A short history of firesetting

Paul T. Craddock

Although firesetting is well recognized as one of the most ancient mining techniques for breaking up rocks, surprisingly little is known about the way in which it was practised. This article reviews not only the archaeological and historical evidence, but also the results of recent experimental studies relating the quantity of fuel burned to the rock disintegrated.

Throughout the history of mining from the Stone Age through to the Industrial Revolution the usual method of breaking hard rock was by heat. The method was still practised in 19th-century Europe and is said to be still used in parts of India today. Thus it is somewhat surprising to discover that there are very few good early descriptions. The best accounts were written in the 18th and 19th centuries when firesetting was already in sharp decline. The best modern account is probably that by Simon Timberlake, written in conjunction with his experiments on early mining methods [1], described in more detail at the end of this paper. Yet the remains of firesetting are preserved in mines of all ages from around the world, and it is clear that the heat was able to be directed with considerable precision and economy, weakening the rock exactly where required and no more.

In essence, a substantial fire was built on, under, or against the rock face, lit, and left to burn itself out. A combination of the differential expansion of the rock and the vaporisation of entrapped water and water of crystallization created great internal stress which caused the rock to crack and shatter. The method was particularly successful against hard, adamant rock that could not adsorb the stresses; it was of little use against soft rock, which anyway could usually be mined directly. Only in exceptional cases would it have been possible to approach the fires after they had been lit; the narrow winding galleries of most mines would have been quite impassable when filled with smoke and poisonous fumes. If the still hot rock face was doused afterwards (the evidence for this is discussed below) then it seems likely that this was usually done to cool down the unbearably hot rock rather than to cause further cracking.

Fireset workings are very distinctive. The rock face tends to be smooth and in general to show few tool marks (figure 1): this is because the rock tends to peel off in flakes parallel to the face. The profile of fireset workings tends to consist of smooth continuous curves (figure 2), which are quite often sinuous (figure 3), with few abrupt changes of angle, sharp projections, or cavities where the flames flowed over the surfaces (figure 4). The other tell-tale evidence of firesetting in underground workings are the deep layers of ash and partially burnt wood—sometimes to be measured in metres on the floors of large mines—and smoke-blackened roofs.

The method was in use from the inception of mining and quarrying, and would have suggested itself as a method to anyone who had observed the fate of a hard rock incorporated in a hearth. Firesetting was in use before the metal ages in the quarries where hard metamorphic or igneous rocks were obtained for the production of stone axes in the Neolithic period. In Britain, for example, such quarries were worked in Cumbria from the late fourth millennium B.C. through to the early second millennium B.C. [2]. The method would have been useless in flint mines as it would have shattered the flint, rendering it useless, but would have had little or no effect on the soft chalk in which the flint lay.

Evidence for firesetting is to be found in the very earliest metalliferous mines all over the world such as the copper mine of Ai Bunar in Bulgaria, currently the oldest known mine in the world, dating from the fifth millennium B.C. [3], and even in the workings for native copper in the Lake Superior region of North America where the smelting of metal was unknown [4].

After the rock was weakened by fire, it was attacked with stone and antler tools. Workings such as these in the British Isles have recently been the subject of detailed study, and shown conclusively to date from the Early and Middle Bronze Age of the second millennium B.C. [5]. Many of the early workings in central Wales and south-west Ireland are in hard metamorphic rocks which were definitely too hard to mine with stone hammers. Workings such as Mt Gabriel in county Cork, Ireland, have the typical rounded profiles (figure 5), and quantities of small round wood fuel have been found preserved in the small waterlogged mines [6]. The ore occurs in small pockets and thus none of the workings penetrate into the hillside for more than about 10 metres; maintaining an adequate air supply would thus not have been a problem.

