signs of extensive heavy use. This could be a consequence of the weak nature of the host rock, or on the very tough igneous rock used for many of the hammers. Few hammers show signs of hafting, and they include a number of very large specimens weighing up to 30 kgs that must have been supported in a cradle and swung against the rock face (see p. 73 for parallels).

Enormous quantities of bone survive in the alkaline limestone environment. Some of the long bones have clearly been utilised as tools, but the vast majority must represent food debris. The distribution of the bone throughout the mine suggests that it was deposited by the miners as the remains of meals. It is rather surprising that no pottery has been recovered, suggesting that some other material was used for containers.

A few mortar stones have been recovered from the site suggesting that the ore was crushed there. The majority of the ore was probably separated manually, but there is some evidence for ore washing at springs lying a few hundred metres from the mine, where heaps of crushed rock and vein stuff with flecks of charcoal and fragments of bone and stone tools have been found. However a radiocarbon date of about 1200 BP obtained on a fragment of bone suggests this is a much later operation.

The radiocarbon dates show the mine had a long life extending through the later part of the second millennium BC and on into the first millennium BC, and in that time very large quantities of ore must have been mined. There is no evidence for smelting activities, although there are undated hut circles in the vicinity which could be the remains of a settlement connected with the mines.

The Mines of the Developed Bronze Age

The role of metal in the establishment of the first great civilisations in the Near and Middle East has been discussed at length elsewhere (Renfrew, 1972 for example) and only the technology of metal production in the Bronze Age will be considered here. The most fundamental technical developments were in the smelting technology, with the adoption of

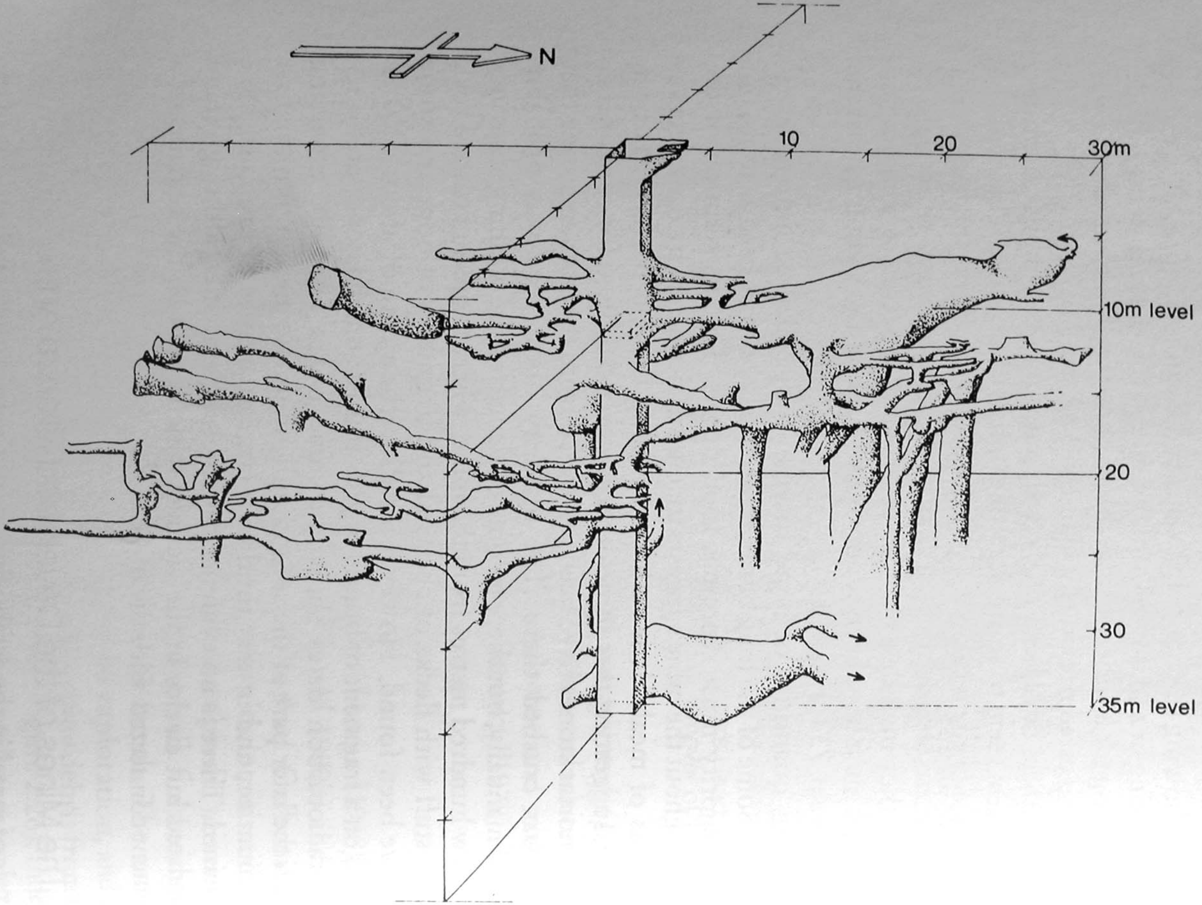


FIGURE 2.27 Three-dimensional plan of the workings in a small part of the mines at *Great Orme's Head (10m level, Vivian's shaft)*, showing the complexity of the workings. *Note the nineteenth century shafts with square sections.*

slagging processes as described in Chapter 4. Overall, the major differences from the more primitive prehistoric mines was in scale and in organisation.

Form of the Mines

Large-scale mining and smelting operations were often established in remote mountainous regions hundreds of kilometres from the great river valleys that formed the natural heartlands of the early empires. The locations were often both environmentally and politically hostile and their establishment, provisioning, maintenance and defence must have created major logistical problems.

As before, the form of the mine was largely dictated by the nature of the ore body, and in many respects was little different from the more primitive mines. There is little evidence of developments in mine drainage which would have enabled the mines to go below the water table, or in general for any form of controlled ventilation, which would have enabled mining to extend beyond the immediate vicinity of the shaft. One of the most noticeable features of mines such as Timna in southern Israel are the hundreds of small shafts separated from each other by only a few metres (Figure 2.29). Closely-spaced shafts are typical of early or primitive mining systems found in very different localities and geological conditions, such as the European Neolithic flint mines as exemplified by Grimes Graves in Norfolk, England (Sieveking, 1979), or recent gold mines in alluvial deposits at Mali, West Africa (Armbruster, 1993). In all of these mines a series of small restricted workings radiate out from the shaft for a short distance to link up with the galleries from the adjacent shafts to create a veritable maze of small tunnels. In such restricted spaces with no provision for the movement of air the working atmosphere would have become foul only a very short distance from the shaft, especially if lamps were burning, and this seems to be the primary reason for the provision of such prodigious numbers of shafts. The smoke and fumes from firesetting would greatly exacerbate the situation, but this was certainly not the prime problem, and the draughts created could conceivably in some situations have helped air circulation.

Tools

The principal change was the adoption of metal tools. Thus chisels, picks and digging sticks now tended to be tipped with copper or bronze (Figure 2.28), and the distinctive cut marks made by them on the rock face can be immediately recognised (Figure 2.9). The extent to which metal hammers were used with the chisels is much less certain as no distinctive marks would have been left and the putative metal hammers themselves would not have been abandoned.

FIGURE 2.28 Copper pick head from Late Bronze Age copper workings at Timna.

The Timna Mines

For this section it is useful to refer to the work of Rothenberg (1972, 1988, 1990; Conrad and Rothenberg, 1980). The mines of Timna in the Arabah valley, now in southern Israel, are amongst the most extensive and best preserved of the great Bronze Age mines, and in addition have been more extensively studied than any other mine system. A brief description here will give some impression of how such a mining camp functioned.

Copper is quite widely distributed through the Sinai peninsula and archaeological surveys have revealed numerous early mining and smelting sites. These are especially prevalent along the sides of the Arabah valley which cuts through the limestones and dolomite country rocks exposing the metalliferous white Nubian sandstones. These sandstones are very soft and permeable and have been penetrated by epigenic

FIGURE 2.29 Area of densely clustered shafts at Timna. Each circular 'plate' represents a buried shaft.

deposits of copper mineralisation, typically in the form of nodules of malachite with some residual sulphidic minerals, chalcocite, brochantite and bornite. The Wadi Timna itself is a great erosional circus that has cut back into the line of the Arabah cliffs, creating a deep ampitheatre walled by cliffs of limestone towering many hundreds of metres above the wadi floor. Beneath these the white sandstone lies exposed, and here the evidence for ancient mining activity is concentrated. The processes of erosion have of course continued since mining ceased and the flash floods that periodically pour down from the Sinai plateau have cut deep channels, washing out nodules of ore so that one can now pick up kilograms of ore from the surface in a short time, much as the first metal smiths must have done at the time of the mines' inception. The exposed outcrops of ore would have been followed back into the sandstone and some of the ancient galleries show very clear evidence for the use of stone hammers (Figure 2.9).

Many of the galleries were reworked in the Late Bronze and Early Iron Ages and it is now difficult to judge the extent of the earlier workings. Only one typical grooved stone mining hammer has been found at Timna and the other stone mining tools found in quantity are the perforated doughnut-shaped ring hammers, pecked and ground to shape from cobbles of hard rock (Figure 2.30). For all their ubiquity at Timna, their date or even function is not at all certain. Where mines have been re-used, and the old debris cleared out, it can be difficult to assign simple

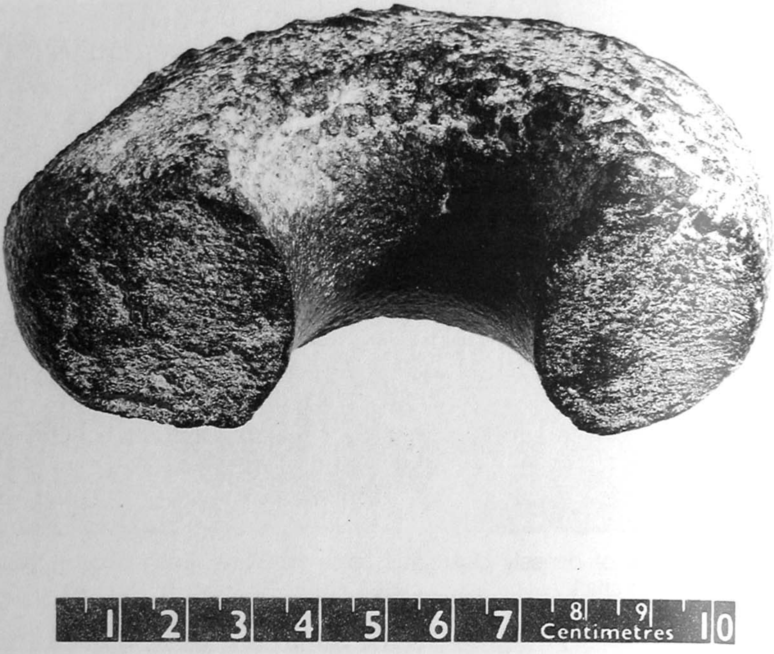


FIGURE 2.30 Broken stone ring 'hammer' from Timna. These are described as hammers, but they could have functioned as weights for digging sticks.

tools lacking any diagnostic feature to their correct period. The stone ring tools have previously been interpreted as Ramesside, Late Bronze Age hammers (Rothenberg, 1972, pl. 20, p. 63), and presumably used in conjunction with the metal chisels and picks. Weisgerber and Hauptmann (1988) have suggested that they are Chalcolithic, based on discoveries of similar tools at the mines at Feinan on the opposite side of the Arabah valley in Jordan, where they are found in unambiguous Chalcolithic mines, although tool marks are not well preserved on the walls due to reworking by the Romans. They also occur on Sardinian Nuragic bronze-working sites, dated to the late second to early first millennium BC, but not obviously associated with mining (Gallin and Tykot, 1993). At Timna they seem to occur in areas of the mines where there are now only metal chisel marks on the gallery walls and it does seem a little unlikely that the Egyptian miners would have removed all trace of the putative original stone hammer marks.

Functionally the ring 'hammers' do not seem very satisfactory tools for delivering hard blows either directly to the mine walls or to the chisels. They are very light, typically weighing only about a kilogram, and the perforation itself is an obvious point of weakness in a hammer.

Furthermore, tools intended for a short life of heavy usage would not be expected to be so carefully worked to a regular shape. A possible alternative is that they could be the weights from a digging stick possibly tipped with some of the crude socketed bronze points found on the site. However, none of these explanations is wholly satisfactory and some experimental work with replicas of these stone tools would be very useful.

During the fourteenth century BC the area attracted the attention of Egyptian prospectors and an enormous enterprise was established to mine and smelt the copper. This period of activity lasted for about 150 years through the thirteenth century BC, and the reigns of Seti I and Ramesses II, until the time of Ramesses V in the mid-twelfth century BC when activity ceased abruptly with the general collapse of Egypt's Asiatic Empire.

Mining activity from the Egyptian period is attested all around the edges of the Wadi Timna and extensive field survey and aerial reconnaissance have estimated that there are over nine thousand mining shafts spread over many square kilometres. These mines would have developed pre-existing workings or followed freshly exposed ore where it outcropped in the wadi sides. At this stage the horizontally-bedded ore was also followed further in from the wadi sides by sinking shafts down from above to link up with the ever spreading system of galleries. Clearly this was only feasible where the ground surface did not rise too swiftly to meet the encircling cliffs. At Timna the three principal areas of fairly level ground surface are each pock-marked by hundreds of buried shafts, often separated by only a few metres (Figure 2.29). Some of these were exploratory, but this great density of shafts was probably necessitated by the general absence of any ventilation system underground. There was, for example, no evidence of fires at any of the shaft bottoms to draw air through the galleries, although one ventilation shaft was identified (Mine 52, shaft 52/3, Conrad and Rothenberg, 1980, p. 165). Firesetting was not necessary to weaken the soft sandstone which was mined directly with copper and bronze tools of which a few examples have been found (Figure 2.28). The tool marks on the sandstone walls are remarkably well preserved, and include both the triangular wedge-shaped marks of the pick blows and the long, running scratches made by chisels (Figure 2.9).

The excellent preservation of the tool marks has enabled some of the mining methods to be reconstructed quite precisely (Conrad and Rothenberg, 1980). The ubiquitous small shafts were sunk by chiseling out an annulus of rock to a depth of about 10 cm, then breaking up the stump of rock remaining in the middle, and repeating the operation to continue down (Figure 2.31) (Conrad and Rothenberg, 1980, p. 74). The resulting shafts are circular and quite regular and well-finished with few protruberances or irregularities that could have impeded the raising of

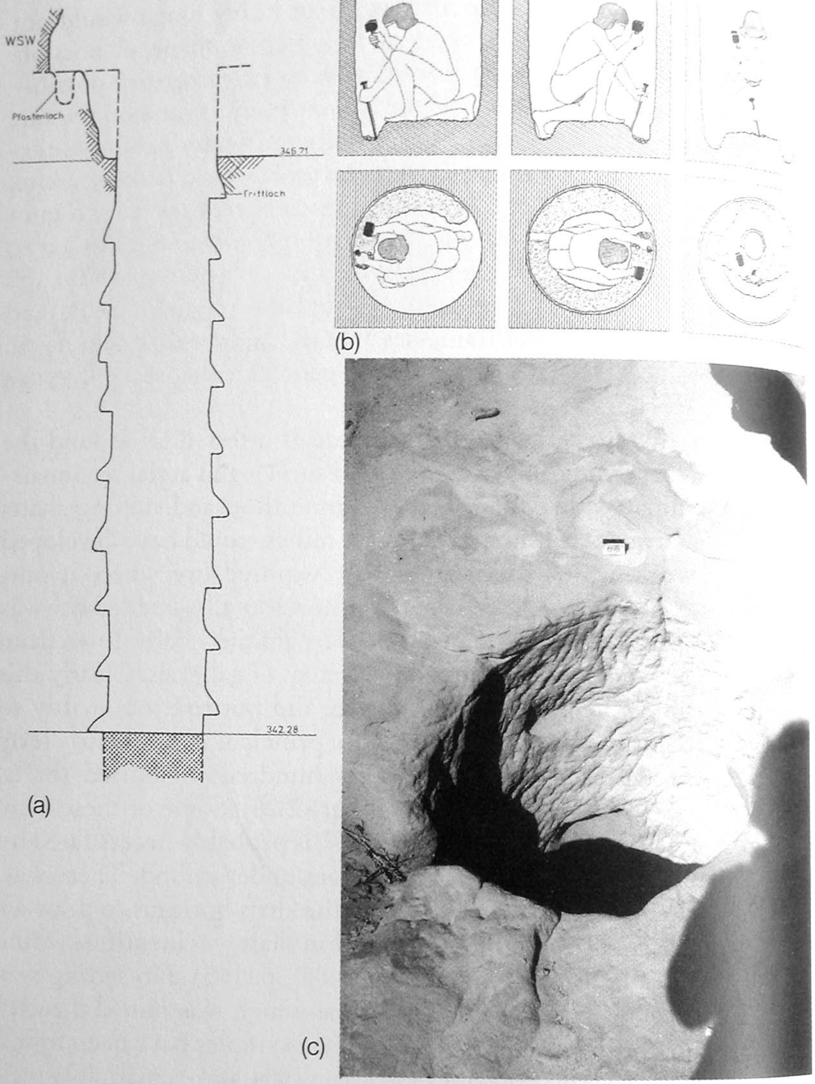


FIGURE 2.31 (a) Typical mine shaft at Timna, Abb 188, Area T Schacht T, 34/2; (b) the postulated method of sinking them; (c) the top of such a shaft. Note the footholds and chisel cuts.

material. The shafts are typically about 60–80 cm in diameter and up to 10 metres deep. In some, footholds were carefully cut, every 30–50 cm or so, although occasionally footholds were left protruding out into the shaft. At the top of some of the shafts are pairs of post holes, presumably to take the uprights of a windlass or some form of raising gear. The shafts served a complex series of galleries underground (Figure 2.32), their shape being largely dictated by the ore body. Where that was not the prime consideration they tend to be rather square in section, although with somewhat bowed-out roofs and walls, typically between 0.5 and 1 m across. The galleries seem to have been advanced by undercutting the rock face at floor level for about a metre beyond the working place, leaving long straight parallel scratches on the walls. This must have been done by chiseling at far arms' length, or using digging sticks as postulated above. Having made the deep undercut, the rock above could then be attacked and large lumps detached.

The host rock is little fractured, and although soft it is quite sound and no supports were needed in the small galleries. The workings survive to this day in pristine condition with little or no collapse or damage beyond that caused by seasonal torrents running through them. Sudden flash floods coming down from the plateau above probably brought about occasional but catastrophic damage to the mining operations.

Despite its extent and seeming complexity the Timna system of mines was basically a small mine repeated thousands of times over until the available ore was exhausted, and beyond the extensive use of metal tools shows little real superiority over the Bronze Age mining systems in temperate Europe. The mines were small, shallow and, although linked underground, display little evidence of any overall mining strategy, or of any knowledge of the possibilities of ventilation or drainage.

Mine Systems of the Iron Age Civilisations

The first millennium BC saw the development of secular philosophy and science throughout the Old World. It is an interesting speculation whether the increasing sophistication of the mines and other engineering works, notably those connected with canals and water supply, inspired and created the need for theoretical science or if the increased levels of theoretical knowledge, above all in mathematics, was translated into practical use in mining. As in the Industrial Revolution over two thousand years later, the answer is probably that the two went hand in hand. It is very noticeable that in those parts of the world where formalised knowledge flourished, sophisticated mining systems also developed.

Form of the Mines

During the first millennium BC in civilisations stretching from the Mediterranean through the Middle East to India and China, mining technology developed dramatically (Shepherd, 1993). Although basically the workings still followed the ore fairly closely with little apparent

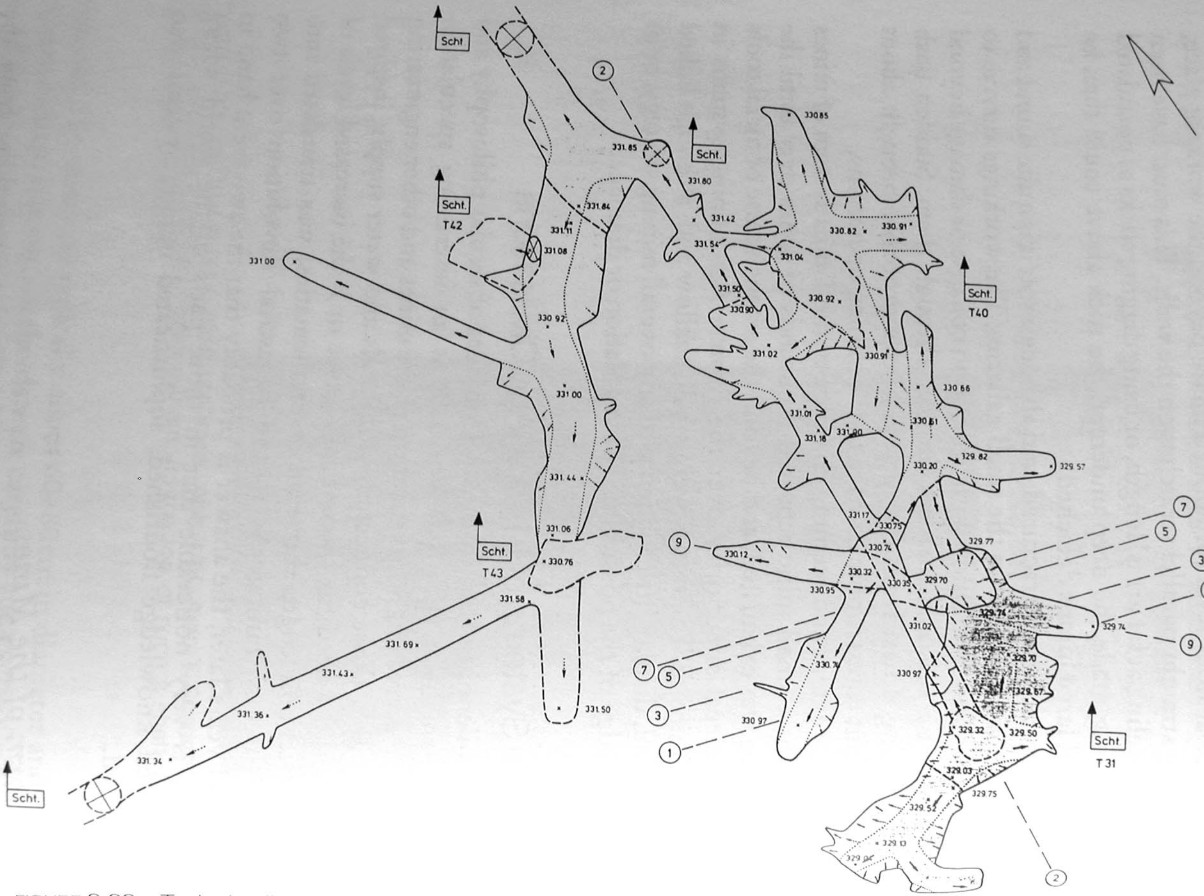


FIGURE 2.32 Typical gallery system at Timna (crossed circles represents shafts).

understanding of their geology, there now seems to be much more evidence of overall underground planning and layout, based on at least practical engineering knowledge backed up by good surveying. The mines of this period now regularly penetrated well below the water table and ran for hundreds of metres beyond the shafts as the problems of drainage and ventilation were overcome. Where major ore bodies required the removal of large quantities of material, adequate support had to be provided either by timbering, or in the form of pillars of ore, which were left for removal only at the end of the mining operation, as evidenced at Zawar in Rajasthan (Figure 2.36). Timbering was especially necessary when mining through loose or soft ground. The massive timbering at the Chinese copper mines at Tonglushan in Daye county, Hubei (Figure 2.33) (Anon, 1980; Zhou Baoquan *et al*, 1988) and at Tongling in Ruichang County, Jiangxi (Shizong Liu *et al*, 1993) provide good examples of this.

