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Gerd Weisgerber, Lynn Willies

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THE USE OF FIRE IN PREHISTORIC AND ANCIENT MINING : FIRESETTING

G. WEISGERBER and L. WILLIES

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Key-Words : *Rocks, Physical properties, Decomposition, Bronze Age, Neolithic, Mining tools, Mining technology.*
Mots Clefs : *Roches, Propriétés physiques, Décomposition, Age du Bronze, Néolithique, Outils miniers, Technique minière.*

INTRODUCTION

In a 1920 mining glossary, "firesetting" is described as : The softening or cracking of the working face of a lode, to facilitate excavation, by exposing it to the action of a wood fire built against it. Now nearly obsolete, but much used in hard rock before the introduction of explosives [1]. In Derbyshire a 1824 glossary said the same but added "preliminary to the use of the pick" [2].

Firesetting is a fundamentally straightforward technique, "the easiest work in mining" as Hooson described it [3]. Agricola had a different opinion, and observed a considerable sophistication in use. The effect of heating rock must have been frequently observed when bonfires were surrounded by stones or pebbles. Thus preheated they were then placed in the cooking pot. Interest in mining archaeology has led to investigate firesetting as a technique, and there have been a number of recent articles [4], as well as primitive bonfire attempts at "experimental archaeology" [5].

It is the purpose of this paper to assess the scientific basis for firesetting using results of research from areas such as mineralogy, refractories, and mineral processing; all of them dealing with the effect of heating on rock-based materials [6]. Secondly we will consider how firesetting has been applied underground on the basis of archaeological records.

HISTORICAL NOTES

As for many things, for firesetting, the oldest written notes can be read or interpreted in the Bible. In Jeremiah, prophet around 628 BC, the Lord says : "Is not my word like as a fire

1. FAY, 1920 : 270, *s.v.* Firesetting.
2. MANDER, 1824.
3. HOOSON, 1747, article "Fire".
4. TIMBERLAKE, 1990a, b ; CRADDOCK, 1992 ; BERG, 1992a, b ; WILLIES, 1987, 1991, 1992a, b.
5. CREW, 1990 ; PICKIN and TIMBERLAKE, 1988.
6. For more details see WILLIES, 1994 ; HOWAT, 1939.

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and like a hammer that breaketh the rock in pieces ?" (Jeremiah 23, 29); The Book of Job in the Bible 28, 5 says (around 400 BC) : "As for the earth, out of it comes bread : and under it is turned up (as it were) by fire". The citation is interpreted as firesetting [7].

Despite widespread knowledge of its use, firesetting was not used in many areas, including the mines of the Levant such as at Timna [8], Feinan [9] or in Sinai because of the relative softness of the sandstone rock. In the famous Athenian silver mines in Attica, so far no traces of firesetting have been reported or have been seen by the authors, possibly because of the softness of the marble and the relative scarcity of timber for fuel. Fire and smoke were forbidden in the Attica mines and were severely punished [10]. Firesetting was also absent on the marble island of Thasos.

A clearer reference to fire-setting in mining is by Agatharchides (2nd century BC) who is quoted by Diodorus Siculus (1st century BC) : "The earth which is hardest and full of gold they soften by putting fire under it, and then work it out with their hands. The rocks thus softened and made more pliant and yielding, several thousands of profligate wretches break in pieces with hammers and pickaxes" [11]. Concerning the gold mines of north-western Hispania it is in the 1st century AD that the use of fire setting is reported : ... "Occasionally a kind of silex (quartz-rich rock) is met with, which must be broken with fire and vinegar, or as the tunnels are filled with suffocating fumes and smoke, they frequently use bruising machines, carrying 150 librae (pound) of iron" [12].

The myth of Hannibal who broke the rocks in the Alps to make his and his elephants' passage possible by the use of fire and vinegar *(infuso aceto)* was first reported by Livy (XXI, 37) 250 years after the event and was several times repeated by Pliny (XXIII, 27 ; XXXIII, 71). The endless contributions [13] to this insoluble problem over the last 150 years at least have produced useful observations of the destructive effects of fire on stones [14], and of the more aggressive effects of strong acetic acid solutions on heated stones, at least in laboratory experiments [15]. In practice the throwing of water or vinegar on rock at high temperatures would be fraught with hazard : dangerous gases, exposure to heat and rock missiles from decrepitation of the rock.

As interesting and as important these early citations might be, to learn the actual working and skillful application of the method, as usual, we have to refer to Agricola (1556). He was the first to describe firesetting in detail after the short references of antiquity. As the art of mining in his days, at least concerning the way to attack the rock, was not so far from ancient times, his report is cited here in full [16] :

> "As I have just said, fire shatters the hardest rocks, but the method of its application is not simple. For if a vein held in hard rocks cannot be hewn out because of the hardness or its thin width/thickness, dried logs are piled up and fired; and if the drift or tunnel is low, one heap, if the drift or tunnel is high, two heaps are necessary, of which one is placed above the other, and both are let burning until the fire has consumed them. Its force does not generally soften a large portion of the vein, but only some shells of the surface. When the iron tools can work the rock in the hanging– or footwall but the vein is so hard that it is not tractable to the same tools, and then the walls are hollowed out; if this were in the end of the drift or tunnel or above or below. The vein is then broken by fire, but not always by the same method. For if the hollow is wide, as many logs are piled into it as possible, but if it is narrow, only a few. By the one method the greater fire separates the vein more completely from the foot-wall or sometimes from the hanging-wall, and by the other, the smaller fire breaks away less of the vein from the rock, but because in that case the heat is confined and kept in check by pieces of the rock set in front of the wood held in the narrow excavation, it can separate the vein from the rock. Further, if the excavation is low, only one pile of logs is placed in it, if high, there are two, one placed above the other, by which plan the lower bundle being kindled sets alight the upper one. And the fire being driven by the draught into the vein, separates it from the rock which, however hard it may be, often becomes softened as to be the most easily breakable of all... Even if a vein is a very wide one, as tin veins usually are, miners excavate into the small streaks, and into those hollows they put dry wood and place amongst them at frequent intervals sticks, all sides of which are shaved down fan shaped, which easily take light, and when once they have taken fire communicate into the other bundles of wood, which easily ignite.
> While the heated veins and rock are giving forth a foetid vapour and the shafts or tunnels are emitting fumes, the miners do not go down in the mines lest the stench affect their health or actually kill the workmen... As for that part of a vein or the exfoliated pieces of the rock which the fire has separated from the remaining mass, if it is overhead, the miners dislodge it with a crowbar, or if it still has some degree of hardness, they thrust a smaller crowbar