Many of the British mines have considerable quantities of charcoal in the dumps of mine waste, once again suggesting that firesetting was extensively employed. These mines have large numbers of stone mining hammers scattered throughout the workings and spoil tips. They are typically cobbles of the local hard rock from stream beds or beaches, weighing between 1 and 5 kg. Most have evidence of hafting, usually in the form of pecked niches on the midriff to take a stiff wooden handle or a continuous groove to accommodate a handle of rope or twisted withies. Other tools found at the mines include antler picks, prepared by cutting off all the tines except that at the base, and a variety of wedges for extending cracks made by the firesetting. These could be stone flakes spalled off the hammerstones, some of which show signs of reuse. The tines cut from the antler picks, even sharpened sticks, were used at Mt Gabriel.

At the tin mine of Kestel in the Taurus Mountains of Turkey, dating to the third millennium B.C. [7], firesetting was extensively used to work the marble rock in which the ore was found [8]. The ancient workings are very well preserved and it is clear that much of the firesetting was very carefully positioned in order to take out small, precisely defined areas, showing that the miners had the ability to direct the heat exactly where it was required (figure 1). In the mine there are few large mining hammers, but a large number of small hand held crushing hammers. Bone and antler tools are also rare, although bone itself is abundant in the occupation deposits in the mine.

This precision, noted at Kestel is a general feature of firesetting around the world. Thus workings at the silver mines at Sui Chang in south west Chekiang, China, dating from the Song dynasty of the 6th–7th centuries A.D., are described as containing large numbers of elliptical depressions in

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Figure 1 Smooth continuous walls are typical of fireset mine workings. These are in the tin mine at Kestel in the Taurus Mountains of Turkey, and date from the third millennium B.C. (30 cm scale).

Figure 2 Large gallery mined by firesetting in the lead/zinc mines at Zawar, in the Aravalli Hills, Rajasthan, India, (late 1st millennium B.C.).

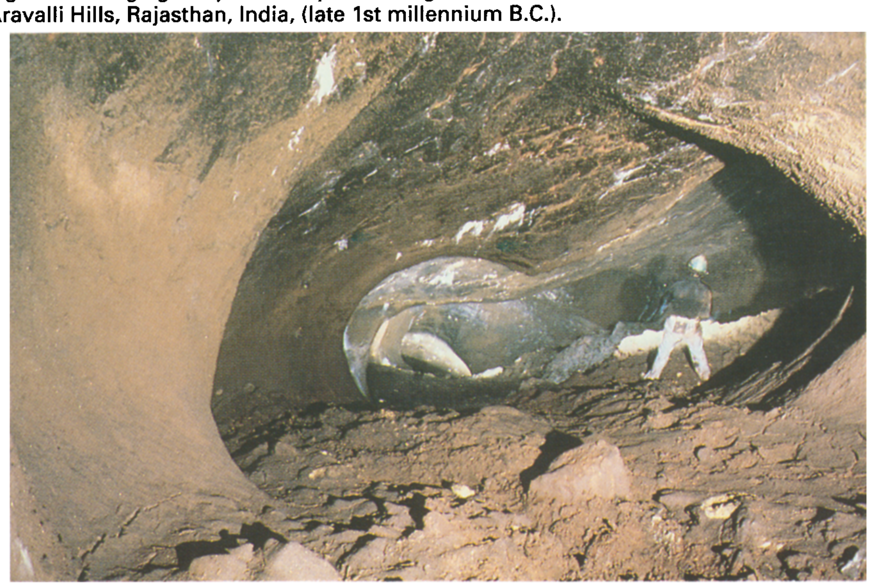


Figure 3 Driving a working forward by successive firesets can produce a very distinctive sinuous profile. Galleries in Zawar Mine.

the shape of an egg cut side-ways [9]. Firesetting was used in many of the great mines of antiquity, often on an extensive scale as at the silver mines of the Mauryean period in the Aravalli Hills of Rajasthan, in north-west India, dating from the second half of the first millennium B.C. [10]. Here huge fires must have roared against the face. In the great galleries concerned there would have been little problem with air supply, and some degree of control should have been possible using the principle that hot air rises, or the fires could be directed using large metal hoods as illustrated in figure 6. In some mines where firesetting was used large galleries could be divided with shutters and the hot fumes and smoke exited through the upper division, sucking in cool clean air along the bottom. With this sort of arrangement it was possible for the miners to approach and manipulate the fires whilst they were still burning. However, evidence of the necessary shuttering or partition has never been reported from an ancient mine, even where timber preservation was good.

