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FIRESETTING TECHNOLOGY

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Abstract: The role of firesetting, which prevailed as the main method of excavation in hard rock before black powder was introduced, is described, and the scientific evidence for its effects is examined. Historical and archaeological evidence is used to show how fire was used in different situations.

INTRODUCTION

There seems a general lack of appreciation of the various methods of excavation before the introduction of explosives, both by mining engineers who come across old workings in the course of modern exploitation, and by historians and archaeologists. Thus Muhly (1978 p44) considered for the Early Bronze Age that "veins of tin, running through granite . . ., were completely inaccessible to the ancient miner or prospector", which is a quite unjustified supposition.

Before explosives, there were four main techniques of exploiting hard-rock: hammering, with stone or metal maul; picking and wedging using wood or antler on weaker joints; from the Iron Age, the use of iron tools on moderately hard rock notably by hammer and gad; and in really difficult hard-rock situations, by use of fire. There is plenty of written testimony about the effectiveness of firesetting, from the reports of Diodorus relating to the 2nd century BC onwards (Howat 1939 p239). Perhaps the most revealing is the well-informed comment by Callon (1876 p176): "There are few, *if any*, rocks so hard that they cannot be successfully attacked *by boring small holes with steel borers and blasting them with charges of dynamite*", but going on to say, "If, however, such rocks should be encountered there remains a last means of cutting through them: it consists in *surprising* the rock first of all by means of fire, and then attacking it by the normal methods" (the italics are Callon's).

Firesetting is a fundamentally straightforward technique "the easiest work in mining" as it was described by Hooson (1749 article *Fire*), though, rather than being just a bonfire technology, it was capable of considerable sophistication in use. It was certainly known before metals were generally exploited, and the effect of heating rock must have been frequently observed when pebbles were preheated and then placed in the cooking pot. There are a substantial number of illustrations of firesetting in use, as sketches or paintings by visitors to mines, as well as the more technical illustrations in mining literature which show a variety of modes of use. These do not show the whole of the wide range of uses which have been observed in mines. Interest in mining archaeology has led to a revival of interest in firesetting as a technique, and there have been a number of recent articles (Timberlake1990; Craddock 1992; Berg 1992a and 1992b; Willies 1987; 1991; 1992a; 1992b), as well as primitive bonfire attempts at "experimental archaeology".

It is the first purpose of this paper to assess the scientific basis for firesetting using results of research from areas such as mineralogy, refractories, mineral processing and storage of atomic wastes, all of which have interests in the effect of heating on rock-based materials. Secondly it will consider how firesetting has been applied underground and will develop hypotheses to explain variations in features observed. Several illustrations of fireset workings are contained in the following article by Brenda Craddock.

ROCKS AND MINERALS

Vein or lode mineralisation involves a small suite of very common minerals, and a large number, but much lesser quantity, of rarer - though these latter might well be the object of exploitation. The commonest vein minerals are quartz, felspars, calcite (and the isomorphous series of calcite with magnesium and iron carbonates - ankerite), haematite and limonite (hydrated iron oxides), pyritic or sulphidic minerals such as pyrite, chalcopyrite, mispickel, sphalerite and galena, and the much softer clay and chlorite groups which have resulted from hydrothermal or groundwater alteration of other minerals or rocks.

The common host or country rocks are wider ranging, but whether igneous, sedimentary or metamorphic, nearly all contain one or more of a relatively small suite of common minerals. Igneous rocks, despite a huge range in the terminology, for present purposes can be described as end-member groups which are felspar and quartz based (coarse grained granites and finer grained volcanics, such as rhyolites, for example), and those which are felspar and ferro-magnesium mineral based such as gabbro and basalts, whilst between them are the conveniently described intermediates, such as diorites and andesites. Sedimentary rocks are usually limestone based (dominantly calcitic but there are also dolomitic limestones), sandstone (quartz based), or clay-based, any of which can at times be very hard and tough to exploit by any means. Finally the metamorphic group (pre-existing rocks changed by application of heat and pressure, by chemical (hydrothermal) activity due to fluids) including the slates, schists and gneisses of many mineralised zones which have compositions based on the original rock, but in which quartz, felspar and ferro-magnesium minerals predominate.

FUELS AND TEMPERATURES

Most firesetting involves the use of wood, though coal has been used in Derbyshire and the Forest of Dean at least, whilst Hooson (1749) has suggested horse-bones were also used, and there is oral evidence of their collection in the Bhilwara district of India for this purpose.

Experimental wood fires

There appeared to be little information about temperatures reached in wood fires, so two simple experiments were carried out to determine the temperatures reached. The first used a November the 5th bonfire. A thermocouple linked to a digital thermometer was inserted in a 6 cm^3 pre-drilled steel block, which in turn was held by a grid of weldmesh to allow positioning within the fire. There was an initial rapid rise in temperature, due no doubt to some of the more igniteable material present, but the fire quickly became dependent on its wood content. It reached the critical quartz inversion temperature (573° Celsius - see below for its significance) after only 12.5 minutes, and reached a maximum temperature after 26 minutes of 709°. After this the fire collapsed on itself, burying the block within bright red embers, maintaining a temperature of over 690° for a considerable time. Until the collapse the fire was very open, and, perhaps unfortunately, the thermocouple was at the windward end: it is considered higher temperatures may well have been reached deeper within the fire, but nevertheless this crude experiment showed temperatures well in excess of those needed to have severe effects on most rocks.

The second experiment used the same rig, but instead relied on commercially

Table 1. Coefficients of thermal expansion for some common minerals (Sincock 1984 p49-50 after Skinner).