7. MASER, 1957 : 11 and 1984 : 95.
8. CONRAD und ROTHENBERG 1980.
9. HAUPTMANN, 2000.
10. DEMOSTHENES XXXVII, 36, cited by WILSDORF, 1952 : 148, note 81.
11. WOELK, 1966.
12. PLINY, *Nat. Hist.* 33.71, translation HOOVER and HOOVER, 1950 : 118f.3-28.
13. For discussion see ROSUMEK, 1982 : 23-28.
14. *Classical Weekly* 15, 1921/1923, 21 : 168; *Classical Weekly* 16, 1922/1923 : 73-76 and 96; *Classical Weekly* 18, 1924/1925 : 88; *Classical Weekly* 22, 1928/1929 : 98-99, 128 and 160. Many thanks to Dr. Peter Rosumek for granting this collection of references to the Deutsches Bergbau Museum together with the articles of his great bibliography.
15. SHEPHERD, 1992.
16. AGRICOLA, 1556 *in* HOOVER and HOOVER, 1950 with a few amendments by the authors.

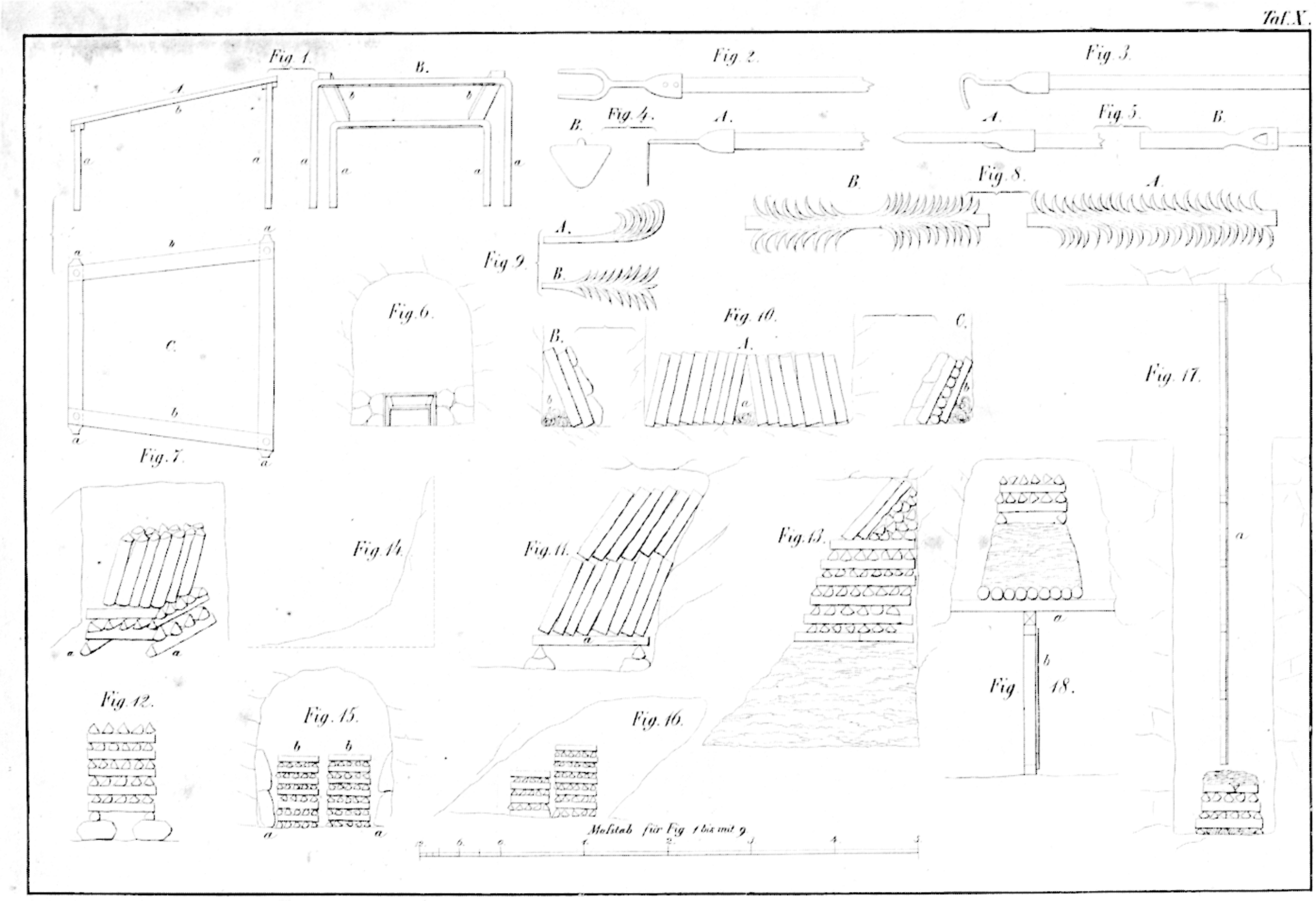

Fig. 1 : *Gätzschmann illustrates 1846 tools and ways of firesetting still in use. 17 is how to sink a shaft where a separation into two parts is necessary for a controlled ventilation.*

into the cracks and so break it down. But if it is on the sides they break it with hammers. Thus broken off, the rock tumbles down; or if it still remains, they break it off with hammers and gads".