Ancient mining practice must have created some problems for firesetting. In antiquity the universal mining method was to locate an ore body and follow it down with a minimum of service passages or shafts. Flames and heat naturally tend to rise, making it easy to direct the flames up the sides of a gallery, or on to the roof but difficult to work downwards. Indeed, some of the detailed descriptions of firesetting from the late 19th century state that it is almost impossible to prevent a fireset working from rising. However the great chambers at Zawar are at a steep angle and those at nearby Dariba are almost vertical, yet they have been worked downwards for hundreds of metres. At mines such as Zawar, where the deposits were many metres thick, the firesetting may have had to proceed in a series of benches against the descending face, although recent experiments (described below) suggest it may have been possible to have covered the whole height of the wall with one fire, carefully directing the flames with flues. Other sources claim that it was not possible to sink shafts by firesetting at all. However the evidence from Zawar and Dariba clearly shows that vertical shafts of great depth were sunk by this method (figure 7), and while our team was in India we were informed that vertical wells are still sunk by firesetting in remote parts of Bihar. It should be noted that all of these examples, chambers, shafts, and wells are quite wide, typically 5 metres or more, there is no suggestion of sinking a very narrow shaft for considerable depths. Shaft sinking was observed by E. T. McCarthy [11] in 1882 at Pestel on the Gold Coast. Dried faggots of wood, 14 x 5 inches, were kept burning at the shaft bottom, which measured 4 x 5 ft. After two days the fires were quenched slowly over another two days and the fire-shattered quartz was broken up with iron

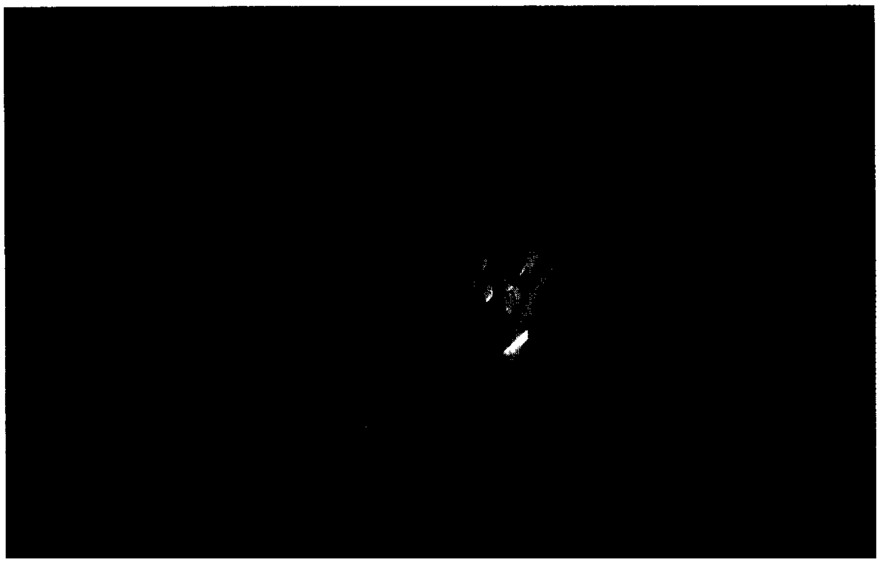


Figure 4 Firesetting experiments at Cwmystwyth, central Wales. Note how the flames flow over the rock surface.

Figure 5 Small fireset trial working at the Early Bronze Age copper mine on Mt Gabriel, County Cork, Ireland (early second millennium B.C.).

Figure 6 Miners at Rammelsberg in the Harz Mountains, Germany, directing the fires using an iron hood (from Simonin 1868 [21]).

chisels mounted on long handles. Each operation lowered the shaft by two feet.