Methods and Tools

The basic methods of deep mining, firesetting and pick and chisel work remained the usual methods of rock breaking as shown by Diodorus Siculus describing Egyptian goldmines of the first century BC (Oldfather, 1933):

> The gold-bearing earth which is hardest they burn first with a hot fire, and when they have crumbled it in this way they continue working it by hand. (III, 12, 1–13, 1)

and continues elsewhere:

> The soft rock which can yield to moderate effort is crushed with a sledgehammer by myriads of unfortunate wretches. And the entire operations are in the charge of a skilled worker who distinguishes the stone and points it out to the labourers; and of those who are assigned to this unfortunate task the physically strongest break the rock with iron hammers, applying no skill to the task but only force and cutting tunnels through the stone, not in a straight line but wherever the seam of gleaming rock may lead. (III, 12, 4f)

Iron was clearly a much stronger and cheaper metal than bronze and could be used more extensively resulting in a greater variety and number of metal tools. In addition, more of the tool could itself be of metal; thus for example, a pickhead would no longer be of wood shod with bronze but made wholly of iron, and with the same variety of chisel, point and adze ends that are found on modern picks (Figure 2.34). Hammer heads were now of iron and often quite substantial, and once again identical to their modern counterparts, although stone hammers may have

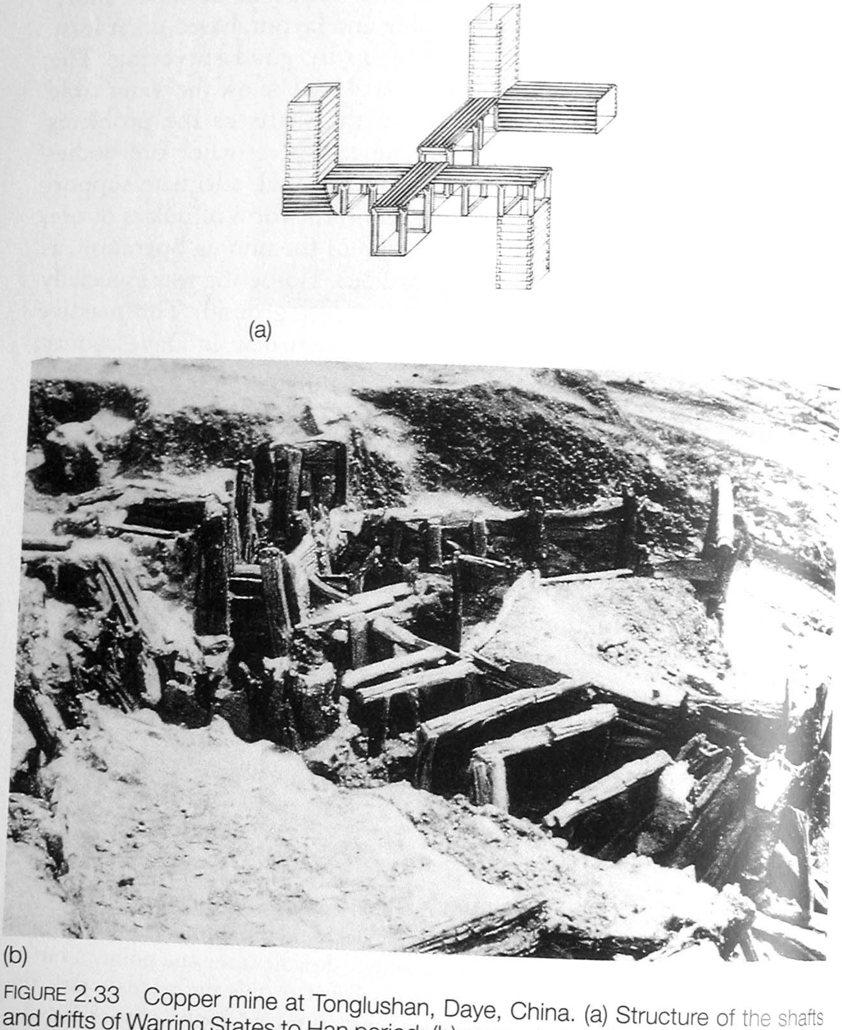
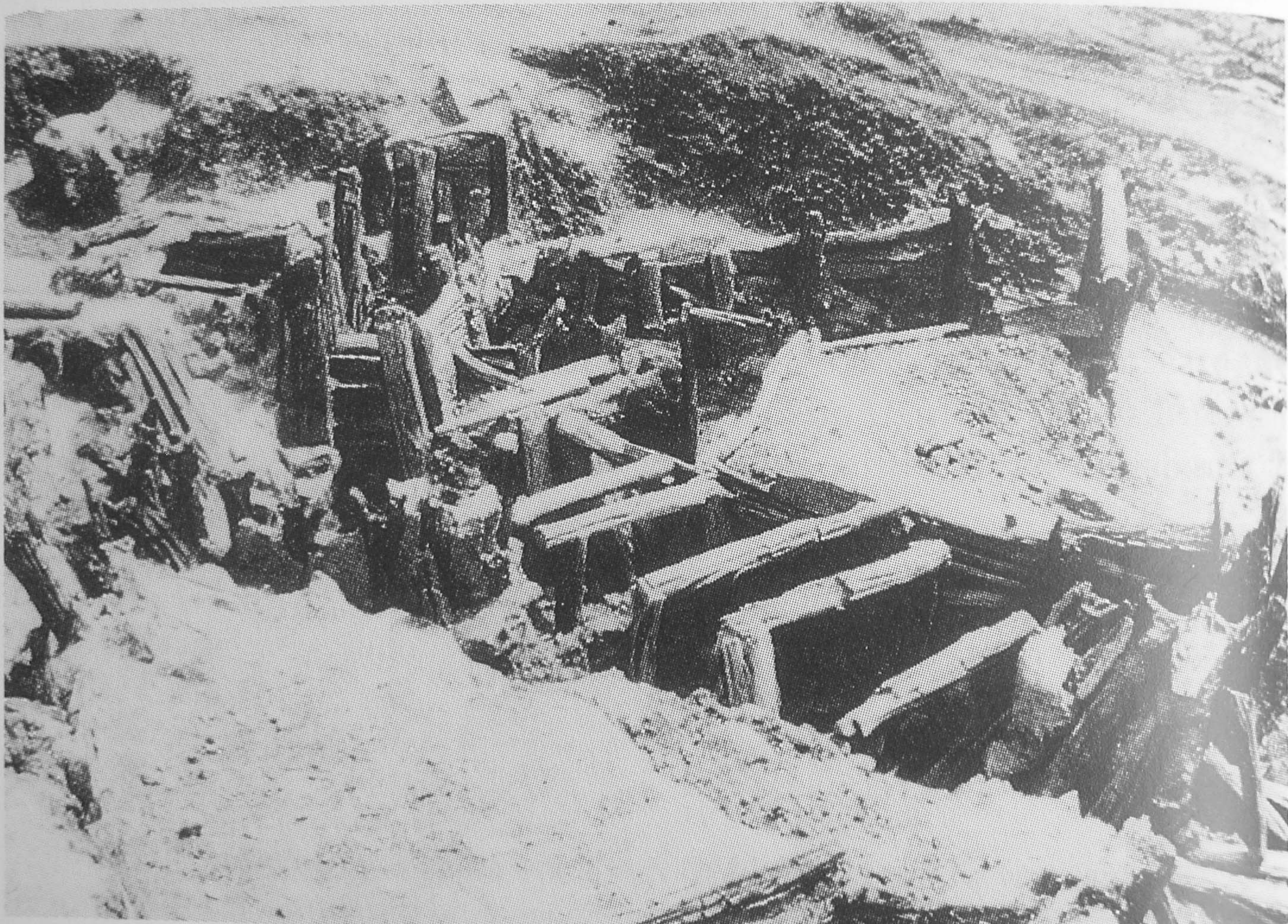


FIGURE 2.33 Copper mine at Tonglushan, Daye, China. (a) Structure of the shafts and drifts of Warring States to Han period; (b) excavated underground layout (*c.* fifth century BC to second century AD). Note the massive timbering needed to support the workings.

continued in use for ore crushing until post medieval times. Rakes and shovels which formerly were of such materials as wood or bone were also now of iron, or at least iron shod (Figure 2.35). Indeed the surviving mining tools are virtually indistinguishable from their modern counterparts in form, although the quality of the metal itself was usually inferior. Examination of a variety of contemporary iron tools has shown that even when attempted, the smiths were rarely completely successful in



(b)

FIGURE 2.34 Selection of Roman iron pick heads and wedges from Rio Tinto.

converting the wrought iron into serviceable steel (see Chapter 7, p. 238 and Tylecote and Gilmour, 1987). Even so, the introduction of iron tools must have increased the overall efficiency of mining, especially when working in a confined space.

In his description of gold mining in the *Natural History* (33.71) Pliny describes the use of machines with iron heads weighing up to 150 lbs to attack the rock. These were almost certainly battering rams. In the contemporary mines at Zawar in India, wooden bipods still survive from which similar battering rams were slung to attack pillars and slabs of rock (Figure 2.36) (Willies, 1987).

Ventilation

The inability to ventilate a mine working for more than a few feet from the shaft had clearly been a major constraint on the development of deep mining. Hubert (1974), in his report on the flint mines at Jandrin-Jandrenouille in Belgium, stated that the maximum distance the miners could work from the shaft was four metres before the air became too foul, although it has been suggested that in some other European flint mines there was artificial ventilation induced by carefully siting the heaps of deads to create channels and fires maintained at strategic points to draw air through to the workings (Migal and Kaminski, *nd*). The possibilities of controlling the draughts created by firsetting or of making draughts especially for ventilation must have been evident. The most obvious

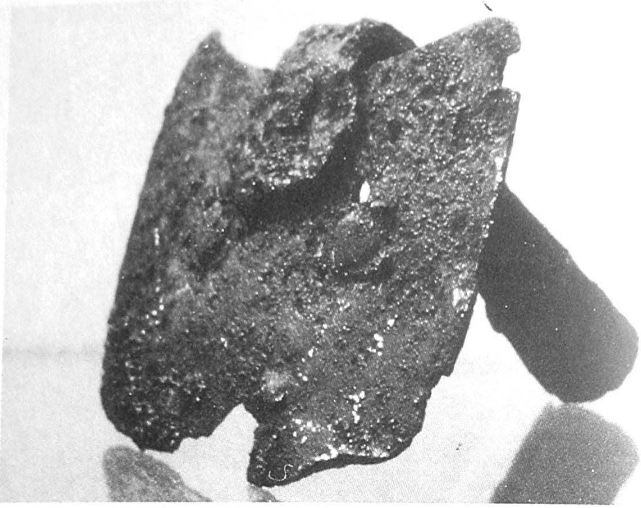


FIGURE 2.35 Roman iron rake from Rio Tinto.

FIGURE 2.36 Wooden bipod in top chamber of Zawar Mala Magra mine. It seems likely that a heavy timber was swung from it against some of the support pillars in a late phase of the main working over two thousand years ago. (The scale is in 20 cm intervals.)

A—TUNNEL. B—LINEN CLOTH.

FIGURE 2.37 Ventilation systems using linen clothes.

method was to induce a draught by lighting a fire at the base of one shaft so that the hot rising air and gases would pull air drawn from other shafts through the galleries. By the careful arrangement of the heaps of waste material stacked within the worked-out galleries as well as by doors and shutters it was possible to control the flow of air through the mine, directing the fumes from firesetting operations away from the rest of the mine, and bringing some measure of fresh air to the miners, although the comments of some of the ancient authors on the conditions within mines suggest conditions were often far from ideal. Evidence of the control of air flow by shuttering has been found at Tonglushan (Zhou Baoquan *et al*, 1988, p. 127). One simple system was to sink shafts in pairs to create a movement of air in the workings between them. A similar result was achieved with a single shaft by partitioning it down the middle with a brattice and inducing a draught by a fire on one side to suck air down the other and through the workings (Healey, 1978, p. 83). Grooves running down the sides of some ancient shafts have been taken as evidence of this, but it must be admitted that traces of wooden partitioning have not been found at mines such as Tonglushan or Dariba, where other shaft timberwork survives in quantity. Pliny (31.49) mentions the use of linen fans, perhaps used in the manner of the Indian *punka*, and illustrated in *De re Metallica* (Figure 2.37), and in China fans were in use from an early period and would have been well-suited to mine ventilation.

FIGURE 2.38 Drainage channel at Zawar made from a hollowed tree trunk and used to channel water to points where it could be collected and carried out of the mine.

Drainage

There are three basic ways to deal with the problem of drainage, and the choice would of course be largely dictated by the particular circumstances of the mine. Where possible the miners would have tried to minimise the flow of water into the mine workings. For example the vein material at Dariba is fairly impervious, and whilst the miners kept within the vein, leaving some at the sides to act as a shield, the drainage problems were containable (see p. 85).

Many mines are situated in mountainous terrain where the valley

FIGURE 2.39 Wooden bailing dam in the side of a shaft at Dariba, dated to the third century BC. The ladder on the right is modern, that on the left is ancient.

bottoms are well below the mine levels, and in these cases it is possible to drive a gently sloping drainage channel (*adit*) in from the valley side to come up under the mine and lead away the water. Major adits were driven by the Romans to drain some of their workings at Rio Tinto. The main adit was over 3 km long, and when the mines reopened in the late nineteenth century it was refurbished and continued to drain the mines for the next century (Salkield, 1987, pp. 10, 40).

Where direct drainage was impractical, the water would have been collected underground (Figure 2.38) and raised up to the drainage level or out of the mine altogether. This could be done in a variety of ways; buckets or pots of water could simply be carried manually or raised on a windlass. If the shaft was on an incline then the water could be removed by bailing up through a series of ponds such as Pliny described at the mine of Baebelo in Spain, which is probably to be identified with Rio Tinto:

> the tunnelling having been carried a mile and half into the mountain. Along the whole of their distance watermen are posted who all night and day in spells measured by lanterns bale out the water and make a stream. (33.97)

At Dariba the recent mine survey found evidence of a system of small dammed bailing ponds (Figure 2.39), and Gowland (1899) illustrates a nineteenth century Japanese mine where the water is being bailed up

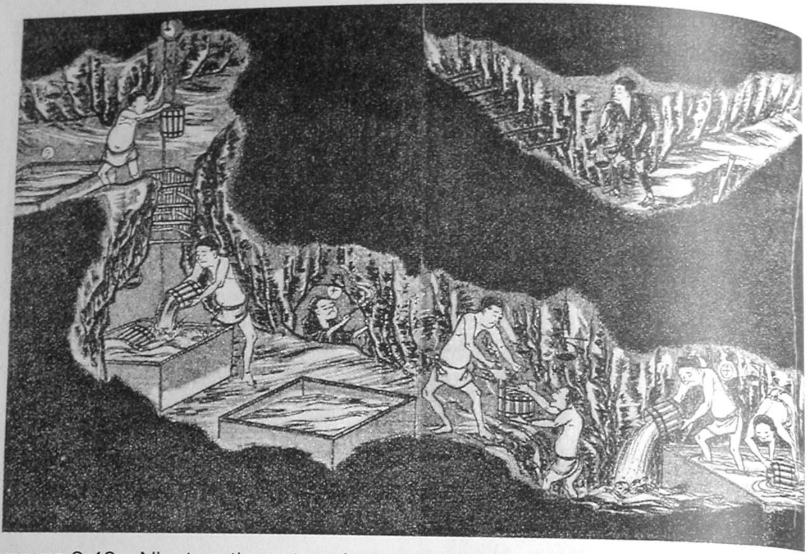


FIGURE 2.40 Nineteenth century Japanese mine bailing system.

with wooden stave buckets through a series of small tanks to the bottom of a small shaft, where the buckets are raised by a rope and pulley to a drainage level above (Figure 2.40). Other more sophisticated methods were also used, probably derived from methods used in irrigation systems, such as the Archimedes screw. Diodorus Siculus specifically describes the use of the screw in mines (V, 37.4) and remains have been found in several Roman mines where they were used in an ascending series to raise water via a series of small ponds or sumps, up an inclined shaft through a considerable height. Typically a screw would be about 3 metres long and set at an angle of between 30–40° and could raise water about a metre. The Archimedes screw was still used in Japanese mines in the nineteenth century and examples were recorded by Treptow (1918) at the gold mines of Sado. Each screw there was about 3.5 metres long, set at an angle of 40° and raised the water through about two metres.

Perhaps the most sophisticated water raising devices of antiquity are the Roman water-raising wheels such as the famous set found at Rio Tinto early in this century (Figure 2.41) (Palmer, 1926/7; Weisgerber, 1979), and less well-preserved remains have been found in other Roman mines such as the gold mine of Dolaucothi in central Wales (Davies, 1935, p. 24). The wheels at Rio Tinto are of wood held together with wooden pegs and their axles are of leaded bronze. Iron could not be used because of the extremely corrosive environment in the mine. The rims of the wheels are divided into compartments, which would scoop up water from the sump and carry it up to a launder above from where it flowed

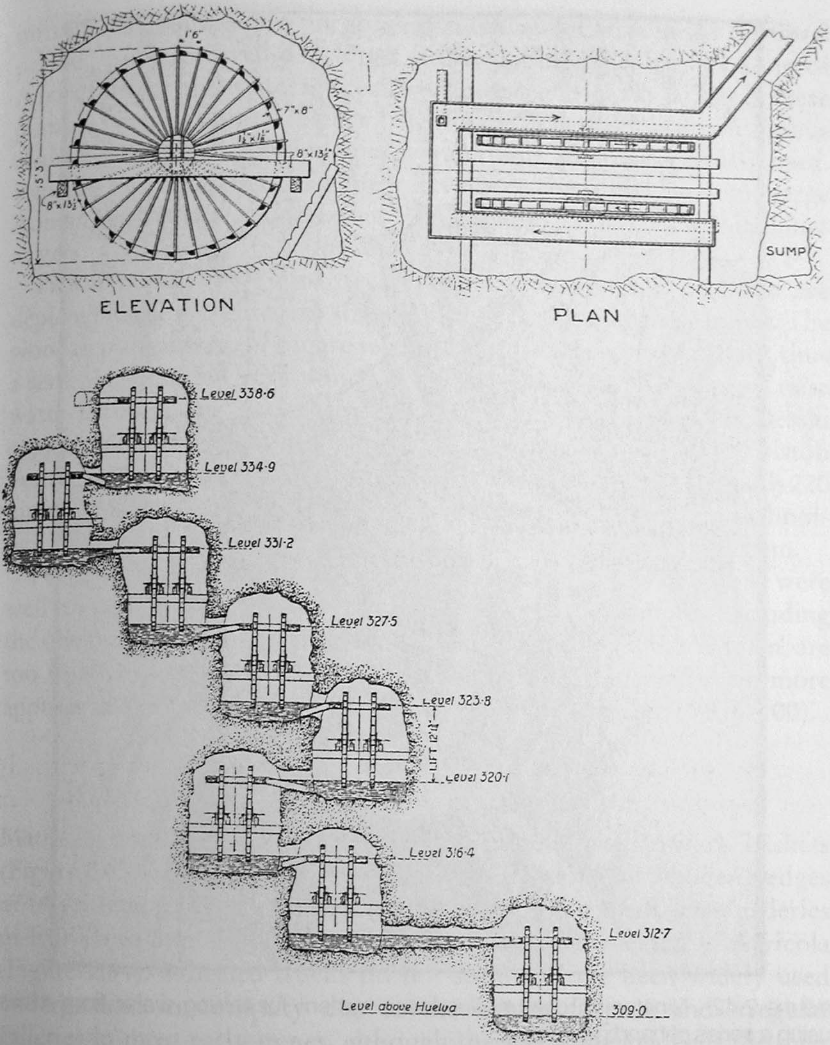


FIGURE 2.41 Set of Roman water wheels to drain the mines at Rio Tinto.

into the sump of the next wheel and so on until the surface was reached. Typically the surviving wheels are between 3.5 and 5 metres in diameter and would have raised the water through about 3 to 4 metres. The narrow treads on the outside show that they were manually-operated tread wheels, and it has been calculated that one man could raise between 82 to 86 litres of water per minute through a height of 3.66 metres. The wheels at Rio Tinto were in opposed pairs; in the best preserved set, eight such pairs set vertically above each other raised the water through about 30 metres.

FIGURE 2.42 Nineteenth century Japanese system for raising water from mines using a series of hand pumps.

It is important not to confuse these water-raising wheels with the water wheels employed in medieval and later mines to drive the pumps where the wheel was providing the motive power rather than actually raising the water. These later wheels required a supply of surface or near surface water to turn them, and thus in contemporary records one sometimes reads the apparently contradictory statement that the mines were in danger of flooding because of a drought.

In China continuous chain pumps with valved buckets were in use over a thousand years ago for pumping brine wells as depicted on impressed bricks from Chergdu, Sichuan, in Zhongguo (Pirazzoli-t' Serstevens, 1982, pp. 25, 72). Pumps of this sort were probably

Agricola in the mid-sixteenth century. The rag-and-chain variant of these pumps, where cloth or leather balls linked together on a continuous chain were pulled up a pipe raising water with them, was widely used. Remains of rag-and-chain pumps have been identified on some large Roman ships (Carre and Jezegou, 1984), although not from within mines as yet.

Piston pumps were also developed early in the Far East and are depicted in use in eighteenth and nineteenth century Japanese mines. The wooden pumps were of square section and about 2 or 3 metres long, thus a series was needed with pumps working one above the other to raise water through any great height (Figure 2.42). At the famous Besshi copper mine in Japan it is recorded in 1769 that no less than 130 piston pumps working in sequence were needed to raise the water through 220 metres (Masuda, 1983). This also shows that even quite simple technology was capable of considerable feats if linked together into a system.

Force action cylinder and piston pumps such as that of Ctesibius were well known in the Roman world but the surviving examples, including the one from the Roman mine at Sotiel Coronada in southern Spain, are too small and fine to have been used in mine drainage and seem more appropriate for providing domestic water supply (Healy, 1978, p. 100).

Moving Ore and Deposits

Materials could be carried through the mine in wickerwork baskets (Figure 2.43) or in very confined spaces pushed along on wooden sledges or trays. Examples of the latter have been found in the Roman galleries of Rio Tinto and almost identical examples are illustrated in Agricola (Figure 2.44). Wheeled trucks do not seem to have been widely used underground in antiquity due to the confined space and irregular galleries in most early mines, although there is some evidence for their use in the broad, straight galleries of the Roman gold mine of Três Minas in northern Portugal (Wahl, 1993). (I am grateful to G. Weisgerber for this information.). There is firm evidence for wheeled transport (the *hundt*) underground in Europe only from the fourteenth century, followed shortly afterwards by evidence for the use of rails, almost invariably formed of parallel planks at the time (Lewis, 1970, pp. 10–12). China had the wheelbarrow over two thousand years ago, but there is no evidence for its use in Europe prior to the medieval period.

The mined material could be carried out of the mine up stairways such as are preserved at Zawar, India or pulled up shafts with a windlass. Every effort was made to minimise the amounts of debris carried to the surface by stacking the waste materials (deads) back into the mined-out

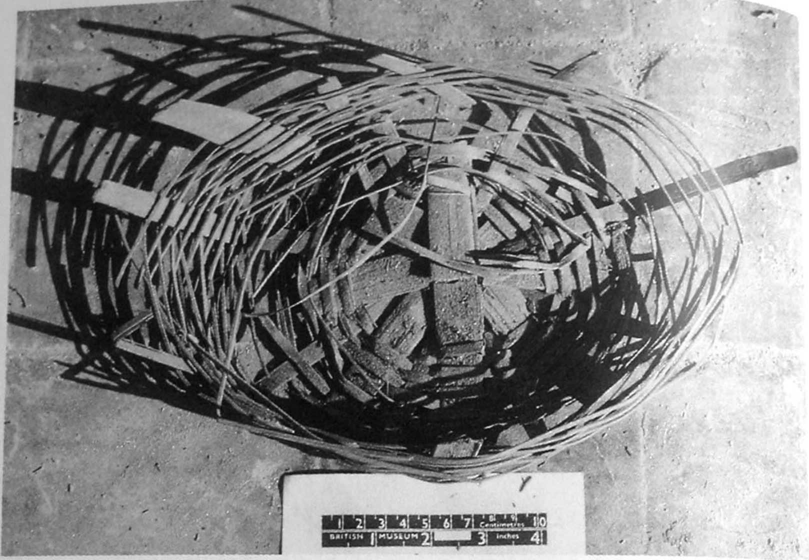


FIGURE 2.43 One of a large number of baskets found in the early mines at Dariba (cf the baskets in Figure 2.13).

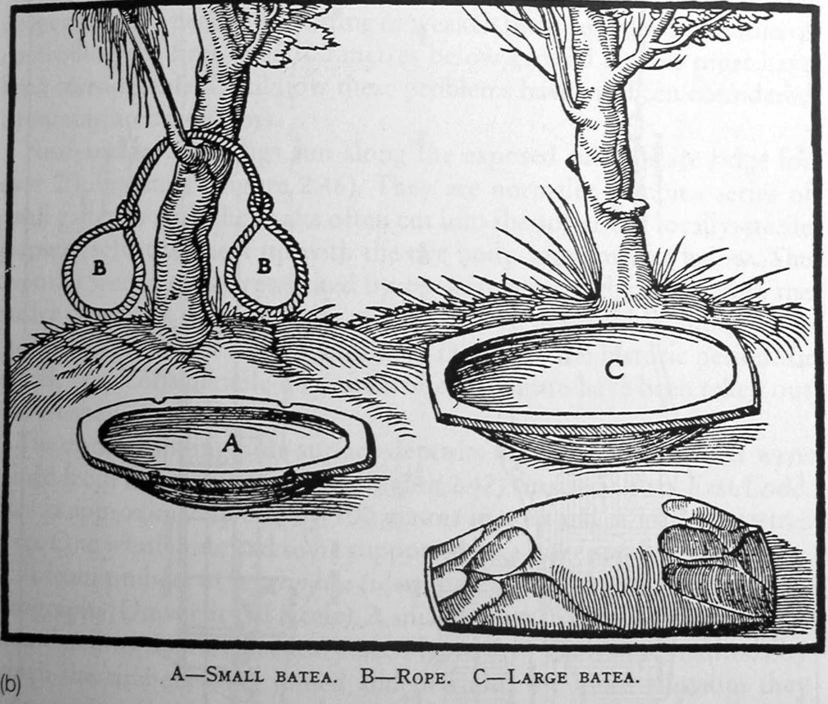
galleries. As noted above, air circulation could be partially controlled by their careful positioning. At Zawar the deads were held back on the steeply-sloping galleries by carefully-constructed drystone walls and stabilised by a series of posts set from floor to ceiling.