Agricola gives a well-known illustration of firesetting, which will not be repeated here [17]. Later texts and illustrations concerning firesetting are informative [18], *e.g.* the Gätzschmannn Table X (fig. 1) gives a lot of details mentioned above. But mainly these books written by mining engineers report other times and other dimensions of mining. In their days explosives were widely used, and firesetting had lost more and more of its former importance. Nevertheless it must be mentioned that firesetting in some areas was still in use until the end of the 19th and, in India [19], even into the 20th century whenever it was economic (because of cheapness of wood, *e.g.* in Scandinavia) or necessary at special geological circumstances with tough rocks because of its superiority compared with explosives [20]. Because "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"... "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" [21]. The efficacy of firesetting is represented in the 21st century by the use of fuel/oxygen lances for cutting-out large blocks of monumental granite in quarries.

17. *Ibid.* : 120.
18. RÖSSLER, 1700; CANCRINUS, 1773; DELIUS, 1773; GÄTZSCHMANN, 1846.
19. CRADDOCK, 1996.

20. *E.g.* in the Harz/Germany, see BARTELS, 1988.
21. CALLON, 1876-1886 : 176.

Table 1 : *Coefficients of thermal expansion for some common minerals (SINCOCK, 1984 : 49-50).*

Mineral (symmetry)	% expansion from 20 °C to orientation				
	100 °C	200 °C	400 °C	600 °C	800 °C
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			

ROCKS AND MINERALS

Vein or lode mineralisation involves a small suite of very common minerals, and a large number, but in much lesser quantity, of rarer ones – though these latter might well be the object of exploitation. The commonest vein minerals are quartz, feldspars, calcite (and the isomorphous series of calcite with magnesium and iron carbonates known as 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 – minerals that have resulted from hydrothermal or groundwater alteration of other minerals or rocks.

The common host or country rocks present a wider range, but whether igneous, sedimentary or metamorphic rocks, nearly all contain one or more of a relatively small suite of common minerals. In a simplified version, igneous rocks such as coarse grained granites and fine grained rhyolites contain mainly feldspar, quartz and mica; gabbro and basalts or the intermediates diorites and andesites contain feldspar and ferro-magnesium minerals such as olivine or pyroxene. 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. Finally the metamorphic group (pre-existing rocks changed by application of heat and pressure, or 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, feldspar and ferromagnesium 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. Wood had to be really dry to reduce vapour and smoke and to achieve higher temperatures.

There appeared to be little information about temperatures reached in wood fires. Measurements in a bonfire by a thermocouple linked to a digital thermometer revealed that the critical quartz inversion temperature (573 °C) was reached after only 12.5 minutes, and a maximum temperature of slightly above 700 °C after 26 minutes. Red embers maintained a temperature of over 690 °C for a considerable time. The experiments suggest that temperatures considerably exceeding 600 °C can easily be achieved in a wood fire and that temperatures over 700 °C 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 achievable.

PROCESSES INVOLVED IN FIRESETTING

In both economic and technological terms, to break rock or mineral successfully always relies a great deal on exploiting the weaknesses within it. In the case of firesetting, this is complex; 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 are the following:

(DIFFERENTIAL) EXPANSION OF MINERALS

Heating [22] 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 feldspars (orthoclase, microcline and, perhaps, pyroxenes and amphiboles). The thermal expansion of fluorite 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.

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/feldspar against mica for example), along cleavage planes (feldspars, 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.

Common minerals, which have relatively high degrees of expansion, include quartz, cassiterite, fluorite and pyrite, whilst orthoclase feldspar has a six fold higher coefficient of expansion along the c axis compared with the others [23]. Minerals in both igneous and metamorphic rocks are frequently associated as intergrowths, notably quartz and feldspar in rocks such as granite or granophyre, which can thus be expected to be vulnerable from differential thermal expansion.

Holman [24], 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. It is possible that practising miners had made similar observations as to how they could optimise the effect of their fires.

For igneous rocks, Dence [25] produced a table of inferred cracking temperatures as follows:

Rock	Cracking temperature
Basalt	550 °C
Fine grained olivine diabase	530 °C
Medium grained quartz diabase	450 °C
Medium grained olivine gabbro	360 °C
Coarse grained quarzite	300 °C
Coarse grained granite	260 °C
Coarse grained granodiorite	200 °C

EXPANSION ACROSS A TEMPERATURE GRADIENT

The heating of a rock face is necessarily anisotropic, with very high temperatures at the heated surface, and a fairly rapid reduction of heat inside the rock. At some point spalling may occur with the spontaneous removal of heat-affected rock, usually a matter of a few centimetres thick with, beyond, relatively unaffected rock.

A major factor in inducing internal stress resulting in weakening or spalling, is the varying thermal behaviour of minerals. High density and high specific heat will both reduce the effect of the thermal gradient which is the principal cause of spalling [26]. Many sedimentary rocks seem likely to have lower thermal diffusivity because of mineral content with low specific gravity, 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.

22. See SINCOCK, 1984 for a fuller discussion.
23. BINNS, 1984 : 67.
24. HOLMAN, 1927.
25. Cited *in* SINCOCK, 1984 : 62.
26. ETHERINGTON H. and ETHERINGTON C., 1961.