In the recent past the usual method of mining has been to sink a shaft beneath the ore body and then to work it from underneath. To do this the roof of the chamber had to be fireset, and this was often achieved by stacking up great heaps of waste, known as deads, and building the fires on top, directly beneath the roof. Although the deads are stacked up in the galleries at Zawar there seems to have been no attempt to fireset the roof with fires built on the stacks. Sometimes further mining or exploratory work was carried out in large galleries well above the floor level, and to do this platforms were built for the fires. In India, at Singhana in the Khetri-Singhana copper belt in the northern Aravallis, there is a colossal chamber known as the Madhan mine. The early history of this mine is unknown and probably largely unknowable now. In its final stages some exploratory work was carried out into the sides some 10 metres above the floor. Great drystone platforms, bonded by acacia twigs were built against the walls and on these the fires were placed. Twigs from the platform illustrated (figure 8) gave a calibrated radiocarbon date of 1680–1740 or 1805–1935 Cal. A.D. at 95 per cent confidence (BM 2796). As a British geologist, visiting in the early 19th century, described the mine as being abandoned, this would seem to date this exploratory work to around 1700 A.D.

Firesetting reigned supreme until the introduction of gunpowder in the 17th century, and even then it continued to be widely used, especially on very hard rock, right up to the end of the 19th century in well-wooded areas such as Scandinavia. A. C. Collins made a detailed survey of firesetting as it was carried out at the Kongsberg mines in Norway in the late 19th century, just as the method was ending there [12]. The reason for this was the introduction of steel drills to replace iron and the new explosive, dynamite, which finally made blasting cheaper than firesetting.

Historical descriptions

Descriptions of firesetting from earlier periods are few and brief, with comments such as that attributed to Agatharchides (recorded by Diodorus in about 50 B.C.) who visited gold mines in Egypt in about 170 B.C. and stated that the hardest rock is softened by putting a fire under it and then it is worked out by hand. Pliny is only a little more detailed, in the *Natural History* where in his description of the gold mines in north west Spain he states 'masses of *silex* (quartz) are encountered which are burst asunder by means of fire and vinegar, though more often, as this method makes the tunnels suffocating through heat and smoke, they are broken in pieces with crushing machines carrying 150 lbs of iron', Bk.33 71 [13].

The suggestion that vinegar was used

Figure 7 Vertical shaft sunk by firesetting at Zawar. Note the small fireset working on the far side of the shaft.

Figure 8 Drystone platform built against the face to support the fire.

has always been treated with great suspicion. The implication of Pliny's statement was that after firesetting the disintegration was completed with vinegar, which does not seem practicable. The Latin for vinegar is *ascetta*, and it has been suggested by Collins that this is a corruption of *ascia*, an axe. This makes much more sense but the use of fire and vinegar for crushing rocks had previously been mentioned by Livy some 20 years earlier in his description of how Hannibal crossed the Alps, with no ambiguity; the fire was quenched with vinegar, and then attacked with iron tools. H. C. Hoover and H. L. Hoover [14] believed that Pliny was merely repeating a literary fiction. Yet another problem is that the same combination of fire and vinegar to break rocks was also described in China only a few hundred years after Pliny was writing [15]. No later text or ethnographic account mentions vinegar, and it seems unlikely that vinegar could make a significant impression on the rock in a short time, but perhaps an experiment should be made.

The first account to describe firesetting with anything approaching accuracy or detail is the *De Re Metallica* written by Georges Bauer, using the pen-name Agricola, published in 1556 [16]. This is one of the great source books on all aspects of extractive metallurgy, accompanied by hundreds of detailed illustrations (figure 9), and it has been rightly said that for those studying early metallurgy, this book marks the end of the 'prehistory' of the subject. Agricola gives some details on the preparation of the wood, and clearly states that after the fire is lit the mine is to be evacuated. As the illustration shows, the miner having lit the fire is retreating with his hand over his face to protect himself from the noxious fumes. Some two centuries later, an illustration in Diderot's *Encyclopédie* similarly shows the miner fleeing from the fire (figure 10), but accidents did happen. The *Laws of ye Mynesdeeps* [17], apparently dating from the 15th century, and relating to the lead mines of the Mendips in Somerset, England, made provision for the recovery and burial of the bodies of those who were overcome by 'stifling with fires'. Another good account is given in *The Miners Dictionary* published in 1748 by William Hooson [18]. He was a Derbyshire miner, and he speaks of firesetting as an old method already largely superseded by blasting. Yet he was able to give details such as the use of mineral coal or horse bones to eke out the wood where the sup-