Dariba

The mines at Dariba (Willies, 1987), in the Aravalli Hills of Rajasthan, go back at least to the late second millennium BC, but were worked on a massive scale a thousand years later in common with other mines in the Aravallis. The impetus behind this activity was probably the demand for silver created by the first Indian coinage.

At Dariba the ridges of erosion-resistant calc-silicate rocks stand out from the weathered graphite schists that make up the surrounding plain (Figure 2.45). Both rock types contain mineralisation, which is primarily a mixed sulphidic ore of argentiferous galena, sphalerite and marcasite. Near the surface the deposit is gossanised and the oxidised form of the ores anglesite and cerussite (lead sulphate and carbonate) and possibly zincite and calamine (zinc oxide and carbonate) may well have been the principal minerals worked in antiquity. However, these putative oxidised minerals are now missing from the gossan, once again highlighting the problem of determining the mineral originally mined from examination

(a)



(b) A—Small batea. B—Rope. C—Large batea.

FIGURE 2.44 (a) Small wooden tray for moving ore in a confined space in the mine (Roman, from Rio Tinto); (b) illustration of a very similar tray in Agricola (sixteenth century, German).

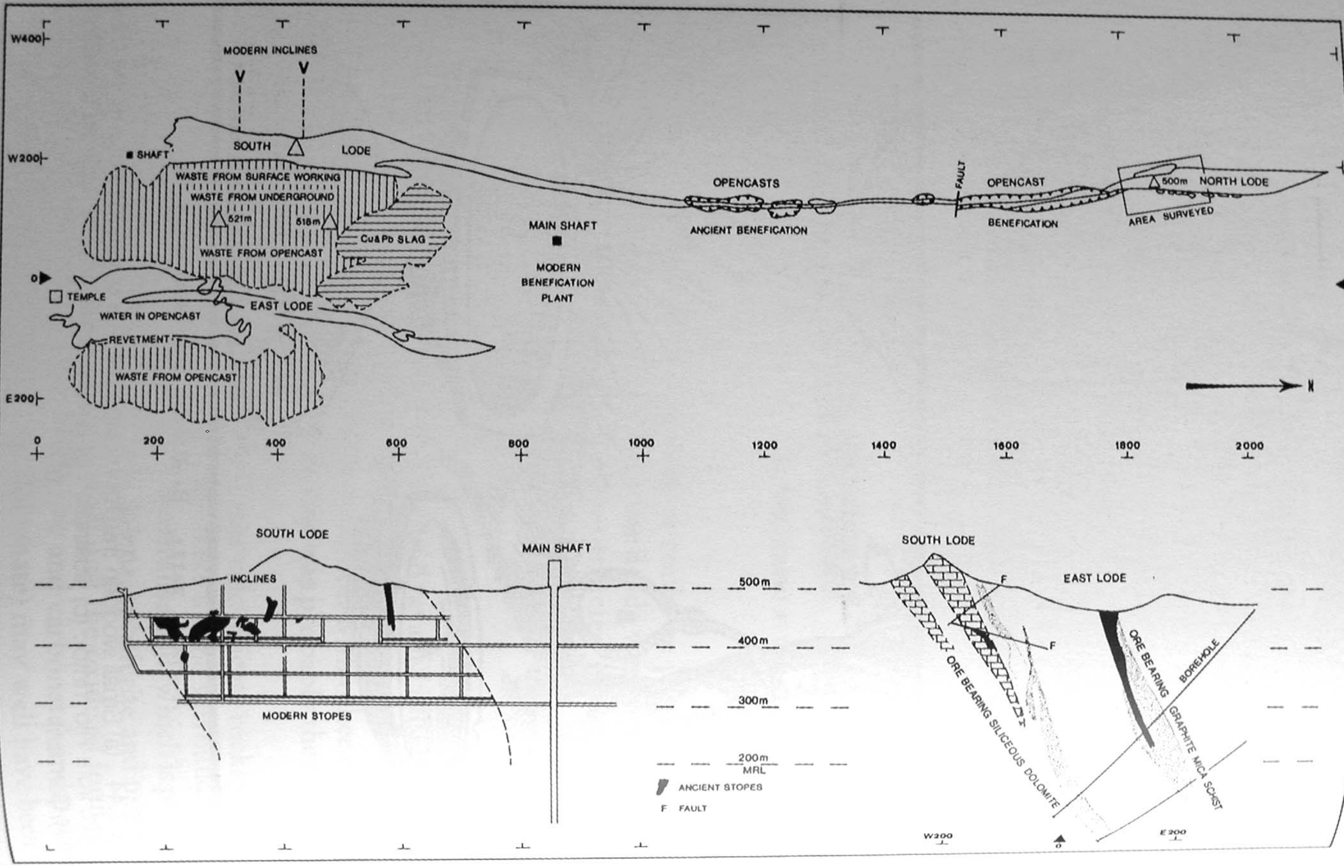


FIGURE 2.45 Plan and section of the main workings at Dariba.

of what is left behind. The ore bodies tend to plunge at a steep angle deep into the plain (Figure 2.7), creating serious drainage problems in the workings which penetrated well over 100 metres below the water table. Indeed these are the greatest depths below water table so far encountered in an ancient mine system. Whilst the workings stayed well within the impervious calc-silicates, drainage was containable. The consequences of not doing this are possibly recorded in a local legend which relates that their goddess told the miners that they must leave some of the ore behind for her, but they became greedy and removed it all, and as a punishment the mine was flooded. The ore in the softer graphite schist was easier to mine, but posed greater drainage problems. In one ancient shaft are the remains of a series of small stepped retaining dams from which water was raised by bailing (Figure 2.39).

The near-surface weathered deposits were soft enough to have been worked directly with pick and gad, and tool marks abound, but the deeper deposits needed firesetting to weaken them, and the difficulties of controlling the fires over 100 metres below ground surface must have been considerable. Until now these problems have not been considered by mining archaeologists.

Near-surface workings run along the exposed calc-silicate ridge for over 2 kilometres (Figure 2.46). They are normally complex series of small galleries with the shafts often cut into the softer but locally-sterile graphite schist to meet up with the ore body some metres below. The deposits were usually reworked by opencasting which cut through the earlier workings, although this too must have occurred in antiquity as there is no record of silver working at Dariba in the historic period. In places, very considerable quantities of calc-silicate have been taken out and crushed nearby.

The corresponding near-surface deposits in the graphite schists were mined from a huge opencast pit (Figure 2.47) situated above East Lode. This is approximately 300 by 100 metres in area and at least 30 metres deep. One whole side had to be supported by a huge stepped revetment, built from timbers of *terminalia* (identified by M. Grant of the Dept of Geography, University of Keele). A small timber from this revetment has been dated to the third century BC. Figure 2.48 shows the methods by which the timbers were joined and tied into the loose alluvium they supported and held back. During the monsoon season the opencast must have acted as a gigantic sump for the surrounding plain, endangering the deep workings beneath. Observations in recent years have recorded over 600 tons of water a day pumped from the opencast without substantially reducing the water level. The task of keeping the opencast tolerably free of water in antiquity must have been colossal, and emphasises once again how little the methods of the ancient miners are understood or their achievements appreciated.

FIGURE 2.46 Old opencast workings at Dariba running along the vein at the surface and cutting through earlier gallery systems.

FIGURE 2.47 Large opencast silver-lead mine at Dariba above East Lode, dated to the third century BC.

FIGURE 2.48 Section of major timber revetment running along one side of the opencast shown in Figure 2.46. The horizontal beam exposed in the foreground held a similar revetment on the next bench down. (The white rectangle is 10 cm long.)

Hydraulic Mining

The effects of swiftly running water on loose ground or alluvium are very obvious, hence water must have suggested itself as a mining method from the earliest times. Simple small-scale operations would leave very little trace, but for larger-scale workings great skill is required to collect, store and direct the considerable quantities of water needed. It was probably

FIGURE 2.49 Small post-medieval hushing dam on Copa Hill, Cwmystwyth.

not until the first millennium BC that sufficient experience had been acquired in managing the collection and channeling of large quantities of water over long distances for urban water supply systems as evidenced by some of the early Greek hydraulic engineering schemes (Burns, 1974; White, 1984, pp. 157–60).

Hydraulic mining is especially suited to secondary alluvial deposits and thus has been extensively used for gold mining from Roman times on, and more recently for tin mining. The principal evidence for hydraulic mining at an old mine are the remains of the dams and sluices of the reservoirs set above the opencasts, very often with the heavily-eroded channels running from them which led the torrent of water to the particular part of the deposit to be worked (Figures 2.22 and 2.49). Note that leats by themselves are not necessarily indicative of the use of water for hydraulic mining as from medieval times water power was extensively used to drive pumps (as mentioned above) as well as powering the ore crushing stamps etc and considerable quantities of water were also needed in the washeries (see Chapter 4).

Basically there are two different ways in which water can be used for mining; *hushing* where considerable volumes of water were suddenly released to remove overburden from the deposit, and *ground sluicing* or *hydraulicking* where the water was continuously run over or played against the deposit itself. These two techniques will now be considered separately below.

Hushing

This technique was especially useful where there was a large quantity of loose overburden such as alluvium or glacial scree on a slope to be removed. The surface would be initially cleared of vegetation and broken up manually before a great torrent of water was released from reservoirs above. Water was collected in reservoirs above the deposit. These were partially cut into the hillside with substantial walls, lined with clay where necessary, and had capacities which ranged from a few hundred to many thousands of cubic metres. Pliny gives an excellent account of hydraulic mining in Spain, that for its detail and immediacy must surely be a first-hand account (*Natural History*, 33.74–6). He described hushing reservoirs as being square with sides of about 200 feet and a depth of 10 feet. The square shape accords well with surviving examples both in Spain and in Wales as described below. Later European dams were usually curved. Sluice gates were set in the front dam wall and sluices cut in the hillside to take the water where it was needed. The sluices had to be as straight and with as few obstructions as possible so that the water arrived with maximum force. After the torrent had passed any major boulders exposed could be removed or broken up to recover the ore, the ground picked over and hushing repeated. Forster (1883) gives an excellent account of hushing as practised in the Pennine lead mines in the late eighteenth and early nineteenth century.

Remains of hushing have been studied at a number of sites, including the Roman gold working in north-west Spain (Lewis and Jones, 1970) and at Dolaucothi in central Wales (Lewis and Jones, 1969; Annels and Burnham, 1986), as well as the more recent and well-preserved systems at Cwmystwyth in central Wales (Hughes, 1981), where hushing was used to wash away the glacial scree and expose lead zinc deposits (Figures 2.22 and 2.49).

In north-west Spain there are a number of high-altitude Roman opencast gold-working sites. At Las Medulas, gold-bearing alluvial deposits lie over a thousand metres above sea level in the Somiedo mountains. The deposits consist of irregular bands of fine sand and clay interspersed with coarse conglomerate. The gold itself was locally-concentrated and thus much of the mining operation would just have been the removal of sterile overburden, a task for which hushing was ideally suited. No less than seven major aqueduct systems brought water from up to 20 kilometres away. There is a height difference of more than 400 metres between the lowest and highest system, suggesting that they were not in simultaneous use, but rather represent a long-term development as the workings moved back and up. This interpretation is supported by observation that the operations from the upper reservoirs seem to have obliterated those from the lower reservoirs. The surviving reservoirs are rectangular, and are either in clusters with dimensions up to 100 by 20 by 1.5 metres, or as single, large reservoirs of 200 by 40 by 3 metres, or 160 by 40 by 0.5 metres, depending on the topography.

At Puerto del Palo a major opencast mine was worked in the highly-weathered and loose primary and eluvial gold-bearing quartz. The main face stands over 200 metres high, and above are the well-preserved remains of a hushing reservoir 55 by 5 metres with walls still standing over 3.5 metres tall. The mine lies in mountainous terrain over a thousand metres above sea level and a long series of leats sometimes running in tunnels through the mountains was needed to supply water to the mine. In one place a channel had been cut along the scarp and then down the mountain side to an area where a continuation of the main quartz ore body could have been expected. However the channel is still clean cut and uneroded suggesting it had not been used much, and in fact the ore body does not continue, suggesting, as Lewis and Jones put it, that this was a prospecting channel that drew a blank.

At Dolaucothi in central Wales a series of opencast mines was worked by hushing in the Roman period. At least four major leat systems supplied the mines at various times. The Cothi leat extends for 11 kilometres and would have fed a series of reservoirs with approximately 2.5 million gallons of water per day. A typical reservoir lying just above an opencast was rectangular with sides of 24 by 6 metres, cut back into the rock at the rear with an 8 metre tall front wall of laminated clay and shale. A leat ran from this to another rectangular tank, 42 by 10 metres which had an estimated capacity of 450 cubic metres (a million gallons). This tank was rock cut at the rear, but probably had a front wall of clay and shale over a clay core.

Hushing almost certainly continued through the medieval period, although it is not mentioned by Agricola. It is well attested from the post-medieval period right up to the beginning of the twentieth century at mines such as Cwmystwyth. Hushing was extensively used on the steep slopes of Copa Hill to remove the glacial scree lying over the main Comet Lode. The technique was first described at the mine by the engineer F. Thompson in 1788 (Hughes, 1981, p. 16). Very clear evidence of hushing still survives with leats, reservoir and a series of deeply-eroded channels (Figures 2.23 and 2.49). The reservoir is oval with a bow-fronted dam retaining the water, fed by a leat from the moorland above, and has an overflow channel leading to an earlier reservoir located in the old Bronze Age quarry already described (p. 55). There are five main channels running across the hillside leading to the various lodes on the hillside, and water could be released from the single sluice gate into the selected channel.

Hydraulicking or Ground Sluicing

In this process water was led continuously over the deposit and into a sluice box to separate the mineral, usually gold or tin from the alluvial gangue. In sixteenth-century Bohemia streams were diverted through tin-bearing sands and the tin extracted as described and illustrated by Agricola (Hoover and Hoover, 1912, pp. 336–8). In recent times the water has been directed against the face from a high pressure nozzle (the so-called hydraulic giant), but previously a stream was channeled to run down over the face of the deposit. Ground sluicing was used to mine many of the alluvial gold deposits of North America in the last century, and good descriptions of the process are to be found in several American mining textbooks (Young, 1916). These simple low-cost systems, suitable for prospectors and small-scale operations, were probably quite similar to those used in antiquity. The length of the sluice depended on how quickly the conglomerate of gravel and clay distintegrated when agitated in the wash water, but a length between 30 and 100 metres was typical. The sluice was made up of a series of wooden troughs each about three to four metres long, on a slope lying between 1:20 to 1:25. Small bars (*riffles*) were set across the flat bottom of the sluice both to aid the distintergration of the gravels and to retain the denser mineral. The flow rate, slope and the riffles were all carefully adjusted to a fine balance such that the sand and gravel were swept down leaving the mineral behind.

Pliny seems to have been referring to ground sluicing where he described how gorse was used in the sluices of the Spanish gold mines to retain the gold (33.78), and Strabo (Jones, 1928) described the use of fleeces lining wooden troughs to trap gold by the Soanes, a tribe who lived in the Caucasus mountains (11, 2, 19), plausibly suggesting that this lay behind the legend of Jason and the Golden Fleece.

There is little surviving evidence for ground sluicing in antiquity, but it is likely to have been used in conjunction with hushing as Pliny implies in the section on gold mining. Lewis and Jones (1970) suggest that the sterile overburden was removed by hushing and the deposit worked by ground sluicing. The water would have come from the same source, even down the same channels as the difference in the two methods lay mainly in the control of the flow of water. At Las Medulas the sides of the opencast are in places deeply cut by gullies fed from channels above, which seem to be the remains of ground sluicing.

Ground sluicing was also used to mine tin at least in the more recent past by the Chinese in Malaya etc (Fawns, *nd*, pp. 61–9; Jones, 1925, p. 79) and is still used in the Jos tinfields of central Nigeria in some mines to separate the ore (see Chapter 5).

Bibliography

Adamson, R. J. (ed.), 1972, *Gold Metallurgy in South Africa*, Chamber of Mines of South Africa, Johannesburg.

Agrawal, O. P., Narain, H. and Prakash, J., 1991, 'Metallographic Studies of Iron Artifacts of Domestic Use, Tools and Weapons from Khairadih (100–400 AD), Uttar Pradesh', in *Role of Chemistry in Archaeology*, ed. M. C. Ganorkar and N. Rama Rao, Birla Institute, Hyderabad, pp. 103–111.

Agrawal, O. P., Narain, H., Prakash, J. and Bhatia, S. K., 1990a, 'Lamination technique in iron artefacts in ancient India', *Journal of the Historical Metallurgy Society*, **24** 1, pp. 12–26.

Agrawal, O. P., Narain, H., Prakash, J. and Joshi, G. P., 1990b, 'Technical Studies of Iron Artifacts from Dwarka (Mahabharta Period), India', in *Metals and the Sea*, ed. J. Lang, Historical Metallurgy Society Ltd, London, pp. 43–6.

Agrawal, O. P., Narain, H, and Prakash, J., 1992, 'Development of Iron Metallurgy in Ancient India', in *Archeometallurgia Richerche e Prospettive*, ed. E. A. Sanpaole, CLUEB, Bologna, pp. 369–99.

al-Hassan, A. Y. and Hill, D. R., 1986, *Islamic Technology*, CUP, Cambridge.

Allan, J. W., 1979, *Persian Metal Technology*, Ithaca Press, London.

Allen, I. M., Britton, D. and Coghlan, H. H., 1970, *Metallurgical Reports on British and Irish Bronze Age Implements and Weapons in the Pitt Rivers Museum*, Pitt Rivers Museum Occasional Paper 10, Oxford.

Almond, J. K., 1990, 'Zinc-Production Technology 1801–1950: A Review', in P. T. Craddock (ed.), pp. 151–234.

Ambers, J., 1990, 'Radiocarbon, Calibration and Early Mining', in Crew and Crew (eds), pp. 59–63.

Ambert, P., Barge, H., Esperou, J. L. and Bourhis, J. R., 1983, 'Les mines de cuivre préhistoriques de Cabrières, Herault', in *Journées de Paleometallurgie*, ed. C. Coddet, Compiegne, pp. 225–36.

Annels, A. E. and Burnham, B. C., 1986, *The Dolaucothi Gold Mines*, University College of Wales, Cardiff.

Anon, 1980, *Tonglushan – A Pearl Amongst Ancient Mines*, Cultural Relics Publishing House, Beijing.

Anstee, J. W. and Biek, L., 1961, 'A study in pattern welding', *Medieval Archaeology*, **5**, pp. 71–93.

Ardaillon, Ed., 1897, *Les mines du Laurion dans l'antiquité*, Bibliothèque des Écoles Françaises d'Athens et de Rome, Paris.

Armbruster, B. R., 1993, 'L'orfèvrerie au Mali', in *Outils et Ateliers d'Orfèvres des Temps Anciens*, ed. C. Eluère, *Antiquités Nationales: Mémoire 2*, pp. 289–96.

Armstrong, L., 1978, *Woodcolliers and Charcoal Burning*, Coach Publishing House, Horsham, Sussex.

Ashton, T. S., 1924, *Iron and Steel in the Industrial Revolution*, Economic History Series **2**, University of Manchester, Manchester.

Assimenos, K., 1983, 'Technological and Analytical Research on Precious Metals from the Chamber Tomb of Philip II of Macedonia (Vergina), in *Preprints of the Second International Symposium Historische Edelmetalle*, Meersburg, pp. 2–4.

Avery, D. H. and Schmidt, P. R., 1986, 'The Use of Preheated Air in Ancient and Recent African Iron Smelting Furnaces: A reply to Rehder', *Journal of Field Archaeology*, **13**, pp. 354–7.

Avery, D. H., van der Merwe, N. J. and Saitowitz, S., 1988, 'The Metallurgy of the Iron Bloomery in Africa', in Maddin (ed.), pp. 261–82.

Bachmann, H.-G., 1980, 'Early copper smelting techniques in Sinai and in the Negev as deduced from slag investigations', in Craddock (ed.), pp. 103–34.

Bachmann, H.-G., 1982a, *The Identification of Slags from Archaeological Sites*, Institute of Archaeology Occasional Publication **6**, London.

Bachmann, H.-G., 1982b, 'Copper Smelting Slags from Cyprus', in Muhly *et al* (eds), pp. 143–52.

Bachmann, H.-G., 1993, 'Zur Metallurgie der römischen Goldgewinnung in Três Minas und Campo de Jales in Nordportugal', in Steuer and Zimmermann (eds), pp. 153–60.

Bachmann, H.-G. and Renner, H., 1984, 'Nineteenth Century Platinum Coins', *Platinum Metals Review*, **28**(3), pp. 126–31.

Bachmann, H.-G. and Rothenberg, B., 1980, 'Die Verhüttungsverfahren von Site 30', in Conrad and Rothenberg (eds), pp. 215–36.

Bailey, K. C., 1929, 1932, *The Elder Pliny's Chapters on Chemical Subjects*, Arnold, London.

Bailey, R. N., Cambridge, E. and Briggs, H. D., 1988, *Dowsing and Church Archaeology*, Intercept, Wimbourne.

Ball, V., 1881, *A Manual of the Geology of India: Part 3 Economic Geology*, Geological Survey of India. Calcutta.

Bamberger, M. and Wincierz, P., 1990, 'Ancient smelting of oxide copper ore', in Rothenberg (ed.), pp. 123–57.

Bar Adon, P., 1980, *The Cave of the Treasure*, Israel Exploration Society, Jerusalem.

Bardgett, W. E. and Stanners, J. F., 1963, 'The Delhi Pillar: A study of the corrosion aspects', *Journal of the Iron and Steel Institute*, **201**(1), pp. 3–16.

Bargalló, M., 1969, *La Amalgamacion de los Minerales de Plata*, Compañia Fundidora de Fierro y Acero de Monterrey, Balderas, 68, Mexico.

Barker, G., 1971, 'The first metallurgy in Italy in the light of metal analyses from the Pigorini Museum', *Bullettino di Paletnologia Italiana*, **80**, pp. 183–212.

Barker, L. and White, R., 1992, 'Early smelting in Swaledale', in Willies and Cranstone (eds.), pp. 15–18.

Barnes, J. W., 1973, 'Ancient Clay Furnace Bars from Iran', *Bulletin of the Historical Metallurgy Society*, **7**(2), pp. 8–17.

Barnes, J. W., 1988, *Ores and Minerals: Introducing Economic Geology*, Open University, Milton Keynes.

Barnes J. W. and Bailey, E. H., 1972, 'Geologists discover ancient retort – evidence points to world's oldest mine', *World Mining* (US Edition), April, pp. 49–55.

Barnes, J. W. *et al*, 1969, *Geology and Ore Deposits of the Sizma-Ladik Mercury District*, Cento Report.

Barraclough, K. C., 1973, 'The origins of the British Steel Industry', *The Metallurgist and Materials Technologist*, December, pp. 623–9.

Barraclough, K. C., 1984a, *Steelmaking Before Bessemer Vol.1: Blister Steel*, The Metals Society, London.

Barraclough, K. C., 1984b, *Steelmaking Before Bessemer Vol.2: Crucible Steel*, The Metals Society, London.

Bayley, J., 1984, 'Roman brass-making in Britain', *Journal of the Historical Metallurgy Society*, **18**(1), pp. 42–3.

Bayley, J., 1990, 'The Production of Brass in Antiquity with Particular Reference to Roman Britain', in Craddock (ed.), pp. 7–28.

Bayley, J., 1991a, 'Processes in Precious Metal Working', in Budd *et al* (eds), *Archaeological Sciences 1989*, Oxbow Monograph **9**, Oxford, pp. 125–31.

Bayley, J., 1991b, 'Archaeological evidence for parting', in E. Pernicka and G. A. Wagner (eds), *Archaeometry '90*, Birkhauser Verlag, pp. 19–28.

Bayley, J., 1992a, 'Lead metallurgy in late Saxon and Viking England', in Willies and Cranstone (eds), pp. 6–8.

Bayley, J., 1992b, *Anglo-Scandanavian Non-Ferrous Metalworking from Coppergate*, The Archaeology of York: The Small Finds, **17/7**, York Archaeology Trust, York.

Bayley, J., 1992c, 'Metalworking Ceramics', *Medieval Ceramics*, **16**, pp. 3–10.

Bellamy, C. V., 1904, 'A West African Smelting House', *Journal of the Iron and Steel Institute*, **66**, pp. 99–126.