FLUID INCLUSION RUPTURE OR DECREPITATION

Fluid inclusions are commonly present in minerals, and represent primary or secondarily derived "bubbles", most of them varying from a few to a hundred micrometer or so. They result from the formation fluid trapped within by the growth of the mineral. Typically, an inclusion has two phases, liquid and vapour, the vapour representing the degree of contraction of the liquid from its formation temperature. On reheating, at the temperature of homogenization, the vapour phase will disappear, which will turn to be the original formation temperature with the proviso there has been no leakage, and with an allowance for pressure regimes. If heated markedly above the homogenization temperature, the inclusion will rupture, and the mineral may decrepitate. Examination of the effect of anthropogenic decrepitation, *i.e.* firesetting, on quartz from a Stone Age quarry in Finland, suggests that a temperature of 300 °C to 500 °C is required[27].

VAPORISATION OF WATER

The heating of water contained in closed pores has an effect which ranges from crumbling or spalling to even explosions, for instance in limestones, or sometimes even in joint systems, especially within clay rocks (which even when indurated commonly contain some 5 % water).

CHEMICAL BREAKDOWN OF MINERALS

Many minerals contain water which is chemically bound, but is released on heating. This particularly effects clay– and chlorite- 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 feldspars and may form inclusions within otherwise unaffected minerals. Hydrated iron minerals, especially minerals of the iron hydroxide series ("$FeO.xH_2O$"), also have a substantial reduction in volume on heating. Temperatures of more than 100 °C should have effects equivalent to the vaporisation effect mentioned 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.

27. KINNUNEN, 1988.

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

THERMAL SHOCK

This takes place at rapid cooling, notably by quenching with water either externally supplied, or held within the rock in pores. It may operate by contraction causing tension within or between minerals and especially creating or propagating micro fractures. Its importance is emphasised by the Holman[28] experiments, 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. 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 have been responsible for a great deal of secondary chemical metamorphism, converting feldspars 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. In some cases such weaknesses must have made firesetting unnecessary, or led to its selective use.

THE TECHNOLOGY OF FIRESETTING

In a 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

28. HOLMAN, 1927.

group, perhaps a family, 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 : although sometimes there will 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 [29].

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 or 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 ore body itself. In the ore body 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.

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. In early mines, before iron was used in daily life, the tools were of stone, antler and wood, though occasionally copper or bronze was used to tip tools, or to make them entirely out of metal. 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.

Berg [30] 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 hammered afterwards or picked extensively to make best use of the weakening produced by fire. This seems to be the most widely used method. In the third firesetting alone is used, with a continuous fire against the face and no mechanical means used, a model probably used in the 16th and 17th centuries in Norway (pl. IX : 1).

In other circumstances the model can be reversed, with firesetting preceding firesetting with hammering. At Kestel [31] in Turkey (pl. IX : 2 and 3), in one of the earliest fireset ore mines examined (Early Bronze Age, from ca. 2 900 BC onwards), 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 rocks are found and the traces of fire are much less obvious. In a probable later stage, shallow-depth parts of the mine were opencast, and the firing evidence very small indeed, though weathering may partially account for this. Probably the early phase in which only firesetting took place when abundant timber was available nearby.

Recognition of firesetting in mines is usually easy when used alone (or at least with little mechanical assistance), 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 little sinuous, deviating just slightly from the centre line though overall on a straight course. Headings often have a small hollow in the floor with a lip, and often a wide face is divided into slightly hollowed panels, each probably representing a separate fire (pl. IX : 3).

Picking with a sharp tool or gentle hammering after firesetting will usually persuade further thin exfoliation sheets to separate from the rock, sometimes almost without leaving a trace-mark of the tools. 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. However, 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 coloration and the aggregation of fine

29. COLLINS, 1893.
30. BERG, 1992.
31. WILLIES, 1991 ; YENER, 2000.

Fig. 2 : *Zawar Mala Mine in India showing upper, earlier period working and lower, later period retreat working with steps leading towards the Upper Chamber, 260° panorama (CRADDOCK, 1994 : fig. 4).*

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 or roofs. 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 (pl. X : 1 and pl. XII : 1).

Where the rock has been hammered as well as fired, the effect is less clear. At Kestel, a firehole developed in the roof of what appears to be a reworked section of the mine (radiocarbon dated to EBII, second half of the 3rd millennium BC). It was heavily hammered by 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 heavily hammered indeed by the mauls, which had broken the rock off on a depth of up to ca. ten centimetres, preserving the general form, but totally destroying any smoothness. Had the battering process been completed, the pocket would not have been easily ascribed to firesetting. We have no idea how much timber was used for the fire, but the yield must have been several times as great than without heavy-hammering.

FIRESETTING APPLICATIONS

This section describes firesetting as it has been either illustrated or described by contemporaries, or has been observed either by engineers or from archaeological survey. The different methods suggest that by careful control of the floor conditions under the fire, it was possible to sink shafts, to drive levels, to construct inclines or raise declines.

Shaft-sinking is one of the least common, and probably the most difficult application of firing. A 19th century AD instruction describes that the shaft had to be separated by a wooden wall to enable a better ventilation (fig. 1) [32]. The fire also had to be covered in order to direct at least some of the heat to the bottom.

The oldest example comes from Kestel (starting 2900 BC) where the bottom of a shaft had a hemispherical shape. At Karnab a second millennium BC site in Uzbekistan, many vertical entrances of mines, after some depth, show intersections that may be related to different fires due to shaft-sinking [33]. More recent archaeological examples are known from medieval Zawar Mochia in India [34]. In Rajpura Dariba, a timber left spanning the shaft suggests that the shaft was divided by a brattice to control the airflow [35], as it has been described by Gätzschmann [36] (fig. 1 : 17).