Mineral (symmetry)	% expansion from 20°C to orientation				
	100°	200°	400°	600°	800°
Quartz (hexagonal)					
perp to c axis	0.02	0.05	0.11	0.19	0.28
parallel to c axis	0.08	0.18	0.43	1.02	0.98
volumetric	0.36	0.78	1.89	4.52	4.42
Microcline (triclinic)					
parallel to a	0.120	0.294	0.628	0.979	1.337
parallel to b	0.004	0.004	0.000	0.000	0.013
parallel to c	0.004	0.010	0.016	0.050	0.088
volumetric	0.128	0.398	0.644	1.029	1.438
Orthoclase (monoclinic)					
parallel to a	0.049	0.140	0.480	0.900	1.455
parallel to b	0.000	0.010	0.040	0.130	0.265
perp to 001	0.000	0.005	0.065	0.155	0.210
volumetric	0.049	0.155	0.585	1.185	1.910
Plagioclase (monoclinic)					
perp to 001	0.03	0.07	0.18	0.30	0.44
volumetric	0.09	0.23	0.59	1.00	1.47
Fluorite (cubic)					
volumetric	0.47	1.12			

available firelighting sticks packed in kilogram packs of fairly regular dimensions, and very dry. The grid was placed against a limestone cliff face in a sheltered location, with the thermocouple about 30 cm above the floor. The fire was made directly on the floor, using paper and an initial 2 kg of sticks. The temperature achieved rose very slowly, and it took just over an hour to achieve 573° . It was found small increments of fuel did not achieve high temperatures, and it was best to add substantial quantities at a time to achieve the highest temperature. A temperature of 779° was finally achieved by this means. A muffle (a section of steel trough) was then placed in front of the fire which caused it to draw very strongly, producing a distinct roar: the temperature then rose to a maximum of 785°. The fire was then obviously so strong that it seems likely it was approaching its highest possible temperature level in "open hearth" conditions.

Roger Doonan, then a Sheffield University research student, achieved a temperature in a wood fire of over 900°, in an ore-roasting experiment using a pit of about two cubic metres (pers comm). These were probably ideal conditions, but indicate that temperatures of up to a 1000° might be achieved in some cases. It is possible that charcoal might also have been used with some form of blower, to achieve even higher temperaures (Andy Lewis, pers. comm.).

These simple and crude experiments suggest that temperatures considerably exceeding 600° can easily be achieved in a wood fire and that temperatures over 700° can readily be sustained for considerable periods. In a carefully constructed fire, with good draught and some form of muffle (thick timbers placed upright at the front for example), working temperatures up to about 800° ought to be achieveable. The expe-riments point to the need to conduct multi-probe temperature investigations using a full-scale wood fire in actual underground conditions, which is currently being planned.

In actual working conditions, however, the highest temperatures would probably not often apply to the rock being heated, for it would be rare to attain temperatures of much more than 700°C (a dull-red heat) more than a few millimetres below the surface, especially where the rock was moist. The discussion below will thus concentrate on effects which take place at temperatures to around this level.

PROCESSES INVOLVED IN FIRESETTING

Very little specific research has beencarried out into firesetting as a process, and though the simple bonfire experiments on well-weathered rock at surface do help convince the uninitiated that it is a viable process, these have only marginal relevence to what actually happens in unweathered material underground. Research into thermal treatment of materials in the laboratory also suffers from similar criticism, but the very substantial body of evidence accumulated by careful recording and observation does provide for a deeper understanding of the separate processes involved, and provides a basis to develop and ultimately test hypotheses about how firesetting was actually applied.

Breaking rock or mineral successfully in both economic and technological terms always relies a great deal on exploiting the weaknesses within it. In the case of firesetting this is complex, and it must be remembered that, unlike samples which might be used in the laboratory, rocks and veins are rarely mono-mineralic, and even more rarely have identical coefficients of expansion, whilst conditions are always anisotropic, as there is always a thermal gradient between the heated surface and the ambient temperature of the rock. Fracturing and ultimate failure are thus due to a whole suite of causes, though it is convenient to treat them separately. The wide range of possibilities can be summarised as follows:

Expansion or differential expansion of minerals or minerals in a rock.

Differential expansion along different crystallographic axes.
Differential expansion of minerals across a temperature gradient.

Fluid inclusion rupture - the decrepitation of fluid inclusions when heated substantially above the homogenisation temperature.

Vapourisation of water in closed pores or joint systems.

Chemical breakdown of minerals, including ignition of sulphidic minerals, and dehydration of chemically bound water.

Thermal shock acting on existing stresses in the rock.

Other weaknesses in the rock.

Expansion and differential expansion of minerals

Heating (see Sincock 1984 for a fuller discussion) causes nearly all minerals to expand. Except for isotropic minerals in the cubic system, this is normally at a different rate along the crystallographic axes of the same crystal. As Table 1 illustrates, the variation in expansion along different axes is considerable, and is most notable in monoclinic and triclinic minerals: the effect is thus likely to be of particular importance in the thermal fracturing of potash felspars (orthoclase, microcline and, perhaps, pyroxenes and amphiboles). The thermal expansion of fluorspar is markedly higher than for other minerals in the lower temperature range, which may make it significant in thermal fracturing within granites and limestones, in which it frequently occurs.

Although there are exceptions, considered below, the unstressed temperature of rocks is generally assumed to be the same as the ambient temperature due to the time elapsed since formation, and the slow cooling. Heating or cooling causes a change in the volume of the mineral or different minerals in a rock, the shear or tensional forces from which may exceed the fracture strength to the point of complete rupture, or may leave it more susceptible to other means of breakage.

If not already present, fractures are most likely to be initiated at zones of existing weakness, along crystal boundaries (especially at high angle interfaces), at boundaries between more and less yielding surfaces (quartz/felspar against mica for example), along cleavage planes (felspars, fluorite, calcite and barite) or pores or cavities or planes of fissility in metamorphic rocks, or layered zones of fluid inclusions. Coarse grained rocks are considered to be more susceptible than finer since fractures in individual crystals can be of greater length. Propagation of cracks will take place once a critical level of stress is reached, or renewed, and may proceed in a stable fashion, or at a certain level may become unstable and accelerate with bifurcation of fractures (Sincock 1984 p54-5), causing sudden failure to occur. Experiments (carried out in isothermal conditions) suggest even modest heating (even to as little as 100°) markedly reduces compressive strength, whilst repeated heating and quenching to and from temperatures of 100° or 200° leads to progressive propagation of micro-fractures, and a high degree of reduction of compressive strength, almost to the point of rupture.