Benzoni, G. (trans. W. H. Smyth, 1857), *History of the New World*, Hakulyt Society, **21**, London.

Bergsøe, P., 1937, *The Metallurgy and Technology of Gold and Platinum among the Pre-Columbian Indians*, Ingenioervidensk Skr, **A44**, Copenhagen.

Bernus, S., and Echard, N., 1985, 'Metalworking in the Agadez Region (Niger): an ethno-archaeological approach', in Craddock and Hughes (eds), pp. 71–80.

Berthelot, M. P. E., 1888, *Collection des Anciens Alchimistes Grecs*, George Stenheil, Paris.

Berthelot, M. P. E., 1893, *La chimie au Moyen Age*, **I–III**, Georges Stenheil, Paris.

Berthoud, Th., Bonnefous, S., Dechoux, M. and Françaix, J., 1980, 'Data analysis: Towards a model of chemical modification of copper from ores to metal', in Craddock (ed.), pp. 87–102.

Bewley, R. H., Longworth, I. H., Browne, S., Huntley, J. P. and Varndell, G., 1992, 'Excavation of a Bronze Age cemetery at Ewanrigg, Maryport Cumbria', Appendix on the tuyere by P. T. Craddock, *Proceedings of the Prehistoric Society*, **58**, pp. 325–54.

Bhardwaj, H. C., 1979, *Aspects of Ancient Indian Technology*, Motilal Banarsidass, Delhi.

Biek, L., 1970, 'Vitrified products – a comment', *Bulletin of the Historical Metallurgy Group*, **4**(2), p. 81.

Biélenin, K., *nd*, 'Bloom Smithies on Early Smelting Sites in the Holy Cross Mountains', in Scott and Cleere (eds), pp. 35–46.

Biélenin, K., 1992, 'Le combustible de la sidérurgie antique des monts de Saint-Croix en Pologne', in *Protoindustries et Histoire des Forêts*, Les Cahiers de l'Isard, **3**, pp. 317–29.

Bird, J. B., 1979, 'The "Copper Man": A Prehistoric Miner and his Tools from Northern Chile', in *Pre-Columbian Metallurgy of South America*, ed. E. P. Benson, Dumbarton Oaks, Washington, pp. 105–32.

Bird, J. M. and Weathers, M. S., 1977, 'Native iron occurrences, Disko Island, Greenland', *Journal of Geology*, **85**, pp. 359–71.

Bjorkman, J. K., 1973, 'Meteors and Meteorites in the Ancient Near East', published simultaneously in *Meteoritics*, **8**, pp. 91–132; and by the Center for Meteor Studies, Arizona State University, Tempe, Arizona.

Blanchard, I., 1992, 'Technical implications of the transititon from silver to lead smelting in twelfth century England', in Willies and Cranstone (eds), pp. 9–12.

Bonnin, A., 1924, *Tutenag and Paktong; with Notes on other Alloys in Domestic Use during the 18th Century*, OUP, Oxford.

Bottinga, Y. and Weill, D., 1972, 'The viscosity of magnetic silicate liquids; a model for calculation', *American Journal of Science*, **272**, pp. 438–75.

Bottinga, Y., Weill, D. and Richet, P., 1982, 'Density calculations for silicate liquids', *Geochimica et Cosmochimica Acta*, **49**, pp. 909–19.

Bowman, S. G. E. (ed.), 1991, *Science and the Past*, BMP, London.

Bowman, S. G. E., Cowell, M. R. and Cribb, J., 1989, '2,000 Years of Coinage in China: an analytical study', *Journal of the Historical Metallurgy Society*, **23**(1), pp. 25–30.

Braidwood, L. S., *et al*, 1983, *Prehistoric Archaeology along the Zagros Flanks*, Oriental Institute Publication no. 105, Oriental Institute, Chicago.

Bray, W., 1978, 'The Gold of Eldorado', Times Newspapers, London.

Briard, J. and Mohen, J.-P., 1974, 'Le Tumulus de la forêt de Cannoit a Quimperle (Finistere)', *Antiquités Nationale*, **6**, pp. 46–60.

Briggs, C. S., 1983, 'Copper Mining at Mt. Gabriel, Co. Cork: Bronze Age bonanza or post famine fiasco?', *Proceedings of the Prehistoric Society*, **49**, pp. 317–35.

Bronson, B., 1986, 'The making and selling of Wootz, a crucible steel of India, *Archaeomaterials*, **1**, pp. 13–51.

Bronson, B., 1987, 'Terrestrial and Meteoritic Nickel in the Indonesian Kris', *Journal of the Historical Metallurgy Society*, **21**(1), pp. 8–15.

Brooke, J. C., 1850, 'Notes on the Zinc Mines of Jawar', *Journal of the Asiatic Society of Bengal*, **19**, pp. 212–15.

Brown, M. A. and Blin-Stoyle, A. E., 1959, 'A Sample Analysis of British Middle and Late Bronze Age Materials using Optical Spectrometry', *Proceedings of the Prehistoric Society*, **25**, pp. 188–208.

Buchanan, F., 1807, *A Journey from Madras through the Countries of Mysore, Canara and Malabar*, 3 vols, T. Cadell and W. Davies and Black Perry and Kingsbury, London.

Buchanan, P. T., 1992, 'Metalliferous plant communities: The flora of lead smelting in the upper Nent Valley', in Willies and Cranstone (eds), pp. 58–61.

Buchwald, V. F., 1975, *Handbook of iron meteorites*, University of California Press, Berkeley.

Buchwald, V. F. and Mosdal, G., 1985, *Meteoritic iron, telluric iron and wrought iron in Greenland*, Man and Society **9**, Meddelelser om Grønland.

Budd, P.,1991, *A Metallographic Investigation of Eneolithic Arsenical Copper*, PhD

Thesis, Dept. of Archaeological Sciences, University of Bradford.

Budd, P., 1992, 'Alloying and Metalworking in the Copper Age of Central Europe', *Bulletin of Metals Museum of the Japan Institute of Metals*, **17**, pp. 3–14.

Budd, P., Chapman, B., Jackson, C., Janaway, R. C. and Ottaway, B. S. (eds), 1991, *Archaeological Sciences '89*, Oxbow Books, Oxford.

Budd, P. D., Gale, D., Pollard, A. M., Thomas, R. G. and Williams, P. A., 1992, 'The early development of metallurgy in the British Isles', *Antiquity*, **66**(252), pp. 677–86.

Budd, P., Gale, D., Pollard, A. M., Thomas, R. G. and Williams, P. A., 1993, 'Evaluating lead isotope data: Further observations', *Archaeometry*, **35**(2), pp. 225–40.

Budd, P. D., and Ottaway, B. S., 1991, 'The properties of arsenical copper alloys: implications for the development of Eneolithic metallurgy', in Budd *et al* (eds), pp. 132–42.

Buddhue, J. D., 1957, *The Oxidation and Weathering of Meteorites*, University of New Mexico Publication in meteorites **3**, Albuquerque.

Burnett, A. M., Craddock, P. T. and Preston, K., 1982, 'New light on the origins of *orichalcum*', in *Proceedings of the 9th International Congress of Numismatists*, Berne, Sept. 1979, ed. T. Hackens and R. Weiller, Association Internationale des Numismates Professionels, Publication **6**, pp. 263–8.

Burns, A., 1974, 'Ancient Greek water supply and city planning', *Technology and Culture*, **15** (3), pp. 289–412.

Burrow, J. C. and Thomas, W., 1893, *'mongst mines and miners*, D. Bradford Barton, Truro (new edition 1965).

Busch, J. A. W., 1972, 'Ironmaking by the bloomery process at Nornäs, Sweden, in 1851', *Bulletin of the Historical Metallurgy Group*, **6**(1), pp. 28–33.

Byng, J. L. C. (ed.), 1963, *An Embassy to China: Being the journal kept by Lord Macartney 1793–4*, Longmans, London.

Cahen, C., 1947/8, 'Un Traité d'Amurerie Composé pour Saladin', *Bulletin d'Etudes Orientales*, **12**, pp. 103–63.

Cahn, R. W. and Lifshin, E. (eds), 1993, *Concise Encyclopedia of Materials Characterization*, Pergamon Press, Oxford.

Caldwell, J. R. (ed.), 1967, *Investigations at Tal-i-Iblis*, University of Illnois Press, Springfield, IL.

Caldwell, J. R., 1968, 'Pottery and cultural history on the Iranian Plateau', *Journal of Near Eastern Studies*, **27**, pp. 178–83.

Caley, E. R., 1964, *Orichalcum and Related Ancient Alloys*, American Numismatic Society: Notes and Monographs **151**, New York.

Calvert, A. F., 1910, *Nigeria and its Tin Fields*, Edward Stanford, London.

Carlon, C. J., 1979, *The Alderley Edge Mines*, John Sherratt, Altrincham.

Carre, M. B. and Jezegou, M. P., 1984, 'Pompes à Chaplet sur des Navires de l'Antiquité et du Début du Moyen Age', *Archaeonautica*, **4**, pp. 115–43.

Carriveau, G. W., 1974, 'Dating of "Phoenician slag" from Iberia using Thermoluminesence techniques', *MASCA Newsletter*, **10**(1), pp. 1–2.

CDA, 1954, *Copper and its Alloys in Engineering and Technology*, Copper Development Association, Radlett, Herts.

Černych, E. N., 1978, 'Aibunar – A Balkan copper mine of the fourth millennium BC', *Proceedings of the Prehistoric Society*, **44**, pp. 203–18.

Chakrabarti, D. K., 1976, 'The Beginning of Iron in India', *Antiquity*, **198**, pp. 114–24.

Chakrabarti, D. K., 1979, 'The Problem of Tin in Early India', *Man and Environment*, **3**, pp. 61–74.

Chakrabarti, D. K., 1992, *The Early Use of Iron in India*, OUP, Delhi.

Charles, J. A., 1967, 'Early arsenical bronzes – a metallurgical view', *American Journal of Archaeology*, **71**, pp. 21–6.

Charles, J. A., 1979, 'From Copper to Iron – The Origin of Metallic Materials', *Journal of Metals*, **30**(7), pp. 8–13.

Charles, J. A., 1985, 'Determinative mineralogy and the origins of metallurgy', in Craddock and Hughes (eds), pp. 21–8.

Checkland, S. G., 1967, *The Mines of Tharsis*, George Allen and Unwin, London.

Chernykh, E. N., 1992, *Ancient Metallurgy in the USSR*, CUP, Cambridge.

Childs, S. T., 1989, 'Clays to Artifacts: Resource Selection in African Early Iron Age Iron-making Technologies', in *Pottery Technology: Ideas and Approaches*, ed. G. Bronitsky, University of Colorado, Boulder, Co., pp. 139–64.

Childs, S. T. and Killick, D., 1993, 'Indigenous African Metallurgy: Nature and Culture', *Annual Review of Anthropology*, **22**, pp. 317–37.

Clark, A. J., Tarling, D. H. and Noel, M., 1988, 'Developments in Archaeomagnetic Dating in Britain', *Journal of Archaeological Science*, **15**, pp. 645–67.

Claughton, P., 1992, 'Medieval Silver-Lead Smelting in Devon', in Willies and Cranstone (eds), pp. 12–14.

Cleere, H. F., 1972, 'The Classification of Early Iron-Smelting Furnaces', *Antiquaries Journal*, **52**(1), pp. 8–23.

Cleere, H., 1976, 'Some operating parameters for Roman ironworks', *Bulletin of the Institute of Archaeology*, **13**, pp. 233–46.

Cline, W., 1937, *Mining and Metallurgy in Negro Africa*, General series in Anthropology, George Banta, Menasha, Wisconsin.

Clough, R., 1985, 'The iron industry in the Iron Age and Romano-British period', in Craddock and Hughes (eds), pp. 179–87.

Cockshutt, E., 1965, 'The Parys Mountain Copper Mines in the Island of Angelsey', *Archaeologia Cambrensis*, **114**, pp. 87–111.

Coghlan, H. H., 1939/40, 'Prehistoric Copper and some Experiments in Smelting', *Transactions of the Newcomen Society*, **20**, pp. 49–62.

Coghlan, H. H., 1941, 'Prehistoric iron prior to the dispersion of the Hittite Empire', *Man*, **41**(58–69), pp. 74–80.

Coghlan, H. H., 1951, *Notes on the Prehistoric Metallurgy of Copper and Bronze in the Old World*, Pitt-Rivers Museum Occasional Paper **4**, University of Oxford, Oxford (2nd edn 1975).

Coghlan, H. H., 1962, 'A Note upon Native Copper: its occurrence and properties', *Proceedings of the Prehistoric Society*, **28**, pp. 58–67.

Coghlan, H. H., 1956, *Notes on Prehistoric and Early Iron in the Old World*, Pitt Rivers Museum Occasional Paper **8**, University of Oxford, Oxford (2nd edn 1977).

Collins, A. C., 1892/3, 'Firesetting: The art of mining by fire', *Transactions of the Federated Institution of Mining Engineers*, **5**, pp. 82–92.

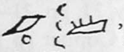
Collins, A. L., 1894, 'The Ghorband lead mines, Afghanistan', *Transactions of the Federated Institution of Mining Engineers*, **6**(3), pp. 449–56.

Conophagos, C. E., 1980, *Le Laurium Antique*, Ekdotike Hellados, Athens.

Conophagos, C. E., 1989, 'La Technique de la Coupellation des Grecs Anciens au Laurium', in *Archaeometry*, ed. Y. Maniatis, Elsevier, Amsterdam, pp. 271-89.

Conrad, H.-G. and Rothenberg, B. (eds), 1980, *Antikes Kupfer im Timna-Tal*, Der Anschnitt Beiheft 1, Bochum.

Coomaraswamy, A. K., 1956, *Medieval Sinalese Art*, 2nd edn, Pantheon Books, New York.

Cooney, J. D., 1966, 'On the meaning of ', *Zeitschrift für Ägyptische Sprache und Altertumskunde*, **93**, pp. 43–47.

Cordellas, A., 1869, *Le Laurium*, Marseilles.

Cornwall, H. R., 1956, A summary of ideas on native copper formation, *Economic Geology*, **51**(7), pp. 615–27.

Cowell, M. R., 1987, 'Chemical Analysis of Egyptian Tools and Weapons', Appendix 1 in W. V. Davies, *Catalogue of Egyptian Antiquities in the British Museum*, BMP, London.

Cowell, M. R., Cribb, J., Bowman, S. G. E. and Shashoua, Y., 1993, 'The Chinese Cash: Composition and Production', in *Metallurgy in Numismatics* **3**, eds M. M. Archibald and M. R. Cowell, Royal Numismatic Society Special Publication **24**, London, pp. 185–98.

Cowell, M. R. and Lowick, N. M., 1988, 'Silver from the Panjhīr mines', in *Metallurgy in Numismatics* **2**, ed. W. A. Oddy, Royal Numismatic Society, London, pp. 65–74.

Cowman D. and Reilly, T. A., 1988, *The Abandoned Mines of West Carbery*, Geological Survey of Ireland, Dublin.

Craddock, B. R., 1990, 'The Experimental Hafting of Stone Mining Hammers', in Crew and Crew (eds), p. 58.

Craddock, P. T., 1977, 'The composition of copper alloys used by the Greek, Etruscan and Roman civilisations', *Journal of Archaeological Science*, **4**, pp. 103–24.

Craddock, P. T., 1978, 'The composition of copper alloys used by the Greek, Etruscan and Roman civilisations' **3**; 'The origins and early use of brass', *Journal of Archaeological Science*, **5**, pp. 1–16.

Craddock, P. T., 1979, 'Deliberate Alloying in the Atlantic Bronze Age', in *Proceeedings of the 5th Atlantic Colloquim*, ed. M. Ryan, Stationery Office, Dublin, pp. 369–85. (And microfiche.)

Craddock, P. T. (ed.), 1980, *Scientific Studies in Early Mining and Extractive Metallurgy*,British Museum Occasional Paper **20**, London.

Craddock, P. T., 1981a, 'The composition of non-ferrous metals from Tejada', in *Ancient Mining and Metallurgy in South-West Spain*, B. Rothenberg and A. Blanco-Freijeiro (eds), IAMS, London, pp. 279–80.

Craddock, P. T., 1981b, 'Report on the composition of metal tools and weapons from Ayia Paraskevi, Vounous and Evreti, Cyprus, in the Birmingham Museum', in *Cypriot Antiquities in Birmingham Museum and Art Gallery*, E. Peltenberg, Birmingham Museum, pp. 77–8.

Craddock, P. T., 1985a, 'Three Thousand Years of Copper Alloys', in *Application of Science in Examination of Works of Art*, eds P. A. England and L. van Zelst, Museum of Fine Art, Boston, pp. 59–67.

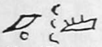
Craddock, P. T., 1985b, 'A History of the Distillation of Metals', *Bulletin of the Metals Museum of the Japan Institute of Metals*, **10**, pp. 3–25.

Conophagos, C. E., 1980, *Le Laurium Antique*, Ekdotike Hellados, Athens.

Conophagos, C. E., 1989, 'La Technique de la Coupellation des Grecs Anciens au Laurium', in *Archaeometry*, ed. Y. Maniatis, Elsevier, Amsterdam, pp. 271-89.

Conrad, H.-G. and Rothenberg, B. (eds), 1980, *Antikes Kupfer im Timna-Tal*, Der Anschnitt Beiheft 1, Bochum.

Coomaraswamy, A. K., 1956, *Medieval Sinalese Art*, 2nd edn, Pantheon Books, New York.

Cooney, J. D., 1966, 'On the meaning of ', *Zeitschrift für Ägyptische Sprache und Altertumskunde*, **93**, pp. 43–47.

Cordellas, A., 1869, *Le Laurium*, Marseilles.

Cornwall, H. R., 1956, A summary of ideas on native copper formation, *Economic Geology*, **51**(7), pp. 615–27.

Cowell, M. R., 1987, 'Chemical Analysis of Egyptian Tools and Weapons', Appendix 1 in W. V. Davies, *Catalogue of Egyptian Antiquities in the British Museum*, BMP, London.

Cowell, M. R., Cribb, J., Bowman, S. G. E. and Shashoua, Y., 1993, 'The Chinese Cash: Composition and Production', in *Metallurgy in Numismatics* 3, eds M. M. Archibald and M. R. Cowell, Royal Numismatic Society Special Publication **24**, London, pp. 185–98.

Cowell, M. R. and Lowick, N. M., 1988, 'Silver from the Panjhīr mines', in *Metallurgy in Numismatics* **2**, ed. W. A. Oddy, Royal Numismatic Society, London, pp. 65–74.

Cowman D. and Reilly, T. A., 1988, *The Abandoned Mines of West Carbery*, Geological Survey of Ireland, Dublin.

Craddock, B. R., 1990, 'The Experimental Hafting of Stone Mining Hammers', in Crew and Crew (eds), p. 58.

Craddock, P. T., 1977, 'The composition of copper alloys used by the Greek, Etruscan and Roman civilisations', *Journal of Archaeological Science*, 4, pp. 103–24.

Craddock, P. T., 1978, 'The composition of copper alloys used by the Greek, Etruscan and Roman civilisations' **3**; 'The origins and early use of brass', *Journal of Archaeological Science*, **5**, pp. 1–16.

Craddock, P. T., 1979, 'Deliberate Alloying in the Atlantic Bronze Age', in *Proceeedings of the 5th Atlantic Colloquim*, ed. M. Ryan, Stationery Office, Dublin, pp. 369–85. (And microfiche.)

Craddock, P. T. (ed.), 1980, *Scientific Studies in Early Mining and Extractive Metallurgy*,British Museum Occasional Paper 20, London.

Craddock, P. T., 1981a, 'The composition of non-ferrous metals from Tejada', in *Ancient Mining and Metallurgy in South-West Spain*, B. Rothenberg and A. Blanco-Freijeiro (eds), IAMS, London, pp. 279–80.

Craddock, P. T., 1981b, 'Report on the composition of metal tools and weapons from Ayia Paraskevi, Vounous and Evreti, Cyprus, in the Birmingham Museum', in *Cypriot Antiquities in Birmingham Museum and Art Gallery*, E. Peltenberg, Birmingham Museum, pp. 77–8.

Craddock, P. T., 1985a, 'Three Thousand Years of Copper Alloys', in *Application of Science in Examination of Works of Art*, eds P. A. England and L. van Zelst, Museum of Fine Art, Boston, pp. 59–67.

Craddock, P. T., 1985b, 'A History of the Distillation of Metals', *Bulletin of the Metals Museum of the Japan Institute of Metals*, **10**, pp. 3–25.

Craddock, P. T., 1986, 'The Metallurgy and Composition of Etruscan Bronze', *Studi Etruschi*, **52**, pp. 211–71.

Craddock, P. T., 1988, 'The Composition of the Metal Finds', in *The Egyptian Mining Temple at Timna*, B. Rothenberg (ed.), IAMS, London, pp. 169–81.

Craddock, P. T., 1989, 'The scientific investigation of early mining and metallurgy', in *Scientific Analysis in Archaeology*, ed. J. Henderson, UCLA, Oxford, pp. 178–212.

Craddock, P. T. (ed.), 1990a, *Two Thousand Years of Zinc and Brass*, British Museum Occasional Paper no. 50, London.

Craddock, P. T., 1990b, Zinc in Classical Antiquity, in Craddock (ed.), 1990a, pp. 1–6.

Craddock, P. T., 1991a, 'Old Ways in the Kolar Gold Field', *Gold Bulletin*, **24**(4), pp. 127–31.

Craddock, P. T., 1991b, 'Copper Production in Bronze Age Britain', in Éluère and Mohen (eds), pp. 197–212.

Craddock, P. T., 1992a, 'A Short History of Firesetting', *Endeavour*, **16**(2), pp. 145–50.

Craddock, P. T., 1992b, 'Copper Production in the Bronze Age of the British Isles', *Bulletin of the Metals Museum of Japan*, **18**(II), pp. 3–28.

Craddock, P. T., 1993, 'A short review of the evidence for Bronze Age mining in the British Isles', in Steuer and Zimmermann (eds), pp. 37–56.

Craddock, P. T., forthcoming, *Roman Non-ferrous Metallurgy*, British Museum Occasional Paper 100, London.

Craddock, P. T., Burnett, A. M. and Preston, K., 1980, 'Hellenistic copper-base coinage and the origins of brass', in *Scientific Studies in Numismatics*, ed. W. A. Oddy, British Museum Occasional Paper **18**, London, pp. 53–64.

Craddock, P. T., Freestone, I. C., Gale, N. H., Meeks, N. D., Rothenberg, B. and Tite, M. S., 1985, 'The investigation of a small heap of silver smelting debris from Rio Tinto, Huelva, Spain', in Craddock and Hughes (eds), pp. 199–218.

Craddock, P. T., Freestone, I. C., Gurjar, L. K., Middleton A. and Willies, L., 1989, 'The production of lead, silver and zinc in ancient India', in Hauptmann *et al* (eds), pp. 51–70.

Craddock, P. T., Freestone, I. C. and Hunt Ortiz, M., 1987, 'Recovery of Silver from Speiss at Rio Tinto (SW Spain)', *IAMS Bulletin*, **10**(1), pp. 8–11.

Craddock, P. T., Freestone, I. C., Middleton A., Gurjar, L. K. and Willies, L., 1990, 'Zinc in India', in Craddock (ed.), pp. 29–72.

Craddock, P. T. and Gale, D., 1988, 'Evidence for early mining and extractive metallurgy in the British Isles', in *Science and Archaeology, Glasgow 1987*, ed. E. A. Slater and J. O. Tate, BAR British Series 196, Oxford, pp. 175–92.

Craddock, P. T. and Giumlia-Mair, A., 1993, '*Ḥśmn-km*, Corinthian bronze, *shakudo*: black patinated bronze in the ancient world', in *Metal Plating and Patination*, ed. S. La Niece and P. T. Craddock, Butterworth Heinemann, Oxford, pp. 101–27.

Craddock, P. T. and Hook, D. R., 1987, 'Ingots from the Sea: The British Museum Collection of Ingots', *International Journal of Nautical Archaeology and Underwater Exploration*, **16**(3), pp. 201–206.

Craddock, P. T. and Hughes, M. J. (eds), 1985, *Furnaces and Smelting Technology in Antiquity*, British Museum Occasional Paper no. 48, London.

Craddock, P. T. and Lambert, J., 1985, 'The Composition of the Trappings', Appendix to 'A Group of Silvered Horse Trappings from Xanten (Castra Vetera)', I. Jenkins, *Britannia*, **16**, pp. 141–64.

Craddock, P. T. and Meeks, N. D., 1987, 'Iron in Ancient Copper', *Archaeometry*, **29**(2), pp. 187–204.

Crew, P., 1991, 'The experimental production of prehistoric bar iron', *Journal of the Historical Metallurgy Society*, **25**(1), pp. 21–36.

Crew, P. and Crew, S. (eds), 1990, *Early Mining in the British Isles*, Plas Tan y Bwlch Snowdonia Study Centre, Maentwrog.