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

Figure 9 Illustration of firesetting from *De Re Metallica* [16]. Note the man on the surface whittling the wood, and the miner retreating from the fire.

ply of timber was limited. It is however difficult to see what use horse bones would have been as a fuel, though possibly the long bones could have been used to form incombustible flues. He also mentions that after firing the mine was abandoned and the fire left to burn itself out, the miners returning next morning to discover:

'When the Fire endureth long the work will be very hot, and then if one have the conveniency of some Water to throw upon it will cool it, and the Stone will crack with a Report much like Pistols shot off, and fly off much more effectually, and better than without it, but one has not the Water always ready.'

A set of rules drawn up in 1665, again in Derbyshire, is even more specific about the timing of the firing, stating that:

'We say that any miner in an open rake may kindle or light his fire after four of the clock in the afternoon, giving his neighbours lawful warning thereof' [19].

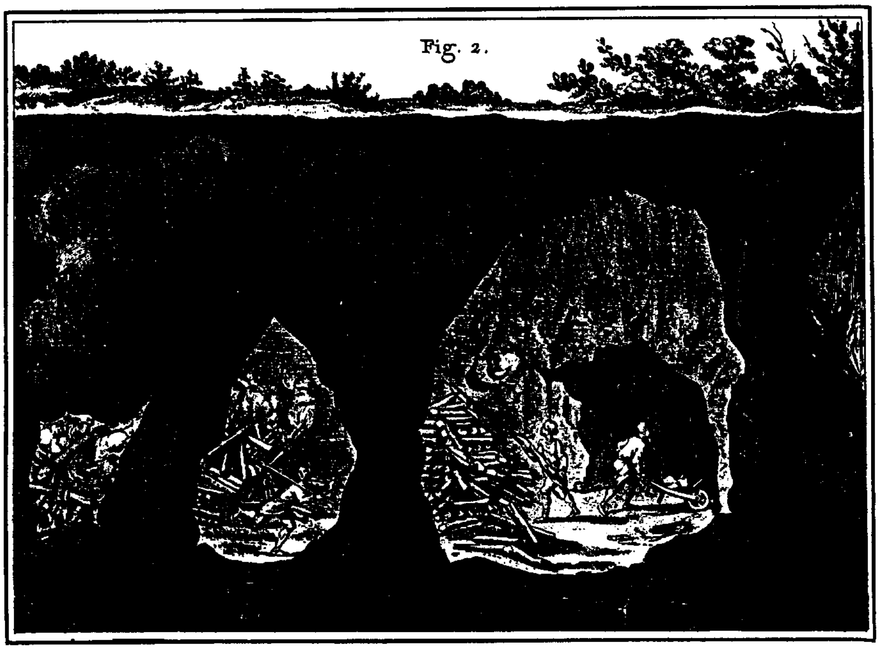


Figure 10 Illustration of firesetting from Diderot's *L'Encyclopédie* of 1743[22]; note again the miner running from the fire.

Experimental studies

In the absence of any detailed early descriptions of firesetting some experiments have been performed to assess the efficiency of the method. The earliest of these were carried out by B. W. Holman [20] in the 1920s at the Royal School of Mines in London. They were inspired by the then recent investigations of the fireset workings at the Roman gold mines at Dolocauthi in central Wales. The fires had apparently been set some feet back from the rock face and the quartz vein material had been reduced to a granular sand apparently without crushing. In his experiments Holman found the best results were obtained by heating the rock quickly to 575°C, and then quenching, and that careful temperature control was necessary. Holman's experiments were conducted in the laboratory. He did not explain how the temperature was to be controlled or the fire quenched in a real mine.