Common minerals which have relatively high degrees of expansion include quartz (see below), cassiterite, fluorite and pyrite, whilst orthoclase felspar has a sixfold higher coefficient of expansion along the c axis compared with the others (Binns 1984 p67). Minerals in both igneous and metamorphic rocks are frequently associated as intergrowths, notably quartz and felspar in rocks such as granite or granophyre, which can thus be expected to be vulnerable from differential thermal expansion.

In addition to their normal "reversable" thermal expansion, some minerals undergo rapid crystallographic re-arrangement when heated or cooled through various critical "inversion" temperatures. The most notable is quartz which occurs in a variety of forms, largely depending in the first instance on the temperature and pressures at formation, but which inverts to other forms with different physical properties, notably the specific gravity (quartz 2.45; tridymite 2.32; crystobalite 2.26). At lower temperatures the normal forms are α and β quartz, which are often found in hydrothermal mineral veins, and at high temperatures tridymite (above 870°) notably in volcanic rocks in the rhyolite-andesite range and cristobalite (about 1470°), which also forms in volcanic rocks, this time including in some olivine basalts, and in metamorphosed sandstones. The occurence of these higher temperature forms may also be secondary due to pneumatolic metamorphism and it is apparent also that some forms can occur outside their equilibrium field, so caution needs to be taken in ascribing forms to particular rock types. Granites for instance, where high temperature forms might be expected, often have lower temperature forms of quartz. This may possibly result from presence of water causing late-stage recrystallisation at lower temperatures. (Deer, Howie, and Zussman 1974).

A great deal of research has been done into the thermal expansion properties of quartz. The α and β1 forms of tridymite are especially unstable and invert quickly at temperatures of 117° and 163° respectively, whilst α and β quartz inverts quickly at about 573°: this latter results in a 0.3% linear expansion, or about 1% by volume. A rapid inversion also takes place between α and β crystobalite at about 250°, with a linear expansion of about 1%, or a volume expansion of some 3%. Other, but slower inversions take place at higher temperatures, the lowest of which, at 870° (β quartz to β2 tridymite) is probably only rarely reached during firesetting.

Holman (1927) at the Royal School of Mines heated samples of different varieties of quartz through their various known inversion temperatures. It was found that quick heating, using much higher temperatures than the inversion temperature, gave best results, avoiding any tendency to equilibrium in the specimen (production of quartz refractories uses a slow heating to gain the opposite effect). The best rule, he found, was to heat the specimen by some 200° for 2.5 minutes, then raise it to 575° over a further 2.5 minutes. Friability was reduced where a longer time was taken, up to an hour. Holman also investigated the effects of heating and quenching, using for the purpose, samples of quartz from Mysore (Kolar Goldfield, where firesetting was much used). This showed that the disintegration normally associated with the 575° inversion could also be attained by about a dozen cycles of heating and quenching at around 300°, and five or six cycles around 400°. He found also that the compressive strength of the rock (using pebbles) was also very much reduced by heating, by 67.8% at temperatures as low as 200° followed by quenching, and by 81.2% at 300°. Slow cooling in air, however, had the contrary effect, of increasing their compressive strength.

The felspars, solid solution families of calcium (anorthite), sodium (albite) and potassium (orthoclase) alumino-silicates, which like quartz are very abundant, share to a lesser degree the temperature instability of quartz, though mostly at higher levels than would be reached in a wood fire. However orthoclase is stable up to 525°, and albite melts at 748°, so that at least partial breakdown of rock can be expected from this cause also. Micas, another frequent mineral in rocks also appears to be reaching its stability limits below 600°, but this mainly appears to be chemical change, though the elasticity of micas may be a factor in fracturing in adjacent less elastic minerals.

Expansion across a temperature gradient

Heating of a rock face is necessarily anisotropic, with very high temperatures at the heated surface, and, given as short as possible heating period to have effect, a fairly rapid reduction into the rock. At some point spalling may occur with the spontaneous removal of heat-affected rock with relatively unaffected rock beyond - usually a matter of a few centimetres thick.

A major factor in inducing internal stress resulting in weakening or spalling, is the varying thermal diffusivity of minerals. High density and high specific heat will both reduce the effect of the thermal gradient which is the principal cause of spalling (Etherington and Etherington 1961), a factor which thus may partially account for the lower susceptibility of some olivine and magnetite (high density) -containing rocks. Many sedimentary rocks seem likely to have lower thermal diffusivity because of low specific gravity-mineral content, and pore space, which would encourage spalling, whilst the presence of water in a permeable rock might cause a very high gradient and spalling by loss of heat by vaporisation.

Fluid inclusion rupture or decrepitation

Fluid inclusions are commonly present in minerals, and represent primary or secondarily derived "bubbles", most from a few to a hundred microns or so across, of formation fluid trapped within by the growth of the mineral. Typically the inclusion has two phases, liquid and vapour, the vapour representing the degree of contraction of the liquid from its formation temperature. On reheating, the vapour phase will disappear at the homogenisation temperature, which with the proviso there has been no leakage, and with an allowance for pressure regimes, will be the original formation temperature. If heated markedly above the homogenisation temperature, the inclusion will rupture, and the mineral may decrepitate. Kinnunen (1988), who examined the effect of anthropogenic decrepitation, ie. firesetting, on quartz from a Stone Age quarry in Finland suggests a temperature of 300° to 500° is required.