Crew, P. and Salter, C. J., 1991, 'Comparative data from iron smelting and smithing experiments, *Materiały Archeologiczne*, **26**, International Archaeometallurgy Symposium, Krakow, pp. 15–22.

Crozier, R. D., 1993, 'Silver processing in Spanish America: the patio and the buytron processes', *Canadian Institute of Mining Bulletin*, **86**(972), pp. 86–91.

Culberg, C., 1968, 'On Artifact Analysis', *Acta Archaeologica Lundensia*, 4(7), Lund.

Curtis, J. E., Wheeler, T. S., Muhly, J. D. and Maddin, R., 1979, 'Neo-Assyrian ironworking technology', *Proceedings of the American Philosophical Society*, **123**(6), pp. 369–90.

Cushing F. H., 1894, Primitive copper working: an experimental study, *American Anthropology*, **7** (old series), pp. 93–117.

Dai Zhigiang and Zhou Weirong, 1992, Studies of the alloy composition of more than two thousand years of Chinese coins, *Journal of the Historical Metallurgy Society*, **26**, pp. 45–56.

Dana, J. D., 1857, *Manual of Mineralogy and Lithology*, Trubner, London.

Dana, J. D., 1868, *A System of Mineralogy*, 5th edn, Wiley, New York.

Davey, C. J., 1979, 'Some ancient Near-Eastern pot bellows', *Levant*, **11**, pp. 101–11.

Davey, C. J., 1988, 'Tell Edh-Dhiba'i and the Southern Near Eastern Metalworking Tradition', in Maddin (ed.), pp. 63–9.

David, N., Heimann R. R., Killick, D. and Wayman, M., 1989, 'Between bloomery and blast furnace: Mafa iron-smelting technology in the North Cameroon', *The African Archaeological Review*, **7**, pp. 183–208.

Davies, O., 1935, *Roman Mines in Europe*, Macmillan, London.

Davies, O., 1937a, 'Ancient mine sites in Montgomeryshire', *Montgomery Collections*, **45**, pp. 55–8, 152–6.

Davies, O., 1937b, 'Prehistoric copper mine at Jarmovac near Priboj na Limu', *Glasnik Zemaljskog Muzeja u Bosni i Hercegovini*, **49**(1), pp. 1–3.

Davies, O., 1939, 'Excavations at Parys Mountain', *Transactions of the Angelsey Antiquarian Society*, pp. 40–42.

Davies, O., 1947, 'Cwm Ystwyth Mines', *Archaeologia Cambrensis*, **99**, pp. 57–63.

Davies, O., 1948, 'The copper mines on Great Orme's Head, Caernarvonshire', *Archaeologia Cambrensis*, **100**, pp. 61–6.

Davis, D., Maddin, R., Muhly, J. D. and Stech, T., 1985, 'A steel pick from Mt. Adir in Palestine', *Journal of Near Eastern Studies*, **44**(1), pp. 41–51.

Day, J., 1973, *Bristol Brass*, David and Charles, Newton Abbot, Devon.

Day, J., 1991, 'Copper, zinc and brass production', in Day and Tylecote (eds), pp. 131–99.

Day, J. and Tylecote, R. F., 1991, *The Industrial Revolution in Metals*, The Institute of Metals, London.

de Jesus, P. S., 1978, 'A copper smelting furnace at Hissarcikki near Ankara', *Journal of the Historical Metallurgy Society*, **12**(2), pp. 104–107.

Delibes, G., Fernandez Miranda, M., Fernandez Posse, Martin C., Montero, I. and Rovira, S., 1991, 'Almizaraque, Alméria, Spain', in Éluère and Mohen (eds), pp. 303–316.

Deo, S. B. and Jamkhedka, A. P., 1982, *Naikund Excavations 1978–1980*, Delhi.

Desch, C. H., 1940, 'Metals as engineering materials', *Journal of the Royal Society of Arts*, pp. 591–632.

Dikshit, K. N., 1986, 'The antiquity of iron in India', in *Dimensions of Indian Art*, ed. L. Chandra and J. Jain, Delhi, pp. 109–119.

Dixon, Capt., 1831, 'Some accounts of the lead mines of Ajmer', *Gleanings in Science*, **28** (April), p. 111.

Domergue, C., 1989a, 'Mines antiques, sur la trace des anciens mineurs et métallurgistes de la Gaulle', *Le Courrier du CNRS*, **73** (Sept), pp. 52–3.

Domergue, C. (ed.), 1989b, *Mineria y Metallurgia en las antiguas civilizaciones Mediterraneas Europeas*, Instituto de Conservación y Restauración de Bienes Culturales, Madrid.

Dorr, J. V. N., 1936, *Cyanidation and Concentration of Gold and Silver Ores*, McGraw-Hill, New York.

Douglass, R. E. and Mathewson, E. P., 1923, *Barba: El Arte de los Metales* (trans.), John Wiley, New York.

Dunlop, D. M., 1957, 'Sources of silver and gold in Islam according to al-Hamdānī', *Studia Islamica*, **8**, p. 29.

Dutrizac, J. E., Jambor, J. L. and O'Reilly, J. B., 1983, 'Man's first use of jarosite', *Canadian Institute of Metallurgy Bulletin*, **76**(859), pp. 78–82.

Earl, B., 1968 *Cornish Mining* Bradford Barton. Truro.

Eaton, E. R. and McKerrell, H., 1976, 'Near Eastern alloying and some textual evidence for the early use of arsenical copper', *World Archaeology*, **8**, pp. 169–92.

Egleston, T., 1879/80, 'The American bloomery process for making iron direct from the ore', *Transactions of the American Institute of Mining Engineers*, **8**, pp. 515–50.

Ehrenreich, R. M., 1985, *Trade, Technology and the Ironworking Community in the Iron Age of Southern Britain*, BAR British Series 144, Oxford.

Ehrenreich, R. M., *nd*, 'A study of iron technology in the Wessex Iron Age', in Scott and Cleere (eds), pp. 105–112.

Eibner, C., 1984, 'Der Bergbau im Herzen des Pongaus', in *Bischofsofen, 5,000 Jahre Geschichte und Kultur*, Bischofsofen, pp. 46–56.

Eisele, J. A., 1988, 'Gold metallurgy – a historical perspective', *Canadian Metallurgical Quarterly*, **27**(4), pp. 287–91.

Eissler, M., 1900, *The Metallurgy of Gold*, Crosby Lockwood, London.

El Gayar, El Sayed and Jones, M. P., 1989a, 'Possible sources of copper fragments found at the Old Kingdom town of Buhen', *Journal of Egyptian Archaeology*, **75**, pp. 31–40.

El Gayar, El Sayed and Jones, M. P., 1989b, 'Old Kingdom copper smelting artifacts from Buhen in Upper Egypt', *Journal of the Historical Metallurgy Society*, **23**(1), pp. 16–24.

Elitzsch, C., Pernicka, E. and Wagner, G. A., 1983, 'Thermoluminescence dating of archaeometallurgical slags', *PACT*, **9**(II), pp. 271–86.

Éluère, C., 1986, 'A prehistoric touchstone from France', *Gold Bulletin*, 19(2), pp. 58–61.

Éluère, C. (ed.), 1989, *Le Premier Or*, Editions de la Reunion des Musées Nationaux, Paris.

Éluère, C. and Mohen, J.-P. (eds), 1991, *Découverte du Métal*, Picard, Paris.

Éluère, C. and Raub, Ch. J., 1991, 'Investigations on the gold coating technology of the Great Plate of Varna', in Éluère and Mohen (eds), pp. 13–30.

Emery, W. B., 1963, 'Preliminary report on the excavations at Buhen, 1962', *Kush*, 11, pp. 116–20.

Engstrom, R., Lankton, S. M. and Lesher-Engstrom, A., 1989, *Sword of Sutton Hoo*, Medieval Institute Publications, Western Michigan University, Kalamazoo.

Epstein, S. M. and Shimada, I., 1983, 'Una reconstruccion de la produccion de la aleacion de cobre en el cerro de los cementerios, Peru', *AVA-Beitrage*, 5, pp. 379–430.

Evans, R. T. and Tylecote, R. F., 1967, 'Some vitrified products of non-metallurgical significance', *Bulletin of the Historical Metallurgy Group*, 1(9), pp. 22–3.

Evenstad, O., 1782, *A Treatise on Iron Ore as Found in the Bogs and Swamps of Norway and the Process of Turning it into Iron and Steel*, trans. N. L. Jensen and reprinted in the *Bulletin of the Historical Metallurgy Society*, 2(2) (1968), pp. 61–5.

Falk, H., 1991, 'Silver, lead and zinc in early Indian literature', *South Asian Studies*, 7, pp. 111–17.

Farnsworth, M., Smith, C. S. and Rodda, J. L., 1949, 'Metallographic examination of a sample of metallic zinc from ancient Athens', *Hesperia (supplement)* 8, pp. 126–9.

Fawns, S., *nd*, *Tin Deposits of the World*, The Mining Journal, London.

Fell, A., 1908, *The Early Iron Industry of Furness and District*, Hume Kitchin, Ulverston, Cumbria. Reprinted 1968, Cass, London.

Figiel, L. S., 1991, *On Damascus Steel*, Atlantis Arts Press, Atlantis, Florida.

Fitzhugh, W. and Olin, J. (eds), 1993, *Archeology of the Frobisher Voyages*, Smithsonian Press, Washington.

Forbes, R. J., 1948, *A Short History of the Art of Distillation*, Brill, Leiden.

Forbes, R. J., 1964a, *Studies in Ancient Technology*, 8, Brill, Leiden.

Forbes, R. J., 1964b, *Studies in Ancient Technology*, 9, Brill, Leiden.

Forster, W., 1883, *A Treatise on a section of the Strata from Newcastle-on-Tyne to the Mountain of Cross Fell, in Cumberland*, Third edn, revised W. Nall, Newcastle.

Fowler, H. N., 1975, *Plato: The Statesman*, Loeb edition, Heinemann, London.

France-Lanord, A., 1949, 'La fabrication des épées damassées aux époques mérovingienne et carolingienne', *Le Pays gaumais*, 10(1–3), Edition du Musée gaumais, ASBL Virton, Belgium, pp. 19–45.

Franklin, U. M., 1982, 'Folding: A prehistoric way of working native copper in the North American Arctic', *MASCA Journal*, 2(2), pp. 48–52.

Franklin, U. M., Badone, E., Gotthardt, R. and Yorga, B., 1981, *An Examination of Prehistoric Copper Technology and Copper Sources in Western Arctic and Subarctic North America*, National Museums of Canada, Ottawa.

Franklin, U. M., Grosjean, J.-C. and Tinkler, M. J., 1976, 'A study of ancient slags from Oman', *Canadian Metallurgical Quarterly*, 15(1), pp. 29–35.

Freestone, I. C., 1989, 'Refractory materials and their procurement', in Hauptmann *et al* (eds), pp. 155–63.

Freestone, I. C., Craddock, P. T., Hegde, K. T. M., Hughes, M. J. and Paliwal, H. V., 1985, 'Zinc production at Zawar, Rajasthan', in Craddock and Hughes (eds), pp. 229–44.

Freestone, I. C. and Middleton, A. P., 1987, 'Mineralogical applications of the analytical SEM in archaeology', *Mineralogical Magazine*, **51**, pp. 21–31.

Freestone, I. C., Middleton, A. P., Craddock, P. T., Gurjar, L. K. and Hook, D.R., 1991, 'Role of materials analysis in the reconstruction of early metal extraction technology', in *Materials Issues in Art and Archaeology*, II, eds P. B. Vandiver, J. Druzik and G. S. Segan, MRS, Pittsburgh, pp. 617–26.

Freestone, I. C. and Tite, M.S., 1986, 'Refractories from the ancient and preindustrial world', in *Ceramics and Civilisation III*, ed. W. D. Kingery, American Ceramic Society, Westerville, Ohio, pp. 35–63

Frey, E., 1988, *The Kris*, Second edn, OUP, Singapore.

Friend, J. N., 1926, *Iron in Antiquity*, Griffin, London.

Fulford, M. G. and Allen, J. R. L., 1992, 'Iron-making at Chesters Villa, Woolaston', *Britannia*, **23**, Appendix on the fuels by Figueiral, I., pp. 188–91.

Gale, D., 1990, 'Prehistoric stone mining tools from Alderley Edge', in Crew and Crew (eds), pp. 47–8.

Gale, N. H., 1989, 'Archaometallurgical studies of Late Bronze Age ox-hide copper ingots from the Mediterranean region', in Hauptmann *et al* (eds), pp. 247–68.

Gale, N. H., Bachmann, H. G., Rothenberg, B., Stos-Gale, Z. A. and Tylecote, R. F., 1990, 'The adventitious production of iron in the smelting of copper', in Rothenberg (ed.), pp. 182–90.

Gale, N. H. and Stos-Gale Z. A., 1981, 'Cycladic lead and silver metallurgy', *Annals of the British School at Athens*, **76**, pp. 169–224.

Gale, W. K. V., 1966, *The Black Country Iron Industry*, The Iron and Steel Institute, London.

Gallin, L. J. and Tykot, R. H., 1993, 'Metallurgy at Nuraghe Santa Barbara (Bauladu), Sardinia', *Journal of Field Archaeology*, **20**(3), pp. 335–46.

Garner, A., Prag, J. and Housley, R., 1994, 'The Alderley Edge Shovel', *Current Archaeology*, **137**, pp. 172–5.

Gechter, M., 1993, 'Römischer Bergbau in der Germania Inferior, Eine Bestandsaufnahme', in Steuer and Zimmermann (eds), pp. 161–6.

Geçkinli, A. E., Bozkurt, N. and Başaran, S., 1988, 'Metallographic studies of archaeological metal artifacts from Çavuştepe', *Aksay Ünitesī Bilimsel Toplanti Bildinileri*, **1** (23–25 November 1988), Middle East University, Ankara, pp. 229–46.

Gee, D. R., 1985, 'Metallurgical analysis of a 16th century Japanese sword', unpublished winning paper in the American Society of Metals international student paper contest (referenced in Rostoker and Bronson, 1990).

Gettens, R. J., Clarke Jr., R. S. and Chase, W, T., 1971, *Two Early Chinese Bronze Weapons with Meteoritic Iron Blades*, Occ. Papers **4**(1), Freer Gallery, Washington.

Ghosh, A. K., 1963, 'The Delhi iron pillar and its iron', *N.M.L. Technical Journal*, **5**(1), pp. 31–45.

Gilchrist, J. D., 1967, *Extractive Metallurgy*, Pergamon, London.

Gillespie, R., Gowlett, J. A. J., Hall, E. T. and Hedges, R. E. M., 1984, 'Radiocarbon measurements by accelerator mass spectrometry: an early selection of dates', *Archaeometry*, **26**(1), pp. 15–20.

Giusti, L., 1986, 'The morphology, mineralogy and behavior of "finegrained" gold placer deposits of Alberta', *Canadian Journal of Earth Sciences*, **23**, pp. 1662–71.

Glumac, P. D. and Todd, J. A., 1991, 'Eneolithic copper smelting slags from the Middle Danube', in *Archaeometry '90*, ed. E. Pernicka and G. A. Wagner, Birkhauser Verlag, Basle, pp. 155–64.

Gonzales, A. R., 1979, 'Pre-Columbian metallurgy of Northwest Argentina', in *Pre-Columbian Metallurgy of South America*, ed. E. P. Benson, Dumbarton Oaks, Washington, DC, pp. 133–202.

Goodway, M., 1987a, 'More on wooden smelting furnaces', *Journal of Field Archaeology*, **14**, p. 383.

Goodway, M., 1987b, 'Phosphorus in antique iron music wire', *Science*, **236**, pp. 927–32.

Goodway, M., 1989, 'Archaeometallurgical news', *SAS Bulletin*, **12**(1), p. 7.

Goodway, M. and Fisher, R. M., 1988, 'Phosphorus in low carbon iron: its beneficial properties', *Journal of the Historical Metallurgy Society*, **22**(1), pp. 21–3.

Goodway, M. and Odell, J. S., 1987, *The metallurgy of 17th and 18th Century Music wire*, Pendragon, Stuyvesant, NY.

Gordon, R. B. and Killick, D. J., 1992, 'The metallurgy of the American bloomery process', *Archaeomaterials*, **6**, pp. 141–67.

Gordon, R. B. and Killick, D. J., 1993, 'Adaption of technology to culture and environment: bloomery smelting in America and Africa', *Technology and Culture*, **34**(2), pp. 243–70.

Gordon, R. B. and van der Merwe, N. J., 1984, 'Metallographic study of iron artefacts from the eastern Transvaal, South Africa', *Archaeometry*, **26**(1), pp. 108–27.

Gowland, W., 1894, 'A Japanese pseudo-speise (shirome) and its relations to the purity of Japanese copper', *Journal of the Society of Chemical Industry*, **13**(5), May, pp. 1–26, and a revised version published separately, Eyre and Spottiswoode, London.

Gowland, W., 1899, 'The early metallurgy of copper, tin and iron in Europe, as illustrated by ancient remains and the primitive processes surviving in Japan', *Archaeologia*, **56**(2), pp. 267–322.

Gowland, W., 1900, 'Remains of a Roman silver refinery at Silchester', *Archaeologia*, **57**(1), pp. 113–24.

Gowland, W., 1901, 'The early metallurgy of silver and lead: Pt 1, lead', *Archaeologia*, **57**(2), pp. 359–422.

Gowland, W., 1915a, 'Metals and metal-working in old Japan', *Transactions of the Japan Society of London*, **13**, pp. 19–100.

Gowland, W., 1915b, 'Report on the metals and metallurgical remains', in *Excavations at Hengistbury Head, Hampshire, 1911–12*, by J. P. Bushe-Fox, Society of Antiquaries, London, pp. 72–83.

Gowland, W., 1917/18, 'Silver in Roman and earlier times', *Archaeologia*, **69**, pp. 121–60.

Granger, F. (trans.), 1934, *Vitruvius: On Architecture*, Loeb Edition, Heinemann, London.

Graves, H. R., 1912, 'Further notes on the early use of iron in India', *Journal of the Iron and Steel Institute*, **194**, pp. 187–202.

Griffin, J. B. (ed.), 1961, *Lake Superior Copper and the Indians*, Anthropology Papers, **17**, Museum of Anthropology, University of Michigan Press, Michigan.

Grzelishvili, I. A., 1964, *Ironworking in Ancient Georgia*, Tbilisi.

Gunther, R. T. (ed.), 1934, *The Greek Herbal of Dioscorides*, John Goodyear's translation of 1655, OUP, Oxford (pp. 623–5 (84) zinc and brass, pp. 638 (110) mercury).

Habashi, F., 1989, 'One hundred years of cyanidation', in Wayman (ed.), pp. 78–83.

Hadfield, R., 1912, 'Sinhalese iron and steel of ancient origin', *Journal of the Iron and Steel Institute*, **85**, pp. 134–86.

Haedecke, K., 1973, 'Gleichgewichtsverhaeltnisse bei der Messingherstellung nach dem Galmeiverfahren', *Erzmetall*, **25**, pp. 229–51.

Halleux, R., 1973, 'L'orichalque et le laiton', *Antiquité Classique*, **42**, pp. 64–81.

Halleux, R. and Yans, A., 1990, *G. Agricola: Bermannus*, Les Belles Lettres, Paris.

Hallström, D. (ed.), 1973, *Early Medieval Studies*, **5**, Almqvist & Wiksell, Stockholm.

Handwerker, C. A., Lechtman, H. N., Marinenko, R. B., Bight, D. S. and Newbury, D. E., 1991, 'Fabrication of platinum-gold alloys in pre-hispanic South America: issues of temperature and microstructure control', in *Materials Issues in Art and Archaeology*, **II**, ed. P. B. Vandiver *et al*, MRS, Pittsburgh, pp. 649–64.

Hanson, D. and Marryat, C. B., 1927, 'Investigation of the effect of impurities on copper, Pt III, the effect of arsenic on copper, Pt IV, the effect of arsenic plus oxygen on copper', *Journal of the Institute of Metals*, **37**, pp. 121–63, and a discussion *ibid*, **37**, pp. 163–8.

Harris, V. and Ogasawara, N., 1990, *Swords of the Samurai*, BMP, London.

Harrison, R., Quero, S. and Priego, C., 1975, 'Beaker metallurgy in Spain', *Antiquity*, **49**(196), pp. 273–8.

Hartmann, A., 1970, 'Prähistorische Goldfunde aus Europa', *Studien zu den Anfängen der Metallurgie*, **3**, Berlin.

Hartwell, R. M., 1967, 'A cycle of economic change in imperial China: coal and iron in Northeast China, 750–1350', *Journal of Economic and Social History in the Orient*, **10**, pp. 102–59.

Hauptmann, A., 1989, 'The earliest periods of copper metallurgy in Feinan, Jordan', in Hauptmann *et al* (eds), pp. 119–35.

Hauptmann, A., 1990, 'The copper ore deposit of Feinan, Wadi Araba: early mining and metallurgy', in *The Near East in Antiquity*, **1**, ed. S. Kerner, Goethe-Institut. Amman, pp. 53–62.

Hauptmann, A., 1991, 'From the use of ore to the production of metal', in Éluère and Mohen (eds), pp. 397–412.

Hauptmann, A., Begemann, F., Heitkemper, E., Pernicka, E. and Schmitt-Strecker, S., 1992, 'Early copper produced at Feinan', *Archeomaterials*, **6**(1), pp. 1–33.

Hauptmann, A., Lutz, J., Pernicka, E. and Yalçin, U., 1993, 'Zur Technologie der frühesten Kupferverhüttung im Östlichen Mittelmeerraum', in M. Frangipane *et al* (eds), *Between the Rivers and over the Mountains*, University of Rome 'La Sapienza', Rome, pp. 541–71.

Hauptmann, A, Pernicka, E. and Wagner, G. A. (eds), 1989, *Old World Archaeometallurgy*, Der Anschnitt, Bochum.

Hauptmann, A. and Slotta, R., 1979, 'Zu den Denkmälern des Quecksilber Bergbaus von Almaden', *Der Anschnitt*, **31**, pp. 81–100.

Hauptmann, A. and Yalçin, U., 1992, 'Frühe Eisengewinnung auf der Schwäbischen Alb', *Heimat- und Altertumsverein Heidenheim*, pp. 47–61.

Hawthorne, J. G. and Smith, C. S. (eds), 1963, *On Divers Arts: The Treatise of Theophilus*, University of Chicago Press, Chicago.

Healy, J. F., 1978, *Mining and Metallurgy in the Greek and Roman World*, Thames and Hudson, London.

Hegde, K. T. M., 1969, 'Technical studies in copper artifacts from Ahar', in *Excavations at Ahar*, (eds), H. M. Sankalia, S. B. Deo and Z. D. Ansari, Deccan College, Poon, pp. 225–8.

Hegde, K. T. M. and Ericson, H. E., 1985, 'Ancient Indian copper smelting furnaces', in Craddock and Hughes (eds), pp. 59–70.

Heine, R. W., Loper, C. R. and Rosenthal, P. C., 1967, *Principles of Metal Casting*, 2nd edn, McGraw-Hill, New York.

Hemptinne, Msg. de, 1926, 'Les "mangeurs de cuivre" du Katanga', Brussels, extract from *Congo*, 7 (March), pp. 371–404.

Herbert, E. W., 1984, *The Red Gold of Africa*, University of Wisconsin Press, Wisconsin.

Herbert, E. W., 1993, *Iron, Gender and Power: Rituals of Transformation in African Societies*, Indiana University Press, Bloomington, Indiana.

Hett, W. S. (trans.), 1936, *Aristotle: Minor Works*, Loeb edition, Heinemann, London.

Heyne, B., 1814, *Tracts, Historical and Statistical, on India*, London.

Hodges, H., 1964, *Artifacts*, John Baker, London.

Hofman, H. O., 1914, *The Metallurgy of Copper*, McGraw Hill, New York.

Holman, B. W., 1927, 'Heat treatment as an agent in rock breaking', *Transactions of the Institute of Mining and Metals*, **36**, pp. 219–62.

Holmyard, E. J. (ed.), 1928, *The Works of Geber Englished by Richard Russell 1678* , J. M. Dent, London.

Hook, D. R., Arribas Palau, A., Craddock, P. T., Molina, A. and Rothenberg, B., 1987, 'Copper and silver in Bronze Age Spain', in *Bell Beakers of the Western Mediterranean*, ed. W. H. Waldren and R. C. Kennard, BAR International Series 331(ii), Oxford, pp. 147–72.

Hook, D. R., Freestone, I. C., Meeks, N. D., Craddock, P. T. and Moreno Onorato, A., 1991, 'The early production of copper-alloys in South-East Spain', in *Archaeometry '90*, ed. E. Pernicka and G. A. Wagner, Birkhauser Verlag, Basle, pp. 65–76.

Hoover, H. C. and Hoover, L. H. (trans.), 1912, *Agricola: De re Metallica*, The Mining Magazine, London.