Driving levels results in very variable passages : if low, they tend to present a sub-circular section, with, commonly, a minimum diameter of about 70-80 cm; so they are moderately comfortable for crawling. Third millennium BC examples are known from Kestel and Agios Sostis [37] on Siphnos Island in Greece (pl. X : 1), and from Veshnoveh, area Chale Ghar [38] in Iran (pl. X : 2). They are also present in medieval and more recent mines. More or less, they have a very characteristic slightly rounded, upright section, high enough to allow a man to walk.

Declines were a normal feature of mining at Veshnoveh/Iran. Sometimes from the declines the working of ore could start on both sides, resulting either in wide chambers or, nor-

32. GÄTZSCHMANN, 1846 : fig. 17.
33. ALIMOV, 1998.
34. WILLIES, 1987 ; CRADDOCK, 1996.
35. WILLIES, 1987.
36. GÄTZSCHMANN, 1846.
37. WAGNER und WEISGERBER, 1985 : fig. 133.
38. HOLZER and MOMENZADEH, 1971.

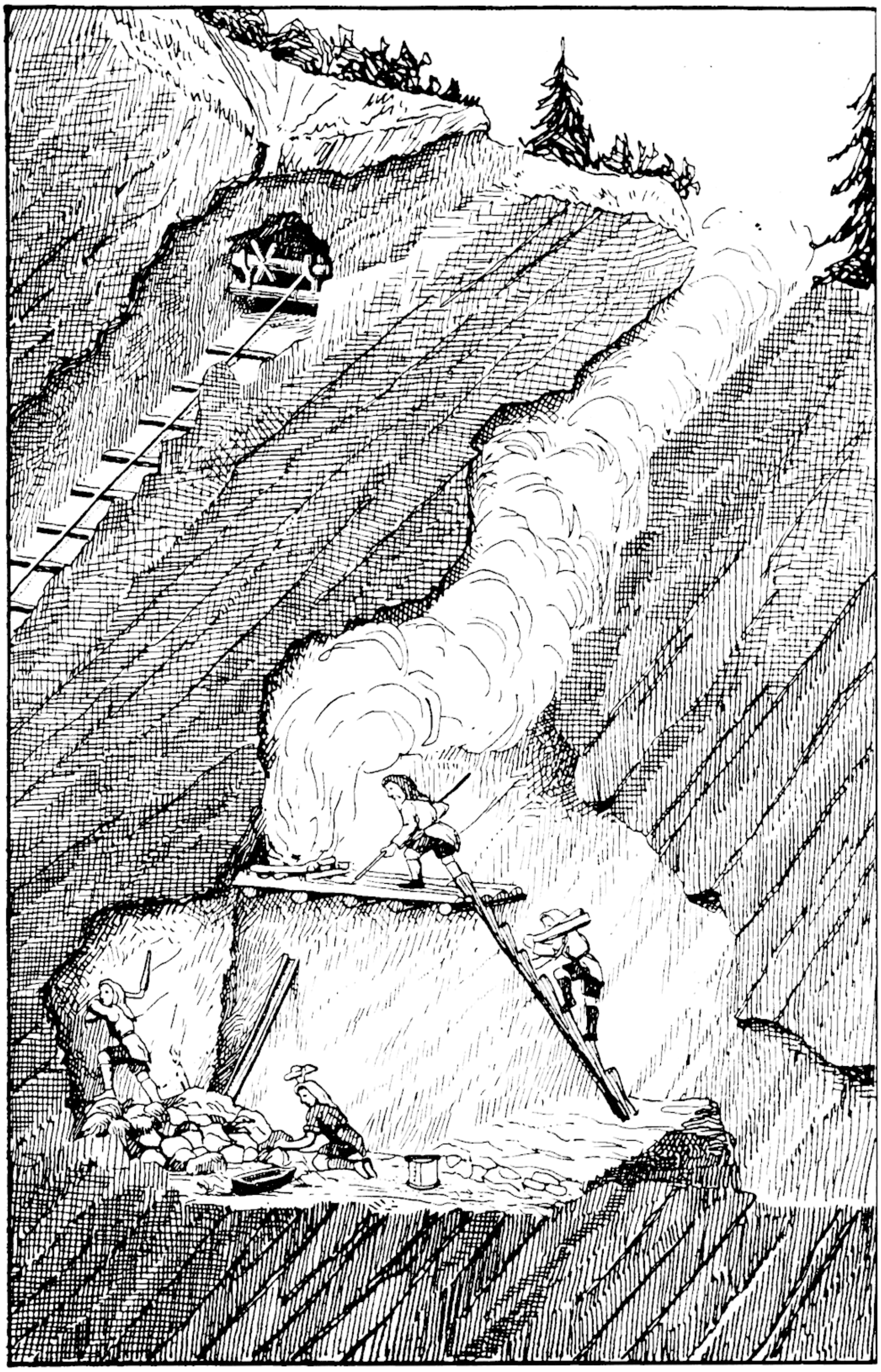

Fig. 3 : *Artist's view of two mining operations to illustrate firesetting on a platform and the hauling of men or water or ore by a winch (KLOSE, 1918 : fig. 1).*

mally, the original decline is still present at the bottom. At the Mitterberg in Austria declines were developed into the hanging walls (stopes) (figs 3 and 5). Many of the recently discovered Bronze Age mines at Schwaz/Austria (around 1 200 BC) also show these characteristics [39].

At Zawar Mochia (fig. 2) in India, declines go down at angles up to 45° and over 50 metres long, with a roughly circular section ca. 2 m diameter [40]. Both firesetting and heavy hammering were used. Some declines were single, others were in pairs; the latter holed through for ventilation at intervals and finally widened laterally to provide very large wide rooms.