The decrepitation process can occur naturally during thermal events and it has been suggested that a blue quartz which shattered explosively did so because of this cause (Sincock 1984 p68 quoting Pardee and Park). The possibility is that migration of fluid inclusions took place during the thermal event, into zones which created the weakness (an alternative explanation is possible - see below).

Sincock (1984 p275-86) carried out

experiment on various granites to determine the effect of fluid inclusion rupture. By use of dyes, it was possible to emphasise the smallest cracking, though it was sometimes difficult to distinguish inclusion rupture from ground boundary friction effects. Even without dyeing, effects were visible between 400° and 500° and, using the dye, microfractures around inclusions were visible at temperatures as low as 200°, and around larger inclusions, intracrystalline fractures were evident from 100° upwards.

Vapourisation of water
The importance of the role of water is apparent from the attention paid to the drying process in the preparation before firing of ceramics and refractories, though experimentally its role is not well established. The heating of water contained in closed pores, for instance in limestones, or sometimes even in joint systems, and especially within clay rocks (which even when indurated commonly contain some 5%), has an effect which ranges from crumbling or spalling to even explosions.

Chemical breakdown of minerals
Many minerals contain water which is chemically bound, but is released on heating. This particularly sffects clay and chloritic minerals, and results in a marked reduction in volume. It may affect a wider range of rocks than is immediately obvious since clay is a breakdown product of felspars and may form inclusions within otherwise unaffected mineral. Hydrated iron minerals, especially the limonite iron oxide series ($FeO.xH_2O$) also have a substantial reduction in volume on heating. Temperatures of more than 100° should have effects equivalent to vaporisation above. Water, especially where residual heat remains after firesetting, may also affect the remaining rock by promoting oxidation and hydration to cause breakdown of minerals possibly within a few hours.

In the case of limestones and iron carbonates, intense heat will cause calcination. This proceeds best at temperatures unlikely to be long maintained in firesetting, since the reaction is endothermic. This, eg, is around 900° for dolomite, but some breakdown, marked by evolution of carbon dioxide, seems to occur by around 450°.

Spontaneous combustion is a problem with broken massive pyrite in presence of air. This is an exothermic reaction which could, in theory, supplement the wood fire once ignition temperature was reached, though whether this could be strong enough to cause a form of autogenous firesetting is unclear. Certainly firesetting in veins containing pyritic minerals gives off copious quantities of sulphur dioxide, and was a particular hazard in firesetting. Instances are also, cited of smelting of lead and silver from veins by firesetting, so some limited contribution to the heat balance is possible from sulphidic minerals, and certainly any reaction would tend to breakdown of the rock or veinstuff.

Thermal shock
This takes place when rapid cooling takes place, notably by quenching with water. It may operate by contraction causing tension within or between minerals and especially creating or propagating microfractures. It may also be important in preventing "annealing", by which adjustment can take place without fracture of grain boundaries if the rate of heating and cooling is slow enough. Its importance is emphasised by the Holman (1927) experiments cited above, though it should be emphasised that firesetting is not dependent on quenching to be effective.

Pre-existing weaknesses
Nearly all rocks, have been affected by tectonic events involving folding and faulting, and the development of joint systems as a result of shear and tensional forces during such activity. Much mineralisation is closely linked to tectonic activity, so mineral veins have especially been subject, sometimes several times, to such forces. Additionally, the mineralising fluids - pneumatolic if very hot (above about 450°), or hydrothermal if cooler - have been responsible for a great deal of secondary chemical metamorphism, converting felspars and ferromagnesium minerals to quartz, clay, mica and chlorite for example, which are susceptible to mechanical as well as firesetting methods.

Sometimes deposition of minerals, or redeposition, has taken place during stress conditions resulting from movement of faults, so that the minerals retain some of the stress until it is released. Explosive slickensides have been reliably reported from Derbyshire (Strahan 1887), which spontaneously, or on slight picking, burst or "slappitt off" from the wall of the vein. The phenomenom is probably related to the explosive rock bursts found in deep mines, and may account also for the explosive blue quartz noted earlier. Although this is an extreme example, to a lesser extent rocks in mines or mineralised areas are frequently under stress and thus may react more readily to shear and stress imposed by firesetting than would occur in a hand sample at surface. Certainly bedding planes, joints, fault planes and cleavage planes were been much favoured by miners for both firesetting and the later use of powder, as "free faces" into which rock could expand on fracture. It seems likely that zoning of fluid inclusions had a similar effect.

In some cases such weaknesses must have made firesetting unnecessary, or led to its selective use. Their frequency certainly means that rock or mineral veins can never be considered as homogenous material, and in practically all cases this will mean the rock will be considerably more susceptible than investigation of a simple hand specimen might suggest.

Discussion
Rocks in which quartz occurs will usually be highly susceptible to firesetting, whilst felspars, micas, olivine, and probably a substantial number of other ferromagnesium minerals are also moderately susceptible. This covers the great variety of igneous and many metamorphic rocks, which otherwise would be amongst the toughest to be tackled in mining. Their susceptibility will be increased by a wide range of other weaknesses which are inherent in the original formation of the rocks, and the chemical and physical changes which subsequently have been imposed on it.

Relating this data to rocks as found in the field is difficult because of the ranges of composition and secondary alteration amongst other factors, but some empirical work has been done. For igneous rocks, Dence (cited in Sincock 1984 p62) produced a table of inferred cracking temperatures as follows:

Table 2

Basalt	550°
- fine grained)	
Olivine diabase	530°
-medium grained)	
Quartz diabase	450°
- medium grained)	
Olivine gabbro	360°
- coarse grained)	
Quartzite	300°
Granite	260°
Granodiorite	200°

It seems likely that metamorphic rocks will often share similar characteristics to those above since they often have similar compositions, whilst characteristics such as cleavage and schistosity will provide further weaknesses. Sedimentary rocks are often much less consolidated and are not usually crystalline compared to the above, but presence of quartz, clay, iron oxide or carbonate, and limestone, means they will normally be very susceptible. The main exceptions are generally soft or easily fragmented enough not to need firesetting anyway. Least susceptible appear to be fine grained plagioclase felspar and pyroxene-based gabbroic or basaltic rocks.