Horne, L., 1982, 'Fuel for the Metalworker', *Expedition*, **25**(1), pp. 6–13.

Hua, Jue-ming, 1983, 'The mass production of iron castings in ancient China', *Scientific American*, **248**(1), pp. 107–14.

Hubert, F., 1974, 'Minères néolithiques à Jandrain-Jandrenouille en Brabant', *Archeologia Belgica*, **167**, pp. 5–45.

Hughes, S. J. S., 1981, *The Cwmystwyth Mines*, Northern Mines Research Society, Sheffield.

Hughes, M. J., Lang, J. R. S., Leese, M. N. and Curtis, J. E., 1988, 'The evidence of scientific analysis: a case study of the Nimrud Bowls', in *Bronze-working Centres of Western Asia*, ed. J. E. Curtis, Kegan Paul, London, pp. 311–15.

Huntingford, G. W. B. (trans. and ed.), 1980, *The Periplus of the Erythraen Sea*, The Hakulyt Society, London.

Hurst, V. J. and Larson Jr, L. H., 1958, 'On the source of the copper at the Etowah Site, Georgia', *American Antiquity*, **24**, pp. 177–81.

IHNC, 1983, *Ancient China's Technology and Science*, Foreign Languages Press, Beijing.

Ingalls, W. R., 1903, *The Metallurgy of Zinc and Cadmium*, The Engineering and Mining Journal, New York.

Jackson, J. S., 1968, 'Bronze Age copper mines on Mt Gabriel, West Co. Cork, Ireland, *Archaeologia Austriaca*, **43**, pp. 92–114.

Jackson, J. S., 1979, 'Metallic ores', in Irish prehistory', in *The Origins of Metallurgy in Atlantic Europe*, ed. M. Ryan, Proceedings of the fifth Atlantic Colloquium, Dublin, pp. 107–25.

Jackson, J. S., 1980, 'Bronze Age copper mining in counties Cork and Kerry, Ireland', in Craddock (ed.), pp. 9–30.

James, D., 1988, 'Prehistoric copper mining on the Great Orme's Head, Llandudno, Gwynedd', in *Aspects of Ancient Mining and Metallurgy*, ed. J. Ellis-Jones, Acta of the British School at Athens Centenary Conference, Bangor, pp. 115–21 (reprinted in Crew and Crew (eds), 1990).

Jenkins, D. A. and Lewis, C. A., 1991, Prehistoric mining on the Great Orme's Head, Llandudno', in *Archaeological Science 1989*, ed. P. Budd *et al*, Oxbow, Oxford, pp. 151–61.

Joly, H. L. and Inada, H., 1913, *The Sword Book and the Book of Same*, privately printed, London.

Jones, H. L. (trans.), 1928, *Strabo: The Geography*, The Loeb Classical Library, Heinemann, London.

Jones, J. E., 1984, 'Ancient Athenian silver mines, dressing floors and smelting sites', *Journal of the Historical Metallurgy Society*, **18**, pp. 65–81.

Jones, J. E., 1988, 'The Athenian silver mines of Laurion and B.S.A. excavations at Agrileza', in *Aspects of Ancient Mining and Metallurgy*, ed. J. E. Jones, Dept of Classics, University College of North Wales, Bangor, pp. 11–22.

Jones, W. R., 1925, *Tinfields of the World*, Mining Publications, London.

Jovanović, B., 1971, *Metalurgija Eneolitskog Perioda Jugoslavije*, Arheološki Institut, Beograd.

Jovanović, B., 1979, 'The technology of primitive copper mining in south-east Europe', *Proceedings of the Prehistoric Society*, **45**, pp. 103–10.

Jovanović, B., 1980, 'Primary copper mining and the production of copper', in Craddock (ed.), pp. 31–40.

Jovanović, B., 1982, *Rudna Glava*, Muzej Rudarstva I Metalurgie/Arheološki Institut, Bor/Beograd.

Jovanović, B., 1988, 'Early metallurgy in Yugoslavia', in Maddin (ed.), pp. 69–79.

Juleff, G., 1990a, 'The Samanalawewa Archaeological Survey', *Towards the Second Centenary of Archaeology in Sri Lanka*, **II**, *Ancient Ceylon*, **9**, pp. 75–106.

Juleff, G., 1990b, 'Crucible steel in Sri Lanka and India: new evidence', *Towards the Second Centenary of Archaeology in Sri Lanka*, **II**, *Ancient Ceylon*, **9**, pp. 33–59.

Juleff, G., forthcoming, Samanalawewa Archaeological Report, *Ancient Ceylon*, 16.

Junghans, S., Sangmeister, E. and Schröder, M., 1960, 1968 and 1974, *Studien zu den Anfängen der Metallurgie*, Gebr. Mann., Berlin.

Kangle, R. P., 1972, *The Kauṭilīya Arthaśāstra*, Bombay University Press, Bombay.

Kapp, L., Kapp, H. and Yoshihara, Y., 1987, *The Craft of the Japanese Sword*, Kodansha, Tokyo.

Kappel, I., 1969, 'Die Graphittonkeramik', in W. Kramer and F. Schubert (eds), *Die Ausgrabungen in Manching 1935–1961*, **2**, pp. 19–49.

Kaptan, E., 1978, 'Ancient miner's shovel discovered at Anayatak Murgul mine', *Bulletin of the Mineral Research and Exploration Institute of Turkey*, **89**, pp. 96–100.

Kassianidou, V., 1992, 'Monte Romero, a silver producing workshop of the 7th century BC in South-West Spain', *IAMS Newsletter*, **18**, pp. 7–10.

Keesman, I., 1993, 'Naturwissenschaftliche Untersuchungen zur antiken Kupfer-Silberverhüttung in Südwestspanien', in Steuer and Zimmermann (eds), pp. 105–22.

Kelley, D. W., 1986, *Charcoal and Charcoal Burning*, Shire, Aylesbury, Bucks.

Kense, F. J., 1983, *Traditional African Iron Working*, African Occasional Papers, 1, University of Calgary, Calgary, Alberta.

Key, C. A., 1980, 'The trace-element composition of the copper alloy artefacts of the Nahal Mismar hoard', in Bar Adon (1980), pp. 238–43.

Kiernan, D, and Van der Noort, R., 1992, 'Bole smelting in Derbyshire', in Cranstone and Willies (eds), pp. 19–22.

Killick, D., 1992, 'The relevance of recent African iron-smelting practice to reconstructions of prehistoric smelting technology', *MASCA Research Papers in Science and Archaeology*, **8**(1), pp. 8–20.

Killick, D. J. and Gordon, R. B., 1988, 'The mechanism of iron production in the bloomery furnace', in *Proceedings of the 26th International Archaeology Symposium*, ed. R. M. Farquhar, R. G. V. Hancock and L. A. Pavlish, Archaeometry Lab, University of Toronto, Toronto, pp. 120–23.

King, R. J., 1989, 'Native copper', *Geology Today*, May/June, pp. 104–6.

Kinnes, I. A., Craddock, P. T., Needham, S. and Lang, J., 1979, 'Tin plating in the Early Bronze Age: the Barton Stacey axe', *Antiquity*, **208**, pp. 141–3.

Klaproth, M. H., 1795/1815, *Beiträge zur Chemischen Kenntniss der Mineralkorper*, Posen and Berlin.

Klaproth, M. H., 1798, *Mémoires de l'académie Royale des Sciences et: Belles-lettres, Berlin, Classe de Philosophie Expérimentale*, pp. 97–113 *et seq*.

Knox, R., 1987, 'On distinguishing meteoritic from man-made nickel-iron in ancient artifacts', *MASCA Journal*, **4**(4), pp. 178–84.

Košak, S., 1982, *Hittite Inventory texts (C.T.H. 241–250)*, Heidelberg.

Koşay, H. Z., 1951, *Les Fouilles d'Alaca*, Höyük Türk Tarih Kurumu Yayinlarindan, **V**, Ankara.

Koucky, F. L. and Steinberg, A., 1982, 'Ancient mining and mineral dressing on Cyprus', in *Early Pyrotechnology*, ed. T. A. and S. F. Wertime, Smithsonian Institution, Washington, pp. 149–80.

Krishnan, M. S., 1954, 'Iron ore, iron and steel', *Bulletin of the Geological Survey of India, Series A – Economic Geology*, **8**, pp. 1–236 (esp. 63–7).

Lamborn, R. H., 1861, *A Rudimentary Treatise on the Metallurgy of Silver and Lead*, Weales Supplementary Series **2**, London.

Landes, C., 1989, 'Les resources mineres antiques des Cevennes', in Domergue (ed.), pp. 223–9.

Lane, H. C., 1973, *Field Surveys and Excavation of a Romano-British Settlement at Scarcliffe Park, East Derbyshire*, Research Report no 1, Derwent Archaeological Society.

Lane, H. C., 1986 *The Romans in Derbyshire*, **2**, Veritas, Bolsover, Derbyshire.

Lang, J., 1991, 'A dirk from Cyprus', *Materiały Archeologiczne*, **26**, pp. 93–6.

Lang, J., *nd*, 'The technology of Celtic iron swords', in Scott and Cleere (eds), pp. 61–72.

Lang, J. and Ager, B., 1989, 'Swords of the Anglo-Saxon and Viking periods in the British Museum: a radiographic study', in *Weapons and Warfare*, ed. S. Chadwick Hawkes, OUCA Monograph **21**, Oxbow, Oxford, pp. 85–122.

Langenscheidt, A., 1989, 'Consideraciones sobre la Evolucion de la Metalurgia del Mercurio en Mexico', *Congreso Mexicano de Historia de la Ciencia y de la Technologia México*, D. F., pp. 289–309.

La Niece, S. and Carradice, I., 1989, 'White copper: the arsenical coinage of the Libyan revolt 241–38 BC', *Journal of the Historical Metallurgy Society*, **23**(1), pp. 9–15.

Lankford, W. T., Samways, N. L., Craven, R. F. and McGrannon, H. E. (eds), 1985, *The Making, Shaping and Treating of Steel*, 10th edn., US Steel/Association of Iron and Steel Engineers, Pittsburgh.

Latham, R. E. (trans.), 1972, *The Travels of Marco Polo*, Pelican Books, London.

Lechtmann, H. N., 1971, 'Ancient methods of gilding silver: examples from the Old and New Worlds', in *Science and Archaeology*, ed. R. H. Brill, MIT Press, Cambridge, MA, pp. 2–31.

Lechtmann, H. N., 1973, 'The gilding of metals in pre-Columbian Peru', *Application of Science in Examination of Works of Art*, ed. W. J. Young, Museum of Fine Arts, Boston, pp. 38–52.

Leese, M. N., Craddock, P. T., Freestone, I. C. and Rothenberg, B., 1986, 'The composition of ores and metal objects from Timna, Israel', *Wiener Berichte über Naturwissenschaft in der Kunst*, **2/3**, pp. 90–120.

Leisner, V. and Schubart, H., 1966, 'Die kupferzeitliche Befestigung von Pedra don Ouro, Portugal, *Madrider Mitteilungen*, **7**, pp. 9–60.

Levey, M., 1959a, 'The refining of gold in ancient Mesopotamia', *Chymia*, **5**, pp. 31–6.

Levey, M., 1959b, *Chemistry and Chemical Technology in Ancient Mesopotamia*, Elsevier, Amsterdam.

Levey, M., 1971, *Chemical Aspects of Medieval Arabic Minting in a Treatise by Manṣūr ibn Baᶜra*, Japanese Studies in the History of Science Supplement **1**, The History of Science Society of Japan, Tokyo.

Lewis, A., 1990a, 'Underground exploration of the Great Orme copper mines', in Crew and Crew (eds), pp. 5–10.

Lewis, A., 1990b, 'Firesetting experiments on the Great Orme's Head', in Crew and Crew (eds), pp. 55–6.

Lewis, M. J. T., 1970, *Early Wooden Railways*, Routledge and Kegan Paul, London.

Lewis, P. R. and Jones, G. D. B., 1969, 'The Dolaucothi gold mines I', *The Antiquaries Journal*, **49**(2), pp. 244–72.

Lewis, P. R. and Jones, G. D. B., 1970, 'Roman gold-mining in North-West Spain', *The Journal of Roman Studies*, **60**, pp. 169–85.

Li Chung, 1979, 'Studies on the iron blade of a Shang Dynasty Bronze *Yueh-axe* unearthed at Kao-ch'eng, Hopei, China', *Ars Orientalis*, **11**, pp. 259–90.

Lins, P. A. and Oddy, W. A., 1975, 'The origins of mercury gilding', *Journal of Archaeological Science*, **2**, pp. 365–75.

Lo Bue, E., 1981, 'Statuary metals in Tibet and the Himalayas', in *Aspects of Tibetan Metallurgy*, ed. W. A. Oddy and W. Zwalf, British Museum Occasional Paper **15**, pp. 33–69.

Loud, G., 1936, *Khorsabad I: Excavations in the Palace and at a City Gate*, Oriental Institute Publication **38**, Chicago.

Lowe, T. L., 1989, 'Refractories in high-carbon iron processing: a preliminary study of the deccani *wootz*-making crucibles', in *Ceramics and Civilisation*, **IV**, eds P. E. McGovern, M. D. Notis and W. D. Kingery, American Ceramic Society. Westerville, Ohio, pp. 237–42.

Lowe, T. L., Merk, N. and Thomas, G., 1991, 'An historical mullite fibre-reinforced, ceramic composite: characterization of the 'wootz' crucible refractory', in *Materials Issues in Art and Archaeology*, **II**, eds P. B. Vandiver, J. Druzik and G. S. Seagan, MRS, Pittsburgh, pp. 627–32.

Lucas, A., 1962, *Ancient Egyptian Materials and Industries*, 4th edn revised by J. R. Harris, Edward Arnold, London.

Lyman, B. S., 1879, *Geological Survey of Japan: Report of Progress for 1878 and 1879*, Tookei.

MacAlister, R. A. S., 1912, *The Excavation of Gezer*, Macmillan, London.

McCartney, A. P. and Mack, D. J., 1973, 'Iron utilization by Thule Eskimos of Central Canada', *American Antiquity*, **38**, pp. 328–38.

McDonald, D., 1960, *A History of Platinum*, Johnson Matthey, London.

McDonald, D. and Hunt, L. B., 1982, *A History of Platinum and its Allied Metals*, Johnson Matthey, London.

McDonnell, J. G., 1983, 'Tap slags and hearth bottoms', *Current Archaeology*, 86, pp. 81–3.

McDonnell, J. G., 1991, 'A model for the formation of smithing slags', *Materiały Archeologiczne*, **26**, International Archaeometallurgy Symposium, Krakow, pp. 23–6.

McDonnell, J. G., *nd*, 'The study of early iron smelting residues', in Scott and Cleere (eds), pp. 47–52.

McKerrell, H. and Tylecote, R. F., 1972, 'The working of copper-arsenic alloys in the Early Bronze Age and the effect on the determination of provenance', *Proceedings of the Prehistoric Society*, **38**, pp. 209–18.

Maddin, R. (ed.), 1988, *The Beginning of the Use of Metals and Alloys*, MIT, Cambridge, MA.

Maddin, R., Stech-Wheeler, T. and Muhly, J. D., 1977, 'How the Iron Age began', *Scientific American*, **237**(4), October, pp. 122–31.

Maddin, R., Stech-Wheeler, T. and Muhly, J. D., 1980, 'Distinguishing artifacts made of native copper', *Journal of Archaeological Science*, **7**, pp. 211–25.

Maddin, R., Stech, T. and Muhly J. D., 1991, 'Cayönü Tepesi', in Éluère and Mohen (eds), pp. 375–86.

Maddin, R. Stech, T. and Muhly, J. D., forthcoming, 'Cayönü and the beginnings of metallurgy in Anatolia and Mesopotamia', in *Proceedings of the Rencontre Assyriologique*, Istanbul.

Magnusson, G., 1985, 'Lapphyttan – an example of medieval iron production', *Medieval Iron in Society*, Symposium in Norberg 6–10 May 1985, eds E. Hook and R. Palsson, Jernkontoret and Riksantikvarineambetet, Stockholm, pp. 22–57.

Mallet, J. W., 1852, *An Account of a Chemical Examination of the Celtic Antiquities in the Collection of the Royal Irish Academy*, M. H. Gill, Dublin.

Manès, M., 1823/4, 'Memoire sur les mines d'étain de Saxe', *Annales des Mines* (3rd series), **8**, pp. 499–595, 837–86; **9**, pp. 281–304, 463–76 and 625–56.

Maréchal, J.-R., 1963, *Reflections upon Prehistoric Metallurgy*, Otto Junker, Lammersdorf, Germany.

Maréchal, J.-R., 1983, *La Préhistoire de la Métallurgie* Révue Archéologie, Sites, Avignon.

Maréchal, J.-R., 1985, 'Methods of ore roasting and the furnaces used', in Craddock and Hughes (eds), pp. 29–42.

Marshall, J., 1951, *Taxila*, CUP, Cambridge.

Masuda, T., 1983, *Kudo Zuroku: Illustrated Book on the Smelting of Copper*, Burndy Library, Norwalk, Conn.

Meeks, N. D., 1986, 'Tin-rich surfaces on bronze – some experimental and archaeological considerations', *Archaeometry*, **28**(2), pp. 133–62.

Meeks, N. D., 1993, 'Surface characterization of tinned bronzes, high tin bronze, tinned iron and arsenical bronze', in *Metal Plating and Patination*, eds S. La Niece and P. T. Craddock, Butterworth-Heinemann, Oxford, pp. 247–75.

Meeks, N. D. and Tite, M. S., 1980, 'The analysis of platinum-group element inclusions in gold antiquities', *Journal of Archaeological Science*, 7, pp. 267–75.

Megaw, B., 1960/1, 'Bakenaldswath and the medieval lead mines', *Journal of the Manx Museum*, **6**, p. 77.

Merkel, J. F., 1983, 'Summary of the experimental results of Late Bronze Age copper smelting and refining', *MASCA Journal*, **2**(6), pp. 173–8.

Merkel, J. F., 1985, 'Ore beneficiation during the Late Bronze Age/Early Iron Age at Timna, Israel', *MASCA Journal*, **3**(5), pp. 164–9.

Merkel, J. F., 1989, 'Experience with refractories in reconstruction copper smelting: archaeo-metallurgical evidence from Timna, Israel', in *Ceramics and Civilisation*, **IV**, eds P. E. McGovern, M. D. Notis and W. D. Kingery, The American Ceramic Society, Westerville, Ohio, pp. 217–34.

Merkel, J. F., 1990, 'Experimental reconstruction of Bronze Age copper smelting based on archaeological evidence from Timna', in B. Rothenberg (ed.), pp. 78–122.

Merpert, N., Munchaev, R. M. and Bader, N. O., 1977, 'The earliest metallurgy of Mesopotamia', *Sovtskaya Arkheologiya*, **3**, pp. 154–65 (Russian with French summary).

van der Merwe, N. J., 1980, 'The advent of iron in Africa', in Wertime and Muhly (eds), pp. 463–507.

van der Merwe, N. J., and Avery, D. H., 1982, 'Pathways to steel', *American Scientist* , **70**(2), pp. 146–54.

van der Merwe, N. J. and Avery, D. H., 1988, 'Science and magic in African technology', in R. Maddin (ed.), pp. 245–60.

Meyers, P., 1983, 'Production, distribution and characterization of silver in the ancient Near East', preprints for the Second International Symposium, *Historische Technologie der Edelmetalle*, Meersburg 25–28 April 1983, pp. 21–3.

Migal, W. and Kaminski, G., *nd*, 'Ventilation of neolithic mines: an experimental study', *Archeologie Aujourd'hui: Archaelogie Experimentale*, **2**, Archéodrome de Beaune, pp. 146–52.

Mighall, T., 1990, 'Copa Hill, Cwmystwyth: preliminary paleoecological observations', in Crew and Crew (eds), pp. 65–8.

Mighall, T. and Chambers, F., 1989, 'The environmental impact of iron working at Bryn y Castell hillfort, Merioneth', *Archaeology in Wales*, **29**, pp. 17–21.

Miller, D. E. and van der Merwe, N. J., 1994, 'Early metalworking in Sub-Saharan Africa', *Journal of African History*, **35**, pp. 1–36.

Moesta, H., 1986, *Erze und Metalle*, Springer-Verlag, Berlin.

Moesta, H., Rüffler, R. and Schnau-Roth, G., 1989, 'Zur Verfahrenstechnik der bronzezeitlichen Kupferhütten am Mitterberg', in Hauptmann, Pernicka and Wagner (eds), pp. 141–54.

Moesta, H. and Schlick, G., 1989, 'The Furance [*sic*] of Mitterberg', *Bulletin of the Metals Museum*, **14**, pp. 5–16.

Moesta, H., Schnau-Roth, G. and Wagner, H.-G., 1984, 'Mössbauer-Studien zu bronzezeitlichen Kupferhütten Prozessen', *Berliner Beiträge zur Archaömetrie*, **9**, pp. 95–112.

Mohen, J.-P., 1990, *Métallurgie Préhistorique*, Masson, Paris.

Molera, P., 1989, 'The Farga Catalana', in Wayman (ed.), pp. 41–4.

Money, J. H., 1971, 'Medieval iron-workings in Minepit Wood, Rotherfield, Sussex', *Medieval Archaeology*, **15**, pp. 86–111.

Moore, D. T. and Oddy, W. A., 1985, 'Touchstones: some aspects of their nomenclature, petrography and provenance', *Journal of Archaeological Sciences*, 12, pp. 59–80.

Moorey, P. R. S., 1985, *Materials and Manufacture in Ancient Mesopotamia: The evidence of archaeology and art, Metals and metalwork, glazed materials and glass*, BAR International Series 237, Oxford.

Moorey, P. R. S., 1988, 'Early metallurgy in Mesopotamia', in Maddin (ed.), pp. 28–33.

Morrogh, H. and Williams, W. J., 1948, 'The production of modular graphite structures in cast iron', *Journal of the Iron and Steel Institute*, **58**, pp. 306–22.

Morton, G. R. and Wingrove, J., 1969a, 'Slag, cinder and bear', *Bulletin of the Historical Metallurgy Group*, **3**, pp. 55–61.

Morton, G. R. and Wingrove, J., 1969b, 'Constitution of bloomery slags: Pt 1, Roman', *Journal of the Iron and Steel Institute*, **207**, pp. 1556–64.

Morton, G. R. and Wingrove, J., 1971, 'The charcoal finery and chafery forge', *Bulletin of the Historical Metallurgy Group*, **5**(1), pp. 24–8.

Morton, G. R. and Wingrove, J., 1972, 'Constitution of bloomery slags: Pt 2, medieval', *Journal of the Iron and Steel Institute*, **210**, pp. 478–88.

MTA, 1970, *Arsenic, Mercury, Antimony and Gold Deposits of Turkey*, Mineral Research and Exploration Institute of Turkey, Ankara.

MTA, 1972, *Lead, Copper and Zinc Deposits of Turkey*. Mineral Research and Exploration Institute of Turkey, Ankara.

Muhly, J. D., 1980, 'The Bronze Age setting', in Wertime and Muhly (eds), pp. 25–68.

Muhly, J. D., 1983, 'Kupfer. B. Archäologisch', in *Reallexikon der Assyriologie und Vorderasiatischen Archäologie*, **6**, de Gruyter, Berlin, pp. 348–64.

Muhly, J. D., 1988, 'The beginnings of metallurgy in the Old World', in Maddin (ed.), pp. 2–20.

Muhly, J. D., Maddin, R. and Karageorghis, V. (eds), 1982, *Early Metallurgy in Cyprus 4000–500 BC*, Pierides Foundation, Nicosia.

Muhly, J. D., Maddin, R., Stech, T. and Özgen, E., 1985, 'Iron in Anatolia and the nature of the Hittite iron industry', *Anatolian Studies*, **35**, pp. 67–84.

Munan, H., 1989, *Sarawak Crafts*, OUP, Singapore.

Mushet, D., 1805, 'Experiments on Wootz', *Philosophical Transactions*, **95**, pp. 163–75.

Mushet, D., 1840, *Papers on Iron and Steel*, London.

Musprat, J. S., 1860, *Chemistry, Theoretical, Practical and Analytical as applied to the Arts and Manufactures*, London.

Nash, W. G. N., 1904, *The Rio Tinto Mine*, Simpkin Marshall Hamilton Kent, London.

Needham, J., 1954, *Science and Civilisation in China*, **I**, CUP, Cambridge.

Needham, J., 1958, *The Development of Iron and Steel Metallurgy in China*, Heffers (for the Newcomen Society), Cambridge.

Needham, J., 1965, *Science and Civilisation in China*, **IV**, CUP, Cambridge.

Needham, J., 1974, *Science and Civilisation in China*, **V**(2), CUP, Cambridge.

Needham, J., 1980a, *Science and Civilisation in China*, **V**(4), CUP, Cambridge.

Needham, J., 1980b, 'The evolution of iron and steel technology in East and Southeast Asia', in Wertime and Muhly (eds), pp. 507–42.