The use of fires in *inclines and raises* would appear to produce difficult ventilation problems. This, for instance, is the case at Veshnoveh where the higher parts of a mining chamber are situated more than 2 m higher than the drive from the entrance. The shape of the faces, together with the hammering marks, give clear evidence of firesetting. Pillars as *in* Callon (fig. 4) [41] or the Mitterberg method (figs 3 and 5) show how a raise might have been made. The fire is supported by a pillar built within the raise, so that the mine airflow is diverted up the raise and down again.

Four principle methods of exploiting ores or other raw materials from the hanging wall (stoping) are mentioned 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 [42], or along a "long wall" face. This last is most probably present at EBI Kestel in Turkey (mid 3rd mill. BC), and in shallow workings at Zawar Mochia in India.

Overhand stoping has been claimed as a natural result of firesetting methods (fig. 4) [43], in such cases, where sufficient broken material is left in the stope to support operations under the roof. The Mitterberg method is efficient both in overhand and in underhand stoping (figs 3 and 5). At Karnab/Uzbekistan, underhand stoping must have played a considerable role but there is not yet enough to reconstruct the procedure in detail.

At Veshnoveh/Iran sometimes rock benches were maintained to keep the fires at the faces and under the roof. Small stepped-benches are also found. No fire debris is found accumulated and associated to a construction indicating an elevated platform. Separate fires, either spatially or possibly in time, must have been kept burning at the mine walls. Mechanical breaking of the intervening ribs lead to faces with slight hollows one beside the other, thus economising on fuel. At the Zawar Mala Mine in Rajasthan, a succession of benches was worked horizontally one behind the other in the chamber floor (fig. 2).

39. RIESER und SCHRATTENTHALER, 1998/1999.
40. WILLIES, 1987.
41. CALLON, 1876-1886 : pl. XVIII.
42. ROESSLER, 1700 : 76.
43. It has been illustrated by CALLON, 1876 : pl. XVIII.

SETTING THE FIRE

For information concerning the actual setting of the fire, and to look at its different effects, one has to go back to the old instructions starting from Agricola [44], Rössler [45], Callon [46], Cancrinus [47], Delius [48] and especially to Gätzschmann [49] where details are given including even the shape and the preparation of the first lighting of the firewood. Except for the muffle of iron rods and sheets to conduct the flames to the faces (fig. 1 : 1) [50] the other variations, *e.g.* to pile up logs or stones to guide the flames, will not have been much different during the prehistory. They are adapted to the different purposes. The simplest one is when the fire is just placed on the floor near the face. An advantage of this procedure 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.

Fires could be small or large; they could attack plain rock faces or particular weaknesses such as *e.g.* joints. Fires could either burn one after the other or simultaneously. The advantage of continuous firing is clearly that the high temperature could be maintained for long periods. The authors cited above recommend having the fires burning continuously to maintain the heat of the rock.

Gätzschmann gives examples of the effectiveness of firesetting as he found them in the previous technical literature [51]. There were experiments made to compare the profitability of firesetting, drilling and blasting. In some instances, firesetting proved to cost only half of the working time. In the deep Beneckestollen at Skuderud in Norway 18 m^3 (8,3 Klafter) of

44. AGRICOLA, 1556 *in* HOOVER and HOOVER, 1950.
45. RÖSSLER, 1700.
46. CALLON, 1876.
47. CANCRINUS, 1773.
48. DELIUS, 1773.
49. GÄTZSCHMANN, 1846.
50. GÄTZSCHMANN, 1846 : fig. X,1.
51. GÄTZSCHMANN, 1846 : 713-717.

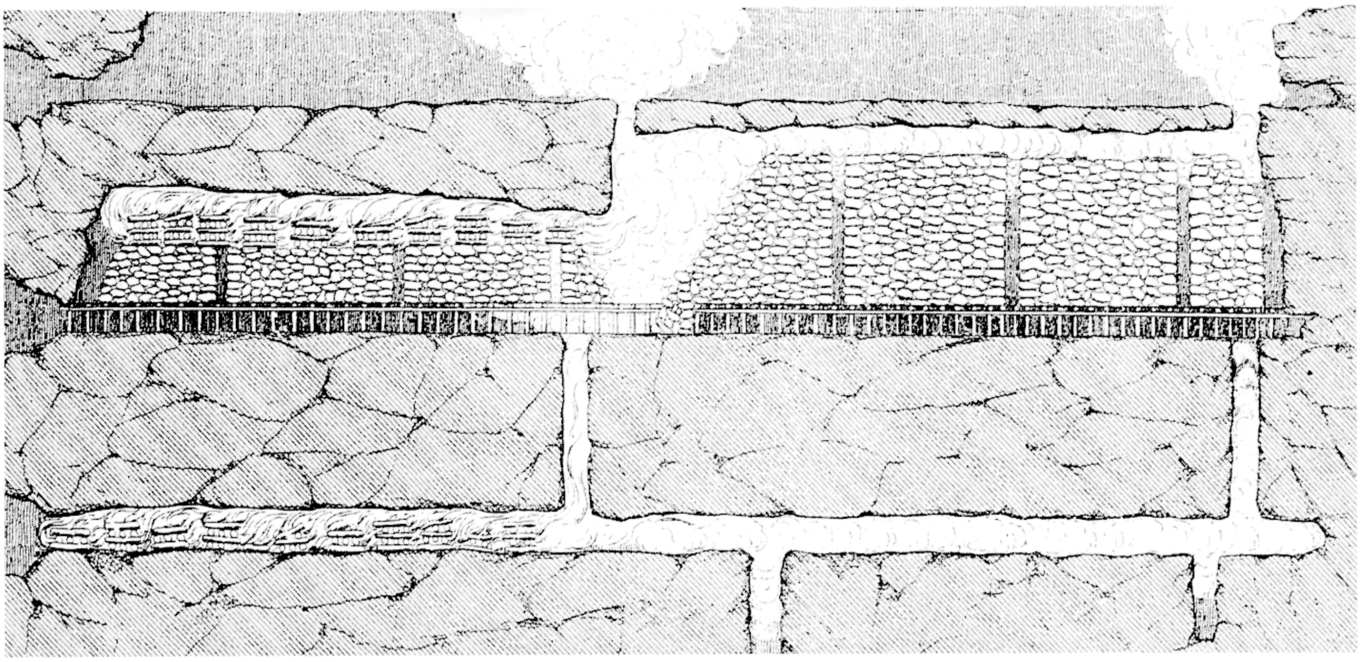

Fig. 4 : *Callon's illustration of large-scale firesetting installations (1876, part of Pl. XVIII).*