It is clear from the above, and from the wide range of factors considered, that disintegration from firesetting sets in at a far lower temperature than might be imagined, with some effects detectable at temperatures only a little above that of boiling water, with substantial effects for many rocks by around 300°, and nearly all rocks being severely damaged by temperatures between 400° and 600°. These are temperatures which are readily attained in a wood fire, though higher temperatures would usually have even greater effect. It is clear, too, that thermal shock from quenching, either by water "dashed" on to the heated rock, or by slow percolation through the rock, has a very considerable effect. Repeated heating to quite modest levels, with quenching, seems to have an effect only otherwise attainable by much greater heat and might indicate a strategy which would economise on fuel.

THE TECHNOLOGY OF FIRESETTING

There is a fairly substantial amount of contemporary information about firesetting for the 16th Century onwards, mainly for the Germanic and Scandinavian countries, and a small amount for Britain. This has been summarised by Timberlake (1990) and Berg (1992a; 1992b). Archaeological work on Bronze Age fireset mines has been carried out in Ireland by O'Brien *et al* (1990), and on Post-Medieval in Norway by Berg. The present writer has examined firesetting of Early Bronze Age at Kestel in Turkey, Roman at Rio Tinto in Spain, Pre-Maurian and Maurian (c.3000 to 1800 BP) onwards to Post Medieval at Zawar, Rajpura Dariba, Kolar and Khetri in India (1987, 1991,1992a and b). Most of what follows is based on contemporary information and the results of archaeological survey.

STRATEGY AND TACTICS IN MINING BY FIRESETTING

Firesetting is one element in the technological and economic environment in which mining takes place. In a very small mine, such as the workings in Ireland described by O'Brien et al (1990), the requirement was fairly simple: discovery of a deposit, development or importation of the necessary mining skills, acquisition of sufficient timber for fuel, hand-picking of the ore, possibe on-site smelting, and marketing of the product. The scale was small, requiring very few people for each unit, and may well have been compatible with subsistence agriculture. Technical difficulties would have been few and water or ventilation problems could in considerable measure be avoided by opening another deposit.

Far more formidable problems occur in larger mines. In the Roman and Maurian empires the state played a considerable role though poorer mines were leased out to contractors, and the same may well be so for the strategically important tin mines at Kestel in Turkey. In the European mines capitalism developed, sometimes in conjunction with state involvement, to cope with similar problems. There was a considerable administration, a sizeable settlement, a demand for food probably beyond the resources of the immediate area, a huge requirement for timber and probably a need to conserve wood by coppicing over a wide area. The mines were complex and specialisation of a large labour force was ineviteable, and can sometimes be demonstrated. There were problems of water, ventilation and transport of timber, ore and waste within the mines, between forests and smelter, and beyond that in marketing the product.

In the small scale mine, firesetting in conjunction with mechanical methods (hammering, picking, wedging etc.) was the principal part of the work. The requirements were simple, and the disguising of capital cost as surplus labour in a small, possibly family, group with no other obvious economic outlet meant that adoption or retention of inefficient or archaic methods was not a severe problem. On larger mines, however, it can be expected that there was a tendency to seek out, adopt and adapt, practices to produce the most effective technological and economic compromise. In examining firesetting methods, therefore, attention also has to be paid to the wider environment in which it operates: by and large, although there will sometimes be examples of precocity as well as conservatism of archaic practices, generally it should be possible to interpret particular methods and techniques as rational responses to the problems which confront the miner.

In a small mine, working would often have been restricted to the ore itself probably with rapid abandonment once this was too difficult or was worked out. On a large mine it was almost ineviteable that the miner would need to adapt early small scale methods to later larger scale. In developing the mine, therefore, he would not only be constrained by the form of the deposit, and the physical and chemical character of the lode or rock, which would only partially, at best, be known to him, but also by past developments. Strategically he would need to provide for suitable access, handling of materials, ventilation, removal of water and to provide for excavation of rock and mineral to allow safe mining (safety of the mine perhaps more than the miner). Firesetting is a tactical excavation process within this overall strategy. A broad range of requirements needed to be met: it was necessary to sink shafts and to rise them upwards, to drive horizontal tunnels and to make inclines and declines. This was done in either barren rock, or wherever possible, within the orebody itself. In the orebody it would be necessary to be able to work large masses, and subsequently to remove pillars no longer needed for stability, to work "underhand" in the floor, or overhand in the roof, or to bench across a horizontal or slightly inclined deposit. Often the space to do this would be limited and, where possible, the ore would be mined selectively to preserve the grade and lessen the later problems of concentration and smelting. Berg (1992b p3) has suggested that the basic technique was not capable of much adaption, and that economic and technological gains came mostly from the (strategic) developments of mine layout and ventilation. The latter is certainly true, but his statement probably underestimates the ability of the miner to adapt his basic excavation methods to the problems he had to solve: there was a great variety of possible solutions open to him which can be seen in his responses and the archaeological remains left behind.