Neuninger, H., Pittioni, R. and Siegl, W., 1964, 'Frühkeramikzeitliche Kupfergewinnung in Anatolien', *Archaeologia Austriaca*, **35**, pp. 98–110.

Newman, W. R. (ed. and trans.), 1991, *The Summa Perfectionis of Pseudo-Geber*, Brill, Leiden.

Nibbi, A., 1987, *Ancient Egyptian Pot Bellows and the Oxhide Ingot Shape*, DE Publications, Oxford.

Northover, J. P., 1980, 'Bronze in the British Bronze Age', in *Aspects of Early Metallurgy*, ed. W. A. Oddy, British Museum Occasional Paper 17, London, pp. 63–70.

Northover, J. P., 1982, 'The exploration of the long-distance movement of bronze in Bronze and Early Iron Age Europe', *Institute of Archaeology Bulletin*, **19**, pp. 45–72.

Northover, J. P., 1989, 'Properties and use of arsenical copper', in Hauptmann *et al* (eds), pp. 111–18.

Nosek, E. M., 1985, 'The Polish smelting experiments in furnaces with slag pits', in Craddock and Hughes (eds), pp. 165–78.

Notton, J. F. H., 1974, 'Ancient Egyptian gold refining', *Gold Bulletin*', 7(2), pp. 50–6.

O'Brien, W. F., 1987, 'The dating of the Mt Gabriel-type copper mines of West Cork', *Journal of the Cork Historical and Archaeological Society*, **92**, pp. 50–70.

O'Brien, W. F., 1990, 'Prehistoric copper mining in south-west Ireland', *Proceedings of the Prehistoric Society*, **56**, pp. 269–90.

O'Brien, W. F., 1994, *Mount Gabriel: A Bronze Age Copper Mine in South West Ireland*, University of Galway Press, Galway.

O'Brien, W. F., Ixer, R. and O'Sullivan, M., 1990, 'Copper resources in prehistory: an

Irish perspective', in Crew and Crew (eds), pp. 30–36.

Oddy, W. A., 1977, 'The production of gold wire in antiquity', *Gold Bulletin*, 10(3), pp. 79–87.

Oddy, W A., 1983, 'Assaying in antiquity', *Gold Bulletin*, **16**(2), pp. 52–9.

Oddy, W. A., 1986, 'The touchstone: the oldest colorimetric method of analysis', *Endeavour* (new series), **10**(4), pp. 164–6.

Oddy, W. A., 1993, 'The assaying of gold by touchstone in antiquity and the medieval world', in *Outils et Ateliers d'orfèvres des Temps Anciens*, ed. C. Éluère, Soc. des Amis du Musée des Antiquités Nationales, Paris, pp. 93–100.

Ogden, J. M., 1976, 'The so-called "platinum" inclusions in Egyptian goldwork', *The Journal of Egyptian Archaeology*, **62**, pp. 138–44.

Ogden, J. M., 1977, 'Platinum group metal inclusions in ancient gold artifacts', *Journal of the Historical Metallurgy Society*, **11**(2), pp. 53–72.

Okafor, E. E., 1993, 'New evidence for early iron smelting in south-east Nigeria', in *The Archaeology of Africa*, ed. T. Shaw, P. Sinclair, B. Aandah and A. Okpoko, Routledge, London, pp. 432–48.

Oldfather, C. H. (trans.), 1933, *Diodorus Siculus: Works*, Loeb Classical Library, Heinemann, London.

Otto, H. and Witter, W., 1952, *Handbuch der ältesten vorgeschichtlichen Metallurgie in Mitteleuropa*, Barth, Leipzig.

Overman, F., 1852, *A Treatise on Metallurgy*, D. Appleton, New York.

Palmer, R. E., 1926/7, 'Notes on some ancient mine equipments and systems', *Transactions of the Institution of Mining and Metallurgy*, **36**, pp. 299–336.

Panseri, C., 1963, 'Damascus steel in legend and reality', *Gladius*, **4**, pp. 5–66.

Panseri, C. and Leoni, M., 1962, 'Research on an iron spearhead from the Etruscan sanctuary of Fanum Voltumnae, fourth–third centuries BC', in *Archaeological Chemistry*, ed. M. Levy, University of Pennsylvania Press, Philadelphia, pp. 205–30.

Patterson, C. C., 1971, 'Native copper, silver and gold accessible to early metallurgists', *American Antiquity*, **36**, pp. 286–321.

Peake, H., 1933, 'The origin and early spread of ironworking', *The Geographical Review*, **23**(4), pp. 639–52.

Pearson, G. and Stuiver, M., 1986, 'High-precision calibration of the radiocarbon time scale 500–2500 BC', *Radiocarbon*, **28**(2B), pp. 839–62.

Penhallurick, R. D., 1986, *Tin in Antiquity*, The Institute of Metals, London.

Percy, J., 1861, *Fuels, Fireclays, Copper, Zinc and Brass*, John Murray, London.

Percy, J., 1864, *Metallurgy: Iron and Steel*, John Murray, London.

Percy, J., 1870, *The Metallurgy of Lead*, John Murray, London.

Percy, J., 1880, *The Metallurgy of Silver and Gold: 1 Silver*, John Murray, London.

Pernicka, E. and Bachmann, H.-G., 1983, 'Archaömetallurgische Untersuchungen zur antiken silbergewinnung', in Laurion III, *Erzmetall*, **36**(12), pp. 592–7.

Pernicka, E., Seeliger, T. C., Wagner, G. A., Bergemann, F., Schmitt-Strecker, S., Eibner, C., Oztunali, O. and Baranyi, I., 1984, 'Archaometallurgische Untersuchungen in Nordwestanatolien', *Jahrbuch des Römisch-Germanischen Zentralmuseum*, **31**, pp. 533–600.

Peters, E. D., 1907, *Modern Copper Smelting*, 7th edn, Scientific Publishing, New York.

Photos, E., 1988, 'The question of meteoritic versus smelted nickel-rich iron:

archaeological evidence and experimental results', *World Archaeology*, 20(3), pp. 403–21.

Photos, E., Koukouli-Chrysanthaki, C., Tylecote, R. F. and Gialoglou, G., 1989, 'Precious metal extraction at Palaia Kavala N.E. Greece', in Hauptmann, Pernicka and Wagner (eds), pp. 179–90.

Photos, E., Tylecote, R. F. and Adam-Veleni, P., 1988, 'The possibility of smelting nickel-rich lateritic ion ores in the Hellenistic settlement of Petres, N.W. Greece', in *Aspects of Ancient Mining and Metallurgy: Acta of a British School at Athens Centenary Conference*, ed. J. E. Jones, University College of North Wales, Bangor, pp. 35–43.

Piaskowski, J., 1982, 'A study of the origin of the ancient high-nickel iron generally regarded as meteoritic', in *Early Pyrotechnolgy*, eds T. A. and S. F. Wertime, Smithsonian Press, Washington, pp. 237–44.

Piaskowski, J., 1992, 'Technical studies on high nickel irons, with special reference to the Indonesian kris', *Archaeomaterials*, **6**, pp. 35–52.

Pickin, J., 1990, 'Stone tools and early metal mining in England and Wales', in Crew and Crew (eds), pp. 39–42.

Pickin, J. and Timberlake, S., 1988, 'Stone hammers and firesetting', *Bulletin of the Peak District Mines Historical Society Ltd*, 10(3), pp. 165–7.

Piel, M., Hauptmann, A. and Schroder B., 1992, 'Naturwissenschaftliche Untersuchungen an bronzezeitlichen Kupferverhüttungsschlacken von Acqua Fredda/Trentino', *Universitätsforschungen zur Prähistorischen Archäologie*, **8**, Universität Innsbruck, pp. 463–72.

Pigott, V. C., McGovern, P. E. and Notis, M. R., 1982, 'The earliest steel from Transjordan', *MASCA Journal*, 2(2), pp. 35–9.

Pigott, V. C. and Natapintu, S., 1988, 'Archaeological investigations into prehistoric copper production', in Maddin (eds), pp. 156–62.

Pinel, M. L., Read, T. T. and Wright, T. A., 1938, 'Composition and microstructure of ancient Chinese iron castings', *Transactions of the American Institute of Mining, Metallurgy and Engineering*, **131**, pp. 174–84.

Pirazzoli-t' Serstevens, M., 1982, *The Han Civilisation of China*, Phaidon, Oxford.

Pittioni, R., 1948, 'Recent researches on ancient copper mining in Austria', *Man*, **48**, p. 120.

Pittioni, R., 1951, 'Prehistoric copper-mining in Austria: problems and facts', *Institute of Archaeology Seventh Annual Report*, pp. 16–43.

Plattes, G., 1639, *A Discovery of Subterraneall Treasure*, Tho. Wykes, London. Reprinted 1980, Institution of Mining and Metallurgy, London.

Pleiner, R., 1965, 'Bericht über die metallkundliche Untersuchung zweier Eskimo-Werzeuge', *Abhandlungen und Berichte des Staatlichen Museums fur Völkerkunde Dresden*, **24**, pp. 31–5.

Pleiner, R., 1980, 'Early iron metallurgy in Europe', in Wertime and Muhly (eds), pp. 375–416.

Pleiner, R., 1981, 'Die Wege des Eisens nach Europa', in *Frühes Eisen in Europa*, ed. H. Haefner, Meili, Schaffhausen, pp. 115–29.

Pleiner, R., 1993, *The Celtic Sword*, OUP, Oxford.

Pleiner, R. and Bialeková, D., 1982, 'The beginnings of metallurgy on the territory of Czechoslovakia', *Bulletin of the Metals Museum of Japan*, **7**, pp. 16–28.

Pleiner, R. and Bjorkman, J. K., 1974, 'The Assyrian Iron Age', *Proceedings of the*

American Philosophical Society, **118**(3), pp. 283–313.

Posnansky, M., 1982, 'African archaeology comes of age', *World Archaeology*, **13**, pp. 345–58.

Pownall, Governor, 1786, 'An account of some Irish antiquities', *Archaeologia*, III pp. 355–6.

Pritchard, J. B. (ed.), 1955, *Ancient Near Eastern Texts*, Princetown University Press, Princetown.

Probert, A., 1969, 'Bartolomé de Medina', *Journal of the West*, **8**(1), pp. 90–124.

Rackham, H. (trans.), 1952, *Pliny: The Natural History*, **IX**, Loeb Classical Library, Heinemann, London.

Raistrick, A., 1953, *Dynasty of Iron Founders*, Longmans Green, London.

Raleigh, Sir W. (ed. R. H. Schomburgh), 1848, *The Discoverie of the Large, Rich and Beautiful Empire of Guiana*, Hakluyt Society Series I, **3**, London.

Ramage, A., 1970, 'Pactolus North', *Bulletin of the American Schools of Oriental Research*, **199**, pp. 16–28.

Ramin, J., 1977, *La Technique Minière et Métallurgie des Anciens*, Latomus, Bruxelles.

Rao, K. N. P., Mukherjee, J. K. and Lahiri, A. K., 1970, 'Some observations on the structure of ancient steel from South India and its mode of production', *Bulletin of the Historical Metallurgy Society*, **4**(1), pp. 12–17.

Rapp Jr, G., 1982, 'Native copper and the beginning of smelting', in Muhly *et al* (eds), pp. 33–8.

Rapp Jr, G., 1988, 'On the origins of copper and bronze alloying', in Maddin (ed.), pp. 21–7.

Rapp Jr, G., Henrickson, E., Miller, M. and Aschenbrenner, S., 1980, 'Trace-element fingerprinting as a guide to the geographic sources of native copper', *Journal of the Minerals, Metals and Materials Society*, **32**(1), pp. 35–45.

Rathgen, B., 1925,' Die Pulverwaffe in Indien', *Ostasiatische Zeitschrift*, **12**, pp. 196–217.

Ray, P., 1956, *History of Chemistry in Ancient and Medieval India*, Indian Chemical Society, Calcutta.

Rehder, J. E., 1986a, 'Primitive furnaces and the development of metallurgy', *Journal of the Historical Metallurgy Society*, **20**(2), pp. 87–92.

Rehder, J. E., 1986b, 'The use of preheated air in primitive furnaces: comment on the views of Avery and Schmidt', *Journal of Field Archaeology*, **13**, pp. 351–3.

Rehder, J. E., 1987a, 'Natural draft furnaces', *Archaeomaterials*, **2**, pp. 47–58.

Rehder, J. E., 1987b, 'The change from charcoal to coke in iron smelting', *Journal of the Historical Metallurgy Society*, **21**(1), pp. 37–43.

Rehder, J. E., 1989, 'Ancient carburization of iron to steel', *Archaeomaterials*, **3**, pp. 27–37.

Rehder, J. E., 1992a, 'The charcoal blast furnace at Normandale', *CIM Bulletin*, **85**(962), p. 128–33.

Rehder, J. E., 1992b, 'Iron versus bronze for edge tools and weapons', *Journal of the Minerals, Metals and Materials Society*, **44**(2), August, pp. 42–6.

Rehren, T., Lietz, E., Hauptmann, A., and Deutmann, K. H., 1993, 'Schlacken und Tiegel aus dem Adlerturm in Dortmund', in Steuer and Zimmermann (eds), pp. 303–20.

Renfrew, C., 1971, 'Carbon 14 and the prehistory of Europe', *Scientific American*, **225**, pp. 63–72.

Renfrew, C., 1972, *The Emergence of Civilisation*, Methuen, London.

Richardson, H. C., 1934, 'Iron, prehistoric and ancient', *American Journal of Archaeology*, **38**, pp. 555–83.

Rickard, T. A., 1905, *The Copper Mines of Lake Superior*, The Engineering and Mining Press., New York.

Rickard, T. A., 1932, *Man and Metals*, Whittlesley House, McGraw-Hill, London.

Rickard, T. A., 1941, 'The use of meteoritic iron', *Journal of the Royal Anthropological Society*, **71**, pp. 55–66.

Riddle, J. M., 1985, *Dioscorides on Pharmacy and Medicine*, University of Texas Press, Austin.

Roberts-Austen, W. C., 1888, 'Cantor lectures on alloys', *Journal of the Society of Arts*, **36**, pp. 1137–46.

Robey, J. A. and Porter, L., 1972, *The Copper and Lead Mines of Ecton Hill, Staffordshire*, Moorland, Stafford.

Roden, C., 1988, 'Blasrohrdüsen', *Der Anschnitt*, 40(3), pp. 62–82.

Rosenqvist, T., 1983, *Principles of Extractive Metallurgy*, 2nd edn, McGraw-Hill, New York.

Rostoker, W., 1987, 'White cast iron as a weapon and tool material', *Archaeomaterials*, **1**, pp. 145–8.

Rostoker, W. and Bronson, B. 1990, *Pre-Industrial Iron*, Archaeomaterials Monograph No. 1, Philadelphia.

Rostoker, W., Bronson, B. and Dvorak, J. R., 1989b, 'Smelting to steel by the Japanese *Tatara* process', *Archaeomaterials*, **3**(1), pp. 11–25.

Rostoker, W., Pigott, V. C. and Dvorak, J. R., 1989a, 'Direct reduction to copper metal by oxide–sulfide mineral interaction', *Archeomaterials*, **3**(1), pp. 69–87.

Rostoker, W. and Shen, G., 1984, 'Copper sulphate as an ancient source of copper', *Journal of the Historical Metallurgy Society*, **18**(1), pp. 13–20.

Rothenberg, B., 1972, *Timna*, Thames and Hudson, London.

Rothenberg, B., 1988, *The Egyptian Mining Temple at Timna*, IAMS, London.

Rothenberg, B., 1990a, 'Copper smelting furnaces, tuyeres, slags, ingot-moulds, and ingots in the Arabah: the archaeological data', in Rothenberg (ed.), pp. 1–74.

Rothenberg, B. (ed.), 1990b, *The Ancient Metallurgy of Copper*, IAMS, London.

Rothenberg, B. and Blanco-Freijeiro, A., 1980, 'Ancient copper mining and smelting at Chinflon (Huelva, S.W. Spain)', in Craddock (ed.), pp. 41–62.

Rothenberg, B. and Blanco-Freijeiro, A., 1981, *Studies in Ancient Mining and Metallurgy in South-West Spain*, IAMS, London.

Rothenberg, B. and Shaw, C. T., 1990, 'The discovery of a copper mine and smelter from the end of the Early Bronze Age (EB IV) in the Timna Valley', *IAMS Newsletter*, **15/16**, pp. 1–8.

De Ruette, M., forthcoming 1994, 'From *counterfei* and *speauter* to zinc: the development of understanding of the nature of zinc and brass in post-medieval Europe', *Post Medieval Archaeology*, **28**.

Rydina, N. V. and Yakhontova, L. K., 1985, 'The earliest copper artifact from Mesopotamia', *Soviet Archaeology*, **2**, pp. 155–65 (in Russian, summary in English).

Sachse, M., 1989, *Damaszener Stahl*, NW, Bremerhaven.

Salin, E. and France-Lanord, A., 1943, *Le fer a l'époque Mérovingienne*, Librairie Orientaliste Paul Geuthner, Paris.

Salkield, L. U., 1987, *A Technical History of the Rio Tinto Mines*, Institution of Mining and Metallurgy, London.

Salter, C. J., 1987, 'Cupelling-hearth residues', appendix report in *Hengistbury Head Dorset*, **1**, by Barry Cunliffe, OUCA, Oxford, p. 194.

Salter, C. J. and Ehrenreich R., 1984, 'Iron Age metallurgy in central southern Britain', in *Aspects of the Iron Age in Central Southern Britain*, eds B. Cunliffe and D. Miles, OUCA, **2**, Oxford, pp. 146–61.

Salter, C. J. and Northover, J. P., 1992a, 'The use of lead in extractive metal-working at Hengistbury Head', in Willies and Cranstone (eds), pp. 4–5.

Salter, C. J. and Northover, J. P., 1992b, 'Metalworking at Hengistbury Head, Dorset and the Durotrigan coinage', in *Materials Issues in Art and Archaeology*, III, eds P. B. van Diver, J. R. Drusik, G. S. Wheeler and I. C. Freestone, MRS, Pittsburgh, pp. 651–8.

Sandars, H. W., 1910, 'On the use of the deer horn pick in the mining operations of the Ancients', *Archaeologia*, **62**, pp. 101–24.

Savory, H. N., 1968, *Spain and Portugal*, Ancient People and Places, Thames and Hudson, London.

Sayce, H. A., 1912, 'Second interim report on the excavations at Meroe', *Liverpool Annals of Archaeology and Anthropology*, **4**, pp. 53–65.

Schaeffer, C. F. A., 1939, *Ugaritica,* **1**, Geuthner, Paris.

Scheel, B., 1989, *Egyptian Metalworking and Tools*, Shire Egyptology, Aylesbury.

Schmid, E., 1981, 'Der jungsteinzeitliche Abbau auf Silex bei Kleinkems and der Silex-Bergbau bei Veaux-Malaucène in Sud-Frankrëich', in *5000 Jahre Feuersteinbergbau*, ed. G. Weisgerber, Deutschen Bergbau Museum, Bochum, pp. 141–78.

Schmidt, P. R. and Avery, D. H., 1978, 'Complex iron smelting and prehistoric culture in Tanzania', *Science*, **201**, pp. 1085–9.

Schnabel, C. and Louis, H., 1905, *Handbook of Metallurgy*, Macmillan, London.

Schwartz, C. von, 1901, 'Über die Eisen- und Stahlindustrie Ostindiens', *Stahl und Eisen*, **21**, pp. 209–11, 277–83 and 391–9.

Scott, B. G. and Cleere, H., *nd*, *The Crafts of the Blacksmith*, USIPP Comité pour la Siderurgie Ancienne/Ulster Museum, Belfast.

Scott, D. A., 1991, 'Technical examination of some gold wire from pre-hispanic South America', *Studies in Conservation*, **36**, pp. 65–75.

Scott, D. A., and Bray, W., 1980, 'Ancient platinum technology in South America', *Platinum Metals Review*, **24**(4), pp. 147–57.

Scott, D. A. and Bray, W., 1994, 'Prehistoric platinum alloys: their composition and use in Ecuador and Colombia', in *Archaeometry of Pre-Colombian Sites and Artifacts*, ed. D. A. Scott and P. Meyers, The Getty Conservation Institute, Los Angeles, pp. 285–321.

Serning, I., 1979, 'Prehistoric iron production', in *Iron and Man*, ed. and trans. H. Clarke, Jernkontoret, Stockholm, pp. 50–98.

Serning, I., Hagfeldt, H. and Kresten, P., 1982, 'Vinarhyttan', *Jernkontorets Berghistoriska Utskott*, **21**.

Shalev, S., 1991, 'Two different copper industries in the Chalcolithic cultures of Israel', in Éluère and Mohen (eds), pp. 413–25.

Shalev, S., Goren, Y., Levy, T. E. and Northover, J. P., 1992, 'A Chalcolithic mace head from the Negev', *Archaeometry*, **34**(1), pp. 63–73.

Shalev, S. and Northover, P. J., 1987, 'Chalcolithic metal and metalworking from

Shiqmim', in *Shiqmim I*, ed. T. E. Levy, BAR International Series 356, Oxford, pp. 357–71.

Shalev, S. and Northover, J. P., 1993, 'The metallurgy of the Nahal Mishmar hoard reconsidered', *Archaeometry*, **35**(1), pp. 35–48.

Shear, Th. L., 1924, 'The gold sands of the Pactolus', *Classical Journal*, **18**, pp. 186–8.

Shepherd, R., 1980, *Prehistoric Mining and Allied Industries*, Academic Press, London.

Shepherd, R., 1992, 'Hannibal the rock breaker', *Minerals Industry International*, September, pp. 39–47.

Shepherd, R., 1993, *Ancient Mining*, Institution of Mining and Metallurgy, London.

Sherby, O. D. and Wadsworth, J., 1985, 'Damascus steels', *Scientific American*, **252**(2), February, pp. 94–9.

Shimada, I. and Merkel, J. F., 1991, 'Copper-alloy metallurgy in ancient Peru', *Scientific American*, **265**(1), July, pp. 62–75.

Shinnie, P. L., 1967, *Meroe, A Civilisation in the Sudan*, Thames and Hudson, London.

Shinnie, P. L. (ed.), 1971, *The African Iron Age*, Oxford University Press, Oxford.

Shizong Liu, Benshan Lu, Jueming Hua and Weijan Zhou, 1993, 'Antiker Kupfererzbergbau von Tongling bei Ruichang', *Der Anschnitt*, **45** (2–3), pp. 50–62.

Sieveking, G. de G., 1979, 'Grimes Graves and prehistoric European flint mining', in *Subteranean Britain*, ed. H. Crawford, John Baker, London, pp. 1–43.

Sim, D. (forthcoming 1994), 'Bloom smithing of ancient iron: some problems and solutions', *Journal of the Historical Metallurgy Society*.

Simonin, L. (edited by H. W. Bristow), 1869, *Mines and Miners, or Underground Life*, Chapman and Hall, London.

Sisco, A. G. and Smith, C. S. (ed. and trans.), 1949, *Bergwerk und Probierbüchlein*, American Institute of Mining and Metallurgical Engineers, New York.

Sisco, A. G. and Smith, C. S. (eds and trans.), 1951, *Lazarus Ercker: Treatise on Ores and Assaying*, University of Chicago Press, Chicago.

Smith, C. S., 1960, *A History of Metallography*, University of Chicago Press, Chicago.

Smith, C. S., 1973, 'An examination of the arsenic-rich coating on a bronze bull from Horoztepe', in *Application of Science in Examination of Works of Art*, ed. W. J. Young, Museum of Fine Arts, Boston, pp. 96–102.

Smith, C. S. and Gnudi M. T. (eds), 1942, *The Pirotechnia of Vannoccio Biringuccio*, Basic Books, Chicago.

Smith, C. S. and Hawthorne, J. G., 1974, *Mappae Clavicula Transactions of the American Philosophical Society*, **64**(4), The American Philosophical Society, Philadelphia.

Smith, C. S. and Wallraff, B. (eds), 1974, 'Anon: notabilia in essays of oars and metalls. A 17th century manuscript', *Journal of the Historical Metallurgy Society*, **8**(1), pp. 75–87.

Smith, R. D. and Brown R. R., 1989, *Bombards*, Royal Armouries Monograph, **1**, London.

Smith, R. H., Maddin, R., Muhly, J. D. and Stech, T., 1984, 'Bronze Age steel from Pella, Jordan', *Current Anthropology*, **25**(2), pp. 234–6.

Smith, W. D. F., 1989, *The Great Orme Copper Mines*, Creuddyn Publications, Llandudno.

Smythe, J. A., 1939/40, 'Roman pigs of lead from Brough', *Transactions of the Newcomen Society*, **20**, pp. 139–44.

Snodgrass, A. M., 1980, 'Iron and early metallurgy in the Mediterranean', in Wertime and Muhly (eds), pp. 335–74.

Solecki, R. S., 1969, 'A copper mineral pendant from northern Iraq', *Antiquity*, 43 172, pp. 311–4.