fire wood were needed to drive a gallery in gneiss with a section of 2,25 m by 1,5 m (sometimes extending to 2-3 m) for a length of 250 m for every 2 m length. In this way, a distance of approximately 4 m has achieved within 4 weeks.

From very early medieval times, mining regulations asked that fires should only burn overnight, or in really deep mines, only over the weekend, all because of the danger of the poisonous smoke. In the lead mines of Derbyshire, England, for example, fires could not be set until after 4 pm in the afternoon. There are even regulations to adapt the schedule of firesetting to special times of the year: in a mining law of Schladming (Alps/near Dachstein) from 1408 (Schladminger Bergbrief) firesetting was regulated. Between St. Michael day (September 29) until St. George (April 24) firesetting should not be lighted before night and in the other parts of the year not before afternoon. The different parties had to inform each other [52]. During the prehistoric times, we presume that similar habits were in use because the same dangerous conditions were faced.

There were other advantages in firesetting for the work in the mines such as a possible improvement to vent, a better light during the work of the workings, and advantages in ore separation.

52. KUNNERT, 1961.

MINING ARCHAEOLOGICAL EVIDENCE FOR FIRESETTING

FLINT AND PIGMENT MINING

In the Near East, mining archaeology is still in *status nascendi*. Only a few studies have been done, mostly on copper ores, but never supported by sufficient excavations.

Concerning the oldest mining of red pigments in Anatolia [53], for example in Konya [54], almost no information is available on underground works. For prehistoric flint mining in the Near East, the situation is worse for the large number of flint mines which must have existed there; the ones in Egypt were dug into the gravel sediments of the Nile [55]; in Israel, no underground works are known from the only flint mine discovered so far. The flint mines in Egypt and Israel date to the Palaeolithic; no Neolithic mining activities are known. In Egypt, the mines known from the Wadi el-Sheikh seem to belong to the 2nd millennium [56]. They do not show any traces of firesetting either.