Firesetting is only rarely the sole excavation technique in use. Generally it was combined with some form of hammering, picking and wedging. In suitable circumstances, of easily broken rock or mineral, these mechanical methods were likely to have been preferred, and in cases of considerable water inflow, may be the only technique possible before powder was introduced. In early mines, before iron, the tools were of stone, antler and wood, though occasionally copper or bronze was used to tip tools, or to make them entirely. Once iron was available, then generally it was used very widely indeed, except for the very hardest rock or for where there was sufficient timber to make firesetting an economic alternative. This latter was generally confined to mining in virgin forest areas, as probably existed in the early phases of the Turkey and India mines (or at the beginning of the very much later revivals), or to mining in areas with low populations and huge forest reserves, as continued in areas such as Norway and Sweden up until the late 19th century, and even after the development of machine drilling and dynamite explosives. Berg (1992a) suggested a tripart mode of classification for the use of firesetting (his hammering would include use of a gad or pick):

Hammering with firesetting
Firesetting with hammering
Firesetting alone

In the first category the main excavation method is battering or picking at the rock or weaknesses within it. Firesetting is only resorted to when this proves impossible or uneconomic. In the second the main excavation method is firing, but the face is afterwards hammered or picked extensively to make best use of the weakening produced by fire. In the third firesetting alone is used, with a continuous fire against the face and no mechanical means used. Berg uses this model to explain the sequence of events in Norway, where German miners had in the 16th and 17th centuries first introduced new firesetting techniques,then black-powder. Fire-setting culminated in the late 19th century at Kongsberg in a method of using a continuously burning, large fire, for tunnel driving which was, at least then and there, the rational, cheapest form of mining for that purpose. Black powder was used in those parts of the mine where it was economic to do so.

In other circumstances the model can be reversed, with firesetting preceding firesetting with hammering. At Kestel in Turkey, in one of the earliest fireset mines examined (Early Bronze Age c.5000-4000 years ago), the first stages of working are very small passages and chambers driven following the better ore. These appear to be almost wholly excavated by fire, though probably a "gentle" battering using stone mauls was also used to scale loose material. These early workings were later extensively cut through by larger-scale pillar and room workings exploiting lower grade ore. In these firesetting was much less intensively used, a great deal of mechanically broken rock is found and the traces of fire are much less obvious. In a probable later stage, shallow-depth parts of the mine were opencasted, and the firing evidence is very small indeed, though weathering may partially account for this. Probably the early firesetting-only phase took place when abundant timber was available nearby, and there is palynological evidence of decline of forests in the later stage periods (Report in preparation). Similar sequences appear likely in India, with the early phase being predominantly firesetting, but a later retreat-mining phase combining fire with mechanical means of mining, including the probable use of a battering ram suspended from a timber bipod, and the use of iron tools. In the Post-Medieval period mining for zinc at Zawar in India the early phase seems to be very extensive smaller-scale, shallow mining using fire predominantly, with a later phase of reworking by large-scale opencast methods relying mainly on mechanical breakage including removing support to use gravity breaking (Willies 1987).

Recognition of firesetting when used alone (or at least with little mechanical assistance) in mines is usually easy, though when it is combined with mechanical methods it is much less apparent. The walls are smooth as a result of exfoliation of thin sheets of rock from the surface and they have rounded profiles with gentle curves and oval sections. Tunnels are usually slightly sinuous, deviating just slightly from the centre line though overall on a straight course. The effect is presumably partly a function of the fluid-flow of hot gases - some instances are not unlike the sinuous rounded tunnels associated with phreatic solution in caves. Headings often have a slight hollow in the floor with a lip, and often a wide face is divided into slightly hollowed panels, each probably representing a separate fire. Picking with a sharp tool or gentle hammmering will usually persuade further thin exfoliation-sheets to separate from the rock, sometimes almost without leaving a tooling trace-mark. The rock is sometimes reddened, in other places blackened with soot (though sometimes the soot has been removed by water oozing from pores in the rock, whilst tonguing marks, reminiscent of soot marks above a fireplace can also be caused by water flowing down rather than hot gases flowing up). There is usually an abundance of charcoal fragments on the floor, together with small, thin, sometimes slightly curved fragments of rock waste, which in some cases shows red-colouration and the aggregation of fine particles giving a crumbly texture. The ash from burning produces a fine silt-like deposit which is found in the airways away from the last fires, either admixed with other waste, or forming a thick layer on ledges. In some cases this, on disturbance, forms a cloud of dust. Small wood particles can sometimes be found in the flue dust (as at Kongsberg), but probably this was more likely with the fibrous softwoods of coniferous timber than the hardwoods found in deciduous, hardwood areas. The soot may cause surfaces to be particularly slippery, especially where it is admixed with clay or ochre. Fireholes are not infrequently found in which the content of the last fire remains, with partially burnt wood surviving. Berg describes roughly split wood in the Norwegian mines, and this is indicated in a number of 16th-18th century German illustrations too, but that found in ancient mines in India and Turkey has usually been thin round-wood. The difference may simply be in the availability of suitable tools for woodcutting, but could also indicate coppicing with use of thin round-wood.

Where the rock has been hammered as well as fired, the effect is less clear. At Kestel in Turkey a firehole developed in the roof of what appears to be a reworked section of the mine (radiocarbon dated to EBII) has been very heavily hammered by use of stone mauls, two of which were found in position. The fire remains were also still largely *in situ*, within a hollow hemisphere of about a metre across. Half the curved roof was still smooth due to exfoliation by the direct effect of the fire, but the other half had been very heavily hammered indeed by the mauls, which had broken rock off for a depth of up to ten centimetres or so, preserving the general form, but totally destroying any smoothness. Had the battering process been completed the pocket would not easily have been ascribed to firesetting at all. We have no idea just how much timber was used for the fire, but the yield must have been several times as great than without heavy-hammering.

Heavy pickwork following firesetting seems to have been favoured in 1st and 2nd century AD working at Rio Tinto in Spain. Here firesetting was recognised in part of the system there known as RT59, from the usual curved surfaces, but other sections were ascribed to pick and gad work, with use of both light and heavy well pointed gads or perhaps small picks. Subsequent excavation however (by Philip Andrews) revealed large quantities of charcoaly debris in the floor, and, belatedly, following more experience of firesetting elsewhere, it was recognised that a curved heading had all the features of a firehole modified by heavy picking.