More recently a number of separate projects have been carried out in connection with the investigation of the Bronze Age mines in Britain to gauge the effectiveness of the Bronze Age mining methods using a combination of firesetting followed by using stone, antler, and bone tools [4]. These experiments have taken place at several localities on different types of rock. The experiments of Timberlake were conducted on the hard metamorphic shales of the mine of Cwmystwyth in central Wales: Those of Lewis were carried out specifically to test the efficacy of firesetting on the relatively soft dolomitized limestones found at the mine on Great Orme's Head, Llandudno, on the coast of north Wales: Crew worked on the mixed shale/quartz deposits found at the old Rhiw Goch copper mine, also in north Wales.

In the Cwmystwyth experiment about 400 kg of dry wood was built into a stack measuring approximately 1.6 metres tall by 0.75 metres deep to maximize contact with the face. The wood was mainly of birth and beech branches about two metres in length. After the fire was burning a further 400 kg of wood was added over about three hours and then left to burn itself out overnight (figure 11(a)). Replenishment of the fire would have been very difficult underground, and may not have been an efficient use of fuel anyway. Next morning the rock was still very hot and buckets of water were thrown over it to extinguish the glowing coals and cool the work area down. Very little further cracking or weakening of the rock resulted from this (contra Hooson). This was as expected because the rock face was already thoroughly weakened, and the interface between sound and fire-cracked rock must have been variously between 5 and 40 cm inside the rock where water, dashed momentarily against the face, could have no possible effect. The cooling however was essential before work could commence (figure 11(b)). The fire had brought down about 360 kg of rock and a morning's work with stone hammers (figure 11(c)) and antler pick brought down a further tonne of rock. These figures sound impressive, but the wood had to be cut, collected, and prepared, and this experiment was carried out in an open quarry: there was no attempt to move the total of about 1.4 tonnes of rock along tortuous passages. After mining, the face had a concave, dished appearance with a maximum depth of about 40 cm.

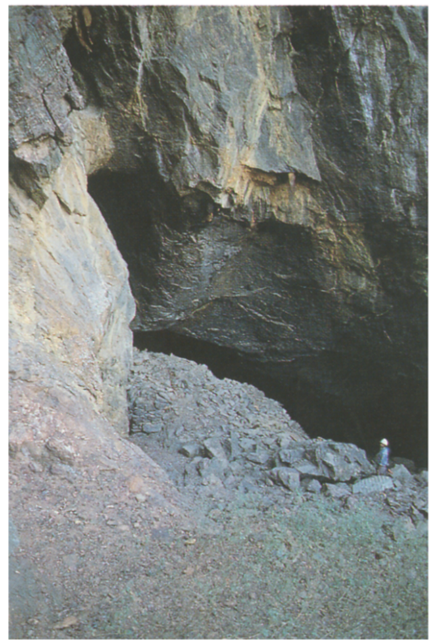
At the Great Orme three experiments were carried out on a dolomitized limestone face, two with wood and one with a combination of wood and charcoal. In the first two experiments 770 kg and 161 kg of soft and hard wood were used, carefully stacked on a prepared base of stone blocks to facilitate updraught through the fire. After the fire was lit more timber was added crosswise to try and direct the flames, based on reports of the operations at the Kongsberg mines in the 19th century. The fires burnt for between one and two hours and brought down 615 kg and 245 kg of rock respectively after mining with stone hammers. Thus the smaller fire represented a more efficient use of fuel. The mixed wood/charcoal fire was left to burn itself out over a period of four to five hours and achieved an even better ratio of fuel to rock removed, namely 171.7 kg for 24 kg of wood and 4.5 kg of charcoal.

In Crew's experiment approximately 0.75 cubic metres (250 kg) of soft and hard wood branch logs were carefully stacked in an old overhanging surface working. The fire burned for about two hours with the flames following the contours of the wall closely, and covering a height of about three metres. The next day mining with stone hammers and antler picks brought down 536 kg of rock. It was clear that the fire had had far more effect on the quartz than on the shale.