Sperl, G., 1980, *Uber die Typologie urzeitlicher, frühgeschichtlicher und mittelalterlicher Eisenhüttenschlacken*, Studien zur Industrie-Archäologie, **VII**, Österreichische Akademie der Wissenschaften, Wien.

Sperl, G., 1990, 'Zur Urgeschichte des Bleies', *Zeitschrift fur Metallkunde*, **81**(11), pp. 799–801.

Squier, E. G. and Davis, E. H., 1848, *Ancient Monuments of the Missisippi Valley*, Smithsonian Contributions to Knowledge, **1**, Smithsonian Institution, Washington.

Stella, A., 1927, 'Alcune osservazioni sui minerali', *Studi Etruschi*, **1**, pp. 421–5.

Stewart, E. and Stewart, J., 1950, *Vounous Belapais 1937/8*, Lund.

Steuer, H. and Zimmermann U. (eds), 1993, *Montanarchäologie in Europa*, Jan Thorbecke Verlag, Sigmaringen, Germany.

Stos-Gale, Z. A., 1989, 'Lead isotope studies of metals and the metal trade in the Bronze Age Mediterranean', in *Scientific Analysis in Archaeology*, ed. J. Henderson, OUCA monograph 19, Oxbow, Oxford, pp. 274–302.

Sun Jen I-Tu and Sun Hsueh-Chuan (eds. and trans.), 1966, *Thien-Kung Khai-Wu, Chinese Technology in the 17th Century, by Sung Ying-Hsing*, Pennsylvania State University, Philadelphia.

Swedenborg, E., 1734, *de Cupro* (trans. A. H. Searle), British Non-Ferrous Metals Association, Misc. Pub. **333**, 1938, London.

Terekhova, N. N., 1974, 'Cast iron production of the Mongols in the Middle Ages', *Soviet Archaeology*, **1**, pp. 69–78.

Thälin-Bergman, L., 1979, 'Blacksmithing in prehistoric Sweden', in *Iron and Man*, ed. and trans. H. Clarke, Jernkontoret, Stockholm, pp. 99–133.

Tholander, E., 1971, 'Evidence of the use of carburised steel and quench-hardening in LBA Cyprus', *Opuscula Atheniensia*, **10**(3), pp. 15–22.

Tholander, E., 1979, 'A study of the technology behind nickel-alloyed prehistoric steel having a laminated structure', in *The Origins of Metallurgy in Atlantic Europe*, ed. M. Ryan, Stationery Office, Dublin, pp. 319–344.

Tholander, E., 1982, 'The Eskilstuna axe-head: reconstruction of its manufacture', *MASCA Journal*, **2**(3), pp. 86–7.

Thompson, F. C., 1958, 'The early metallurgy of copper and bronze', *Man*, **58**(1), pp. 1–7.

Timberlake, S., 1987, 'An archaeological investigation of early mineworkings on Copa Hill, Cwmystwyth', *Archaeology in Wales*, **27**, pp. 18–20.

Timberlake, S., 1990a, 'Excavations of Parys Mountain and Nantyreira', in Crew and Crew (eds), pp. 15–21.

Timberlake, S., 1990b, 'Excavations and fieldwork on Copa Hill, Cwmystwyth, 1989', in Crew and Crew (eds), 1990, pp. 22–9.

Timberlake, S., 1990c, 'Review of the historical evidence for firesetting', in Crew and Crew (eds), 1990, pp. 49–52.

Timberlake, S., 1990d, 'Firesetting and primitive mining experiments, Cwmystwyth, 1989', in Crew and Crew (eds), 1990, pp. 53–4.

Timberlake, S., 1992a, 'Prehistoric copper mining in Britain', *Cornish Archaeology*, **31**, pp. 15–34.

Timberlake, S., 1992b, 'Llancynfelin mine', *Archaeology in Wales*, **32**, pp. 90–1.

Timberlake, S. and Mighall, T., 1992, 'Historic and prehistoric mining on Copa Hill, Cwmystwyth', *Archaeology in Wales*, **32**, pp. 38–44.

Timperley, W. A., *nd*, *Archaeological Discoveries at Oakes Park, Norton*, Brincliffe Historical Society, Sheffield.

Tite, M. S., 1972, *Methods of Physical Examination in Archaeology*, Seminar Press, London.

Tite, M. S., Freestone, I. C., Meeks, N. D. and Bimson, M., 1982a, 'The use of scanning electron microscopy in the technological examination of ancient ceramics', in *Archaeological Ceramics*, eds J. S. Olin and A. D. Franklin, Smithsonian, Washington, pp. 109–20.

Tite, M. S., Freestone I. C., Meeks, N. D. and Craddock, P. T., 1985, 'Examination of refractory ceramics from metal production and metalworking sites', in *The Archaeologist and the Laboratory*, ed. P. Phillips, CBA Research Report **58**, London. pp. 50–55.

Tite, M. S., Hughes, M. J., Freestone, I. C., Meeks, N. D. and Bimson, M., 1990, 'Technological characterisation of refractory ceramics from Timna', in Rothenberg (ed.), pp. 158–75.

Tite, M. S., Maniatis, Y., Meeks, N. D., Bimson, M., Hughes M. J. and Leppard, S. C., 1982b, 'Technological studies of ancient ceramics from the Near East, Aegean and Southeast Europe', in *Early Pyrotechnology*, eds T. A. and S. F. Wertime, Smithsonian, Washington, pp. 61–71.

Toll, C., 1968, *Al-Hamdānī: Die beiden Edelmetalle Gold und Silber*, Almqvist and Wiksell, Uppsala.

Treptow, E., 1918, *Beiträge zur Geschichte der Technik und Industrie*, **8**, p. 155.

Tylecote, R. F., 1962, *The Prehistory of Metallurgy in the British Isles*, Arnold, London (2nd edn 1986).

Tylecote, R. F., 1964, 'Roman lead working in Britain', *British Journal of the History of Science*, **2**(5), pp. 25–43.

Tylecote, R. F., 1973, 'The pit-type iron-smelting shaft furnace: its diffusion and parallels', *Early Medieval Studies*, **6**, Antikvarisk Arkiv, **53**, pp. 42–7.

Tylecote, R. F., 1974, 'Can copper be smelted in a crucible?' *Journal of the Historical Metallurgy Society*, **8**(1), p. 54.

Tylecote, R. F., 1975a, 'Iron smelting at Taruga, Nigeria', *Journal of the Historical Metallurgy Society*, **9**(2), pp. 49–56.

Tylecote, R. F., 1975b, 'The origin of iron smelting in Africa', *West African Journal of Archaeology*, **5**, pp. 1–9.

Tylecote, R. F., 1976, *A History of Metallurgy* , The Metals Society, London (2nd edn 1992).

Tylecote, R. F., 1981a, 'Iron sands from the Black Sea', *Anatolian Studies*, **31**, pp. 137–9.

Tylecote, R. F., 1981b, 'From pot bellows to tuyeres', *Levant*, **13**, pp. 107–18.

Tylecote, R. F., 1981c, 'The earliest iron in Europe', in *Frühes Eisen in Europa*, ed. H. Haefner, Peter Meili, Schaffhausen, pp. 21–4.

Tylecote, R. F., 1982a, 'Metallurgical crucibles and crucible slags', in *Archaeological Ceramics*, ed. J. S. Olin and A. D. Franklin, Smithsonian Institution, Washington DC, pp. 231–42.

Tylecote, R. F., 1982b, 'Metal working at Meroe, Sudan', *Meriotic Studies*, **6**, pp. 29–42.

Tylecote, R. F., 1984, 'Early metallurgy in India', in *The Metallurgist and Materials Technologist*, (July), **16** (7), pp. 343–50.

Tylecote, R. F., 1985, 'The early history of the iron blast furnace in Europe: a case study of East–West contact?' in *Medieval Iron in Society*, **II**, eds E. Hook and R. Palsson, Conference in Norberg 6–10 May 1985, Jenkontoret and Riksantikvarieämbetet, pp. 158–73.

Tylecote, R. F., 1986, *The Prehistory of Metallurgy in the British Isles*, 2nd ed., The Institute of Metals, London.

Tylecote, R. F., 1987, *The Early History of Metallurgy in Europe*, Longman, London.

Tylecote, R. F., 1991a, 'Recent highlights in archaeometallurgy', in *Archaeological Sciences 1989*, ed. P. Budd *et al*, Oxbow, Oxford, pp. 194–201.

Tylecote, R. F., 1991b, 'Iron in the Industrial Revolution', in Day and Tylecote (eds), pp. 200–60.

Tylecote, R. F., Austen, J. N. and Wraith, A. E., 1971, 'The mechanism of the bloomery process in shaft furnaces', *Journal of the Iron and Steel Institute*, **209**(5), pp. 342–63.

Tylecote, R. F., Austen, J. N. and Wraith, A. E., 1973, 'Iron-smelting experiments with a shaft furnace of the Roman period', in *Proceedings of the Symposium Eisenbibliothek on Metallurgie des Eisens*, pp. 25–49.

Tylecote, R. F., Balmuth, M. S. and Massoli-Novelli, R., 1984, 'Copper and bronze metallurgy in Sardinia', in *Studies in Sardinian Archaeology*, ed. M. S. Balmuth and R. J. Rowland Jr, University of Michigan Press, Ann Arbor, pp. 115–62.

Tylecote, R. F. and Boydell, P. J., 1978, 'Experiments on copper smelting', in *Chalcolithic Copper Smelting*, ed. B. Rothenberg, IAMS, London, pp. 27–49.

Tylecote, R. F. and Clough, R. E., 1983, 'Recent bog iron ore analyses and the smelting of pyrite nodules', *Offa*, **40**, pp. 115–18.

Tylecote R. F. and Day, J. (eds), 1991, *The Industrial Revolution in Metals*, Institute of Metals, London.

Tylecote, R. F., Ghaznavi, H. A. and Boydell, P. J., 1977, 'Partitioning of trace elements between ores, fluxes, slags and metal during the smelting of copper', *Journal of Archaeological Science*, **4**(4), pp. 305–33.

Tylecote, R. F. and Gilmour, B. J. J., 1986, *The Metallography of Early Ferrous Edge Tools and Edged Weapons*, BAR British Series 155, Oxford.

Tylecote R. F. and Merkel, J. F., 1985, 'Experimental smelting techiques: achievements and future', in Craddock and Hughes (eds), pp. 3–20.

Untracht, O., 1982, *Jewelry*, Robert Hale, London.

Vandiver, P, Yener, K. A. and May, L., 1992, 'Third millennium B.C. tin processing debris from Göltepe (Anatolia)', in *Materials Issues in Art and Archaeology*, **III**, ed. P. B. Vandiver *et al*, MRS, Pittsburgh, pp. 545–70.

Van Grunderbeek, M. C., 1992, 'Essai de délimitation chronologique de l'Âge du Fer Ancien au Burundi, au Rwanda et dans la région des grands Lacs', *Azania*, **27**, pp. 57–80.

Van Grunderbeek, M. C., Roche, E. and Doutrelepont, H., 1983 *Le Premier Âge du Fer au Rwanda et au Burundi Archéologie et Environnement*, IFAQ, Brussels.

Varoufakis, G., 1981, 'Investigation of some Minoan and Mycenaean iron objects', in

Frühes Eisen in Europa , ed. H. Haefner, Meili, Schaffhausen, pp. 25–32.

Varoufakis, G., 1982, 'The origin of the Mycenaean and Geometric iron on the Greek mainland and in the Aegean Islands', in *Early Metallurgy in Cyprus 4000–500* BC, ed. J. D. Muhly *et al*, Pierides Foundation, Nicosia, pp. 315–24.

Verhoeven, J. D., 1987, 'Damascus steel Pt 1, Indian wootz steel', *Metallography*, 20, pp. 145–51.

Verhoeven, J. D. and Jones, L. L., 1987, 'Damascus steel Pt 2, origin of the Damask pattern', *Metallography*, 20, pp. 153–80.

Verhoeven, J. D. and Pendray, A. H., 1992, 'Experiments to reproduce the pattern of Damascus steel blades', *Materials Characterization*, 29, pp. 195–212.

Verhoeven, J. D. and Pendray, A. H., 1993, 'Studies of Damascus steel blades Pt I, experiments on reconstructed blades', *Materials Characterization*, 30, pp. 175–86.

Verhoeven, J. D., Pendray, A. H. and Berge, P. M., 1993, 'Studies of Damascus blades Pt II, destruction and reformation of the pattern', *Materials Characterization*, 30, pp. 187–200.

Vlček, E. and Hájek, L., 1963, 'A ritual well and the find of an Early Bronze Age dagger at Gánovce near Poprad, Czechoslovakia', in *A. Pedro Bosch Gimpera en el Septuagesimo Aniversario de su Nacimiento*, Mexico, pp. 427–39.

Voss, O., 1962, 'Jernudvinding i Danmark i forhistorisk tid,' *Kuml*, pp. 7–32.

Voysey, H. W., 1832, 'Description of the native manufacture of steel in India', *Journal of the Asiatic Society of Bengal*, 1, pp. 245–7.

Wadsworth, J. and Sherby, O. D., 1980, 'On the Bulat-Damascus steels revisited', *Progress in Materials Science*, 25, pp. 35–68.

Wagner, D. B., 1985a, *Dabieshan*, Scandanavian Institute of Asian Studies Monograph **52**, Curzon Press, London and Malmo.

Wagner, D. B., 1985b, 'The transmission of the blast furnace from China to Europe', in *Medieval Iron in Society*, **II**, eds E. Hook and R. Palsson, papers and discussion at the Norberg Symposium 6–10 May 1985, Jernkontoret and Riksantikvarieämbetet, pp. 50–60.

Wagner, D. B., 1986, 'Ancient Chinese copper smelting, sixth century BC: recent excavations and simulation experiments', *Journal of the Historical Metallurgy Society*, 20(1), pp. 1–16. Extensive corrections, 1987, 21(1), p. 51.

Wagner, D. B., 1989, *Toward the Reconstruction of Ancient Chinese Techniques for the Production of Malleable Cast Iron*, East Asian Occasional Papers, **4**, University of Copenhagen.

Wagner, D. B., 1990, 'Ancient carburization of iron to steel: a comment', *Archaeomaterials*, **4**, pp. 111–7.

Wagner, D. B., 1993, *Iron and Steel in Ancient China* , Brill, Leiden.

Wagner, G. A., Gentner, N., Gropengiesser, H. and Gale, N. H., 1980, 'Early Bronze Age lead-silver mining and metallurgy in the Aegean', in Craddock (ed.), pp. 63–86.

Wahl, J., 1993, 'Três Minas-Vorbericht über die archäologischen Ausgrabungen in Bereich des römischen Goldbergwerks 1986/7', in Steuer and Zimmermann, 1993, pp. 123–52.

Waldbaum, J. C., 1978, *From Bronze to Iron*, Studies in Mediterranean Archaeology **54**, Paul Aströms Förlag, Göteborg.

Waldbaum, J. C., 1980, 'The first archaeological appearance of iron and the transition to the Iron Age', in Wertime and Muhly (eds), pp. 69–98.

Walsh, R., 1929, 'Galen visits the Dead Sea and the copper mines of Cyprus (166 AD), *Bulletin of the Geographical Society of Philadelphia*, **25**, pp. 92–110.

Warrington, G., 1965, 'The metalliferous mining district of Alderley Edge, Cheshire', *Mercian Geologist*, **1**, pp. 111–31.

Wasson, J. T. and Sedwick, S. P., 1969, 'Possible sources of meteoritic material from Hopewell Indian burial mounds', *Nature*, **222**, pp. 22–4.

Watson, R., 1786, *Chemical Essays*, **4**, Evans, London.

Watson, V., 1950, *The Wulfing Plates, Products of Prehistoric Americans*, Washington University Studies n.s. Social and Philosophical Studies, **8**, Washington.

Wayman, M. L., 1989a, 'Native copper: humanity's introduction to metallurgy?' in Wayman (ed.), pp. 3–6.

Wayman, M. L., 1989b, 'On the early use of iron in the Arctic', in Wayman (ed.), pp. 94–100.

Wayman, M. L. (ed.), 1989c, *All That Glisters: Readings from Metallurgical History*, Canadian Institute of Mining and Metallurgy, Montreal.

Wayman, M. L., 1993, 'The early use of metal by native Americans on the northwest coast', *Journal of the Minerals, Metals, and Materials Society*, **45**(7), July, pp. 60–4.

Wayman, M. L., King, J. C. H. and Craddock, P. T., 1992, *Aspects of Early North American Metallurgy*, British Museum Occasional Paper **79**, London.

Wayman, M. L., Smith, R. R., Hickey, C. G. and Duke, M. J. M., 1985, 'The analysis of copper artifacts of the Copper Inuit', *Journal of Archaeological Science*, 12, pp. 367–75.

Webster, J., 1671, *Metallographia or An History of Metals*, London.

Wegewitz, W., 1957, 'Ein Rennfeueofen aus einer Siedlung der älteren Römerzeit in scharmbeck (Keis Harburg)', *Nachr. Niedersachs Urgeschichte*, **26**, pp. 3–25.

Weins, W. N. and Bleed, P., 1991, 'Why is the Japanese sword curved?' in *Materials Issues in Art and Archaeology*, **II**, eds P. B. Vandiver, J. Druzik and G. S. Wheeler, MRS, Pittsburgh, pp. 691–70.

Weisgerber, G., 1979, 'Das römische Wasserheberad aus Rio Tinto in Spanien im British Museum London', *Der Anschnitt*, **31**(2–3), pp. 62–80.

Weisgerber, G., 1989 and 1990, 'Montanarchaologie **1** and **2**, *Der Anschnitt*, **41** and **42**', pp. 190–204, 2–18.

Weisgerber, G., 1992, 'Der Kupfermann', in *Amerika 1492–1992 Neue Welten – Neue Wirklichkeiten*, Braunschweig, pp. 159–67.

Weisgerber, G. and Hauptmann, A., 1988, 'Early copper mining and smelting in Palestine', in Maddin (ed.), pp. 52–62.

Weisgerber, G. and Roden, C., 1985, 'Römische Schmiedeszenen und ihre Gebläse', *Der Anschnitt*, **37**(1), pp. 2–21.

Weisgerber, G. and Roden, C., 1986, 'Griechische Metallhandwerker und ihre Gebläse', *Der Anschnitt*, **38**(1), pp. 2–26.

Werner, O., 1970, Über das Vorkommen von Zink und Messing im Altertum und im Mittelalter', *Erzmetall*, **23**, pp. 259–69.

Wertime, T. A., 1961, *The Coming of the Age of Steel*, Brill, Leiden.

Wertime, T. A., 1964, 'Man's first encounter with metallurgy', *Science*, **146**(3649), pp. 1257–67.

Wertime, T. A., 1973, 'How metallurgy began', *Actes du VIIIe Congrès internationale des sciences préhistoriques et protohistorique Beograd 1971*, **2**, Belgrade, pp. 481–92.

Wertime, T. A., 1980, 'The pyrotehnologic background', in Wertime and Muhly (eds), pp. 1–24.

Wertime, T. A. and Muhly, J. D. (eds), 1980, *The Coming of the Age of Iron*, Yale University Press, New Haven.

West, G. A., 1929, *Copper: Its Mining and Use by the Aborigines of the Lake Superior Region*, Milwaukee Public Museum, Milwaukee. Republished 1970, Greenwood Press, Westport, Connecticut.

White, K. D., 1984 *Greek and Roman Technology*, Thames and Hudson, London.

Williams, A. R. and Maxwell-Hyslop, K. R., 1976, 'Ancient steel from Egypt', *Journal of Archaeological Science*, **3**, pp. 283–305.

Williams, D., 1950, 'Gossanised breccia ores, jarosites and breccia at Rio Tinto, Spain', *Transactions of the Institute of Mining and Metallurgy*, **59**, pp. 509–20.

Williams, D. and Ogden, J., 1994, *Greek Gold*, BMP, London.

Willies, L., 1982, *Lead and Leadmining* , Shire Album **85**, Aylesbury.

Willies, L., 1987, 'Ancient zinc-lead silver mining in Rajasthan, India', *Bulletin of the Peak District Mines Historical Society Ltd*, 10(2), pp. 81–124.

Willies, L., 1990, 'An Early Bronze Age tin mine in Anatolia, Turkey', *Bulletin of the Peak District Mines Historical Society Ltd*, 11(2), pp. 91–6.

Willies, L., 1991, 'Lead: ore preparation and smelting', in Day and Tylecote (eds), pp. 84–130.

Willies, L., 1992a, 'Report on the 1991 archaeological survey of Kestel tin mine, Turkey', *Bulletin of the Peak District Mines Historical Society Ltd*, 11(5), pp. 241–7.

Willies, L., 1992b, 'Ancient and post medieval mining sites in the Khetri copper belt and the Kolar gold field, India', *Bulletin of the Peak District Mines Historical Society Ltd*, **11**(6), pp. 285–95.

Willies, L., 1992c, 'Problems in the interpretation of cupola lead smelting sites', in *Boles and Smeltmills*, eds L. Willies and D. Cranstone, Historical Metallurgy Soc., London, pp. 40–2.

Willies, L., 1993, 'Development of lead smelting', in *Archaeologia delle Attivatà Estrattive Metallurgiche*, ed. R. Francovitch, Universita Siena, Siena, pp. 497–514.

Willies, L. and Cranstone, D. (eds), 1992, *Boles and Smeltmills*, Historical Metallurgy Society, London.

Willoughby, C. C., 1903, 'Primitive metalworking', *American Anthropologist*, n.s., **5**, pp. 55–7.

von Winkelmann, H., 1971, *Der Bergbau in der Kunst*, Gluckauf, Essen.

Woolley, L. C., 1937/8, 'Excavations at Al Mina, Sueidia', *Journal of Hellenic Studies*, **58**, pp. 1–30.

Woolrich, H. and den Ouden, A. (trans. and ed.), *nd*, *The Art of Converting Red, or Rosette Copper into Brass by means of Calamine Stone etc. by Messrs. Galon and Duhamel du Monceau*, De Archaeologische Pers., Eindhoven.

Wright, J. H., 1972, 'Metallurgical examination of a Roman iron beam from Catterick Bridge, Yorkshire', *Bulletin of the Historical Metallurgy Group*, **6**(1), pp. 24–7.

Wyckoff, D. (trans.), 1967, *Albertus Magnus: Book of Minerals*, Clarendon Press, Oxford.

Wynne, E. J. and Tylecote, R. F., 1958, 'An experimental investigation into primitive iron smelting techniques', *Journal of the Iron and Steel Institute*, **190**, pp. 339–48.

Xu Li, 1990, 'Traditional zinc-smelting technology in Guma district of Hezhang county', in Craddock (ed.), pp. 103–22.

Yalçin, U. and Hauptmann, A., 1994, 'Zur Archäometallurgie des Eisens auf der Schwäbischen Alb', *Forschungen und Berichte zur Vor- und Frühgeschichte in Baden-Württemberg*, .

Yener, K. A. and Vandiver, P. B., 1993, 'Tin processing at Göltepe, an Early Bronze Age site in Anatolia', *American Journal of Archaeology*, **97**, pp. 207–38.

Young, G. J., 1916, *Elements of Mining*, McGraw-Hill, New York.

Yumoto, J. M., 1958, *The Samurai Sword*, Charles E. Tuttle, Rutland, Vermont.

Zacharias, S. K., 1989, 'Brass making in medieval western Europe', in Wayman (ed.), pp. 35–40.

Zhou Baoquan, Hu Youyan and Lu Benshan, 1988, 'Ancient copper mining and smelting at Tonglushan', Daye in Maddin (ed.), pp. 125–9.

Zhou Weirong, 1993, 'A new study on the history of the use of zinc in China', *Bulletin of the Metals Museum of the Japan Institute of Metals*, **19**, pp. 49–53.

Zhou Weirong and Fan Xiangxi, 1993, 'A study on the development of brass for coinage in China', *Bulletin of the Metals Museum of the Japan Institute of Metals*, **20**, pp. 35–45.

Zhu Shoukang, 1986, 'Ancient metallurgy of non-ferrous metals in China', *Bulletin of the Metals Museum of the Metals Society of Japan*, **11**, pp. 1–13.

Zhuravlev, A. P., 1975, 'O drevneishem tsentre metalloobrabotki medi v Karelii', *Kratkie soobshcheniya Instituta arkheologii AN SSSR*, **142**, pp. 31–8.

Zimmer, G. F., 1916, 'The use of meteoritic iron by primitive man', *Journal of the Iron and Steel Institute*, **94**, pp. 306–56.

Zwicker, U., 1989, 'Untersuchungen zur Herstellung von Kupfer und Kupferlegierungen im Bereich des östlichen Mittelmeeres', in Hauptmann, Pernicka and Wagner (eds), pp. 191–202.

Zwicker, U., Greiner, H., Hofmann, K.-H. and Reithinger, M., 1985, 'Smelting, refining and alloying of copper and copper alloys in crucible furnaces during prehistoric up to Roman times', in Craddock and Hughes (eds), pp. 103–16.