Kestel offers examples of the use of hammering assisted by firesetting. The deepest part of the workings are within a fault zone in which the rock is much shattered. A weathered pegmatite with limonitic clay within a portion of the fault is soft enough for excavation with a bone, and once a free face was obtained, then the rock was (is) frequently so shattered that it was broken down with one of the several stone mauls left lying there. However, it is clear from scattered fire-remains that firing has been done also. Probably this was to break up large resistant pieces of the quartzite rock, or possibly to open up existing joints within it. Roughly contemporary adjacent areas show most of the rock has been broken down by mechanical means rather than fire, leaving a large chamber. Mechanical breaking may well have been easier because of more space. Huge amounts of debris remain which shows little evidence of fire, and much of mechanical breakage.

FIRESETTING APPLICATIONS

This section describes firesetting as either illustrated or described by contemporaries, or which has been observed by engineers or from archaeological survey.

Shaft-sinking

Shafts are one of the least common, and probably most difficult applications of firing. Examples are known at Zawar Mochia in India, which take the form of a circular-section slow spiral, but are vertically open at the centre, and up to two metres across. No mechanical work is evident on the walls, and the true bottoms were not seen. What may have been intended ultimately to be a vertical shaft was archaeologically excavated (by Paul Craddock), to a base in the solid metamorphosed dolomitic rock just over a metre below the lowest part of surface level. This showed it to have a hemispherical bottom, slightly developed into the weakness of a joint which had been chosen on which to sink. There was no evidence of the fire, and sinking was probably done by repeated lighting of the fire, and subsequent gentle hammering of the rock beneath. At Kestel a shaft was sunk underground in marble on a steep angle for some 5m. Excavation at the bottom showed its base was a smooth walled hemisphere, but though it was sunk on a joint, this had hardly any effect on the morphology.

At Rajpura Dariba, in workings of c.500 BC, a wide shaft followed down an oreshoot about 100 metres below surface, to which it was ultimately connected by two small separate near-vertical shafts, one used for manually lifting water by ladder from small reservoirs, which probably also acted as the air-intake, the other probably to remove smoke. The shaft was some 5 m wide, sub-circular, and at least 20 metres deep. A timber left spanning the shaft suggests the shaft was divided by a division or brattice to control the airflow (Willies 1987). A somewhat similar shaft arrangement was used at Falun in Sweden in the 17th Century, in which the brattice survives. The large size of such shafts would have made working much easier, as once a small hole had been sunk, the remainder of the shaft bottom could be benched from it, but there is no actual knowledge of the technique. It has been reported by contemporaries that sinking downwards sometimes was made easier by placing some form of cover over the fire - heavy baulks of wood for instance, or possibly a duct made of stone. This would have been hard to place in the small Zawar and Kestel shafts, but such a method would be applicable in shafts several metres wide. It is feasible that benching (see stoping below) in a wide shaft could be so carried out as to sink downwards in a shallow spiralling firehole.

A further technique was observed south of the Kolar Goldfield in India (Willies 1992 p288), where a petaloid form of shaft had been developed, either by simultaneous sinking of several fires, or by developing the `petals' out from a single central shaft.

Driving levels

These are very variable: if low they tend to take on a sub-circular section, with, commonly, a minimum diameter of about 70-80 cm., i.e. moderately comfortable to crawl in. Examples are known from Kestel and Zawar Mochia. Smaller sections when seen can usually reasonably be ascribed to holing-through, sometimes for ventilation. Some passages in Derbyshire, for instance in Owlet Hole Mine, Matlock Bath, are developed in thin veins within limestone, and are sharp-ended, eliptical in section, a metre or so high and barely 30 cm wide at the centre. It is probably this type about which Hooson (1749) was referring when he described the need to open them out by blasting to allow 18th century miners to work. Rather longer tunnels, especially, perhaps, those used to drain mines, are larger in both width and height - so that tunnels probably from the 16th century at Goldscope Mine in the Lake District, and tunnels of a similar age in Germany, for instance at Rammelsberg (Bartels 1988), have a very characteristic slightly rounded, upright section of such size as to allow a man to walk comfortably.

Firesetting was last used in Norway to drive a level at Kongsberg into the 1890s: this was of very large section, equipped with a flue in the roof, formed from a brick arch much of which still survives. (Collins 1893; Berg 1992a;b).

Declining

Declines were a normal feature of mining at Zawar in India, both from the surface, and underground, at angles up to 45° (Willies 1987). One example sunk to the 470 m level in Zawar Mala Mine was over 50 metres long, with a roughly circular section of about 2 m diameter, without any special provision for ventilation: it suggests sufficient stratification of the air was available for the fire to burn properly. A further example had used two parallel tunnels, which presumably were advanced together and holed through at intervals. The two tunnels were subsequently joined together, using both fire and very heavy hammering. At Zawar Mochia, a decline sunk from the surface had clear evidence of a very small fire indeed being used to create a small cavity at the side.

Inclines and raises

The use of fires in inclines and raises would appear to produce difficult ventilation problems. However metal-working in Pooles Cavern at Buxton, Derbyshire was done at a site higher than the entrance (Branigan, pers. comm.), and a similar situation was found in the Zawar Mala mine in India. Both sites were in fairly wide areas: this implies at least a measure of stratification and down-slope, under-roof, movement of the heated air. Callon (1876 Pl.XVIII) includes a diagram showing how a raise might be made. The fire is supported on a pillar built under and within the raise, so that the mine airflow is diverted up the raise and down again.

Stoping

Four principle methods are contained in the literature, or can be demonstrated archaeologically. The simplest is a form of chambering in which fires are lit in panels around the wall of the chamber (Goldbergen 1700 fp.76), or along a `longwall' face - this last seen in probable EBI workings at Kestel in Turkey, and in shallow workings at Zawar Mochia in India. The panels may approximate to separate fires, either spatially or possibly in time, and may reflect the use of mechanical breaking of the intervening ribs, thus economising on fuel.