In all the experiments the fires followed the rock face, but naturally burned up and, as Crew noted, there was a definite step or sole left on the floor. Lewis's experiment with charcoal was important in this respect as it did burn into the floor, potentially allowing the miners to go down. Also the small slow-burning fire did allow a much more closely defined area to be removed, suggesting this was the way the very precise ancient small workings were achieved. It was also pointed out that a charcoal fire would produce much less smoke and such fires would be able to be tended during combustion. This may be true of very

(a)

(b)



(c)

Figure 11 Experimental firesetting at Cwymstwyth. (a) After the fire was lit it was fed with more wood before being left to burn out overnight. (b) By next morning some 360 kg of rock had been brought down by the fire alone. It was still intensely hot and had to be doused with water before mining could begin. (c) The fireset face was then attacked with a stone hammer, which was very effective in crushing and further cracking the weakened rock.

small fires in large well ventilated galleries that were quite near the surface, such as at Kestel, but large quantities of quite lethal, if invisible, fumes would still be given off, and attending the fires would have been dangerous in the extreme.

Acknowledgment

All photographs are by the author except for some from Zawar which are by L. Willies.

References

[1] Timberlake, S. 'Review of the Historical Evidence for the use of Firesetting', in Crew and Crew (eds) [5], pp. 49–52.

[2] Claris, P. and Quartermaine, J. *Proceedings of the Prehistoric Society*, **55**, pp. 1–27, 1989.

[3] Cernych, E. N. *Proceedings of the Prehistoric Society*, **44**, pp. 203–218, 1978.

[4] Griffin, J. R. *Anthropological Papers,* No. **17** Museum of Anthropology, Michigan University, 1961.

[5] Crew, P. and Crew, S. (eds), 'Early mining in the British Isles', Plas Tan y Bwlch, 1990.

[6] O'Brien, W. F. *Proceedings of the Prehistoric Society*, **56**, pp. 269–290, 1990.

[7] Yenner, K. A., Ozbal, H., Kaptan, E., Pehlivan, A. C. and Goodway, M. *Science*, **244**, pp. 200–203, 1989.

[8] Willies, L. *Bulletin of the Peak District Mines Historical Society*, **11**, 2, pp. 91–96, 1990.

[9] Ch'ieh Liang-ch'ing to be quoted in 'Science and Civilisation in China' **6**, devoted to mining, by P. Golas, Cambridge University Press. Forthcoming

[10] Willies, L. *District Mines Historical Society*, **10**, 2, pp. 81–124, 1987.

[11] McCarthy, E. T. 'Gold Mining on the Gold Coast', *Mining Journal*, 1 July, 1882.

[12] Collins, A. C. *Transactions of the Federation of Mining Engineers*, **5**, pp. 82 92, 1892–3.

[13] Rackham, H. (Trans.) 'Pliny: The Natural History', Loeb Classical Library, Heinemann, London, 1952.

[14] Hoover, H. C. and Hoover, H. L. Comment on ancient firesetting in [16], pp. 118–120.

[15] The use of firesetting in China has already been briefly covered in Needham, J. 'Science and Civilisation in China', **4**, 3, pp. 278, 1971, and **5**, 7, pp. 533–536, 1986, Cambridge University Press.

[16] Hoover, H. C. and Hoover H. L. (trans.) *Agricola: de re metallica*, The Mining Magazine, esp. p. 120. London. 1912, repub. Dover, New York, 1950.

[17] Quoted in Hunt, R. 'A Historical Sketch of British Mining', esp. pp. 135–7. Crosby Lockwood, London, 1887, repub. E. P. Wakefield, England, 1978.

[18] Hooson, W. 'The Miners Dictionary', 1747, repub. Institution of Mining and Metallurgy, London, 1979.

[19] Burt, R. '*A Short History of British Mining Technology*', p. 30. De Archaeologische Pers, Aalst-Waalre, Holland, 1982.

[20] Holman, B. W. *Transactions of the Institute of Mining and Metals*, **36**, pp. 219–262.

[21] Simonin, L. 'Mines and Miners, or Underground Life', H. W. Bristow (ed.), London, 1868.

[22] Diderot, D. 'A Diderot Pictorial Encyclopedia of Trades and Industry' being illustrations taken from the *Encyclopedie* of 1743, Pl. 132, Dover, New York, 1959.