Overhand stoping, where sufficient broken material is left in the stope to support operations under the roof, has been claimed as a natural result of firesetting methods. It has been illustrated by Callon (1876 pl. XVIII), and an example occurs in a small mine in Eyam Dale, Derbyshire, shown to me by John Beck. Fire debris is found along the length of a very low and narrow passage above accummulated deads in the vein and it is evident that it has been used to attack the roof. There is no indication that material was drawn off below and it is likely that it was removed from the top of the deads after cooling. An alternative method in open stopes was to support the fire on either stones or stone-protected timbers.

Underhand stoping is possible by covering the burning wood below heavy timbers or a temporary stone duct, though the efficiency of such a method is likely to be poor. A better method for use in both flat and vertical veins is benching, in which fires at successive levels burn into both backwall and floor, producing a series of hollowed out steps: several examples were seen in Zawar Mala Mine, one of which is illustrated in Craddock's paper, which follows.

Other techniques

In order to tackle rock considerably above floor level, platforms have been built of either piled stones, common in the Khetri Copper Mines (Willies 1992). Examples are also illustrated by Ødegaard (1982). There are plenty of instances of timbers placed between the walls, with stones placed on top to protect them from the fire. A scaffold of timbers originally several metres high in Zawar Mala Mine seems likely to have been used in this way to get at the roof in a high chamber during retreat-removal of a pillar.

SETTING THE FIRE

Very little detail has been published on the detail of the actual setting of the fire to accomplish different effects, with the exception of Berg's (1992a;b; 1993) and Ødegaard's (1982) work in Norway.

It is apparent from the size of fireholes that fires could be set both small and large. The presumed advantage of a small fire is that it can be selectively used to attack a particular weakness, or alternatively to break down a section of hard rock whilst not wasting effort on the weakness, such as a joint. Hooson (1749) refers specifically to the value of exploiting joints, into which the flame penetrated deeply, suggesting that greater effect still could be obtained by picking out a joint. The experiment with a small fire however suggests that it takes a considerable time to get to an adequate fierceness and working temperature, which must reduce the overall efficiency: this might be countered by the use of continuous firing, where conditions permit. This would appear to be necessary in many cases as the space for the small fire was simply otherwise too small to be effective: the grouping and small size of fireholes at Zawar Mala Mine in India make it very likely that firing there was a specialised task carried out at several holes burning simultaneously, probably with the still burning material transfered from hole to hole as necessary.

Large fires have the probable advantage of reaching very high temperatures, but at some expense of waste of fuel. Examples of their use can be seen in the mines at Khetri, or, in Europe, especially easily at the Flobergets Gruva, now part of the Bergslagen Ekomuseum, in Sweden. They are advantageous, organisationally, in poorly ventilated workplaces by permitting a large amount of fuel to be brought in during a working shift, with the actual firing taking place during the night: the alternative of continuous firing with large fires would have been very difficult, except where conditions were designedly or otherwise especially favourable. This would have been especially so in levels or inclines due to both high air and radiation temperatures as well as fumes (except where the Kongsberg or double-drift methods were applied). Simonin (1868 p409) does however show a method of using a muffle to direct the flames which clearly required continuous operation, and illustrations of Falun and other large chambered mines show spectators as well as workmen at the fires.

The advantage of continuous firing is clearly that the high temperature could be maintained for large periods. Berg (1992a) suggests it was realised in Norway that it was the heating up which caused the damage to the rock, and that cooling (or dashing on of water) was not necessary. It is probable that where fuel economy was a less important factor than wages or speed, that this advantage overwhelmed the more subtle practices of earlier miners, but application of water to hot rock can be a most potent factor in its breakdown, where it can be applied!

At its simplest the fire can simply be placed on the floor near the face (see for instance, the beginning of laying a fire in Lehmann (1990 p272). An advantage of this is the accumulation of hot embers which sustain their temperature for a considerable time and attack the floor: the floor effect can be improved by using a 'muffle' of heavier logs, or a stone duct to reflect the heat back. Many illustrations show timbers placed leaning almost vertically against the face, sometimes held back from it by a crosspiece fastened to a post to form a flue. This, with heavier timbers on the outside, provides both a reflecting/insulating layer, and create a fierce updraught. Goldbergen (1700), amongst others, shows wood neatly stacked horizontally with the ends pointing into the face. A much more rapid build-up of a fire, which probably gives it a higher efficiency can be gained by placing the timber so as to form a flue under the fire. Berg (1992a) has illustrations showing logs placed longitudinally to form a flue, with a single log placed away from the face to cause logs above it to incline and roll into the fire as it burnt away: the main disadvantage of this is the floor tended to rise, and had afterwards to be 'dinted' using another technique. The different methods suggest that by careful control of the floor conditions under the fire it was possible to decline, (or sink vertically) drive level, or incline or raise.

OTHER ADVANTAGES OF FIRESETTING

A sometimes cited example of firesetting is the improvement to ventilation which takes place through the mine (except in the flue-section itself). This may however have somtimes have been offset by the reversal in ventilation which was necessary to get the smoke away, and in some cases, permanent fires may have been necessary to maintain air circulation. A more positive effect was probably to illuminate the workings thoroughly!

There may also have been advantages in ore separation. Rock affected by fire is more friable, and may either be already fragmented, or require less effort for comminution. In some cases, including possibly for the very fine tin ore found at Kestel, the fires may also have promoted intergranular cracking, both liberating the ore from the matrix, whilst maintaining the particle size as much as possible, which, with tin ore, is important in preventing loss of finer material (Wills 1988 p295; Binns 1984).

CONCLUSIONS

Firesetting is thus not just a simple bonfire technology. Miners have proved extremely versatile in devising ways of using it to meet their specific problems. It has been possible to use it within very small and confined passages, as well as within very large scale mining works. It could be combined with mechanical methods of breaking rock, either with firesetting predominant, or using it only to tackle specific problems. It may also have beneficial effects in reducing the amount of energy required for comminution.

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