53. KOSAY, 1949.
54. SHARPLESS, 1908.
55. VERMEERSCH *et al.*, 1991.
56. WEISGERBER, 1987.

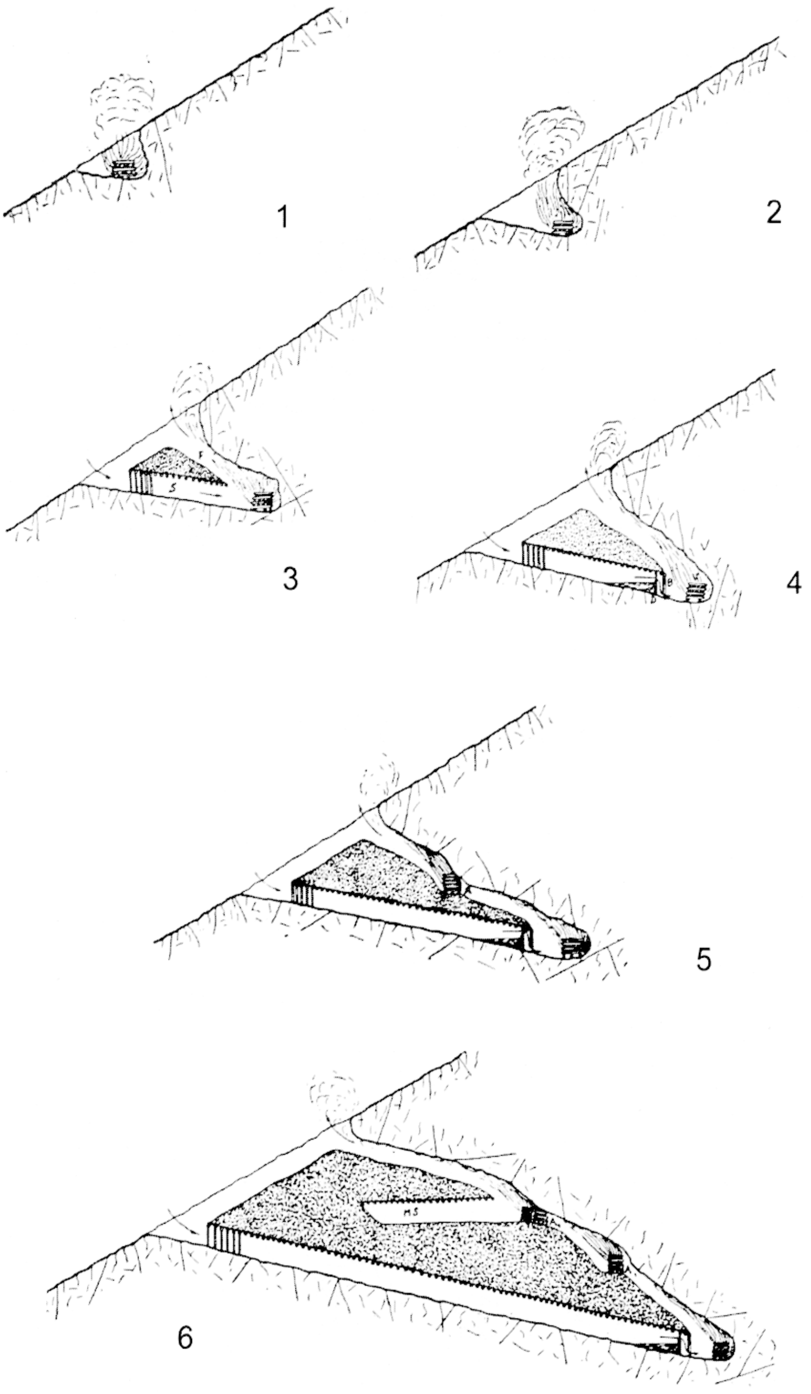

Fig. 5 : *Bronze Age mining methods at the Mitterberg near Bischofshofen, Austria, as it was met at many places along the vein and described by ZSCHOCKE/PREUSCHEN (1932) :* ***1.*** *First working at the outcrop of the ore vein by hammering and fire.* ***2.*** *Heading of the inclined shaft under the surface.* ***3.*** *Systematic vertical and horizontal timber support prevents rock fall. The waste was dumped on the timbers. The mine now has two levels and two openings.* ***4.*** *The advancing fire has to be protected from the water at the bottom by a dam. On the higher level and on the dumped waste rock additional fires help to win the ore.* ***5.*** *The initial development work has been extended systematically into production stoping of the ore.* ***6.*** *The main ore production phase. Sometimes a third level has to be installed to enable the fire to burn high enough under the roof.*

In Europe as well the technique of fire-setting is rare among more than 200 flint mines that are known. As they were mainly dug in marl, chalk, clay or soft limestone, no techniques to break hard rock were needed. There are just two exceptions. The first is the Isteiner Klotz near Kleinkems upper Rhine area. The hard calcareous rocks (coral limestones) belong to the Middle Malm (Rauracien, ma 2). They contain nodules of banded flint, which, due to its quality, is called "white jasper". The flint occurs in three levels. Mining took place during the 4th millennium BC. The rock was attacked by firesetting and by hammer stones which were made of pebbles from the Rhine. Reddened rock faces and reddened deads, together with charcoal, are strong indicators of the use of fire which was applied only on the rock *between* the chert layers; fire was not set on the chert itself ! Fire traces are always found 10-15 cm above and below the chert. Botanical investigations of charcoal showed oak (75 %), willow and poplar (6 %), ash-tree (7.7 %), maple (2.9 %), linden (lime) (2.4 %), and some other. This vegetation represents the forest growing in the valley and the slopes of the Rhine at that time, but nevertheless it seems that the miners preferred oak because of its heating qualities. The excavator E. Schmid performed firesetting experiments inside the old mine. The results are the following :

Wood was piled up 1 m high and burned for 2.5 hours. Half of the rock face was quenched by two buckets of cold water. The "production" of broken rock was as follows :

1. Hammering on fresh rock	15 min.	675 g	fine grained
2a. Hammering after firesetting	10 min.	9.080 g	coarse pieces
2b. continuing	10 min.	1.253 g	fine grained
3a. Hammering after firesetting + water	10 min.	18.887 g	coarse pieces
3b. continuing	10 min.	3.255 g	coarse pieces

The experiment showed that firesetting can be successfully applied to hard limestone and that calcination was not a problem. In the case of Kleinkems, the effect of heat on the chert was obviously not wanted [57].

The second European example of Neolithic firesetting comes from Veaux-Malaucène in the south of France, east of the Rhône river, from a wide opencast exploitation in the extremely hard limestone of the Crête du Rissas of Mont Ventoux. E. Schmid, after her experience in Kleinkems, suggested that firesetting was applied there, because the quantity of charcoal found was much more than needed for lightening purposes. However, the scale of the archaeological excavation, carried out by the German Mining Museum Bochum in 1959 and 1962, was too small to get further information [58].

Firesetting is also known from prehistoric quarries, where lumps of rocks were exploited for making axes. One of the best-studied examples are the quarries of Sélédin in France [59]. In the authors opinion it is only a question of time until more evidence for firesetting, in flint-, chert-, obsidian- and pigment mining or quarrying will be found in the Near East. A possible candidate in Jordan is, for example, Maqita near Dana, where several flat caves with rounded faces were observed in limestone. Here many flint nodules occur in the rock.

METAL MINING COPPER MINES

THE MITTERBERG EXAMPLE

The copper ore deposit of Mitterberg near Bischofshofen (Austria), a nearly vertical vein consisting of chalcopyrite, was re-discovered in 1827. The mine was reopened. Traces of earlier mining activities were found. It was J. Pirchl, who, in an almost unique way, took care of ancient workings and finds which were carefully mapped and documented. The technique of firesetting had been carried out in a sophisticated way.

The upper part of the vein was exploited down to a depth of more than 100 m below surface. The main method of attacking both vein and rock were firesetting and hammerstones. The problems came when the stope became too high for the flames and when it was too far from the entrance for simple ventilation.

Mining started with inclined shafts, which were dug partly by firesetting and partly by bronze picks and hammerstones. When workings over the decline became too high and fire could not attack the roof effectively, platforms had to be constructed, reached by trunks (figs 3 and 5). Waste rock was dumped on the wooden platforms thus bringing the fire near to the roof and avoiding the work to bring all the deads to the surface. Air could circulate to and from the fires by keeping the main incline free and leaving a gap under the roof. Due to the inclination, water percolated down to the lowest face, where it was stopped by a dam of trunks and clay (fig. 5).

57. SCHMID, 1999a.

58. SCHMID, 1999b.
59. RODEN, 1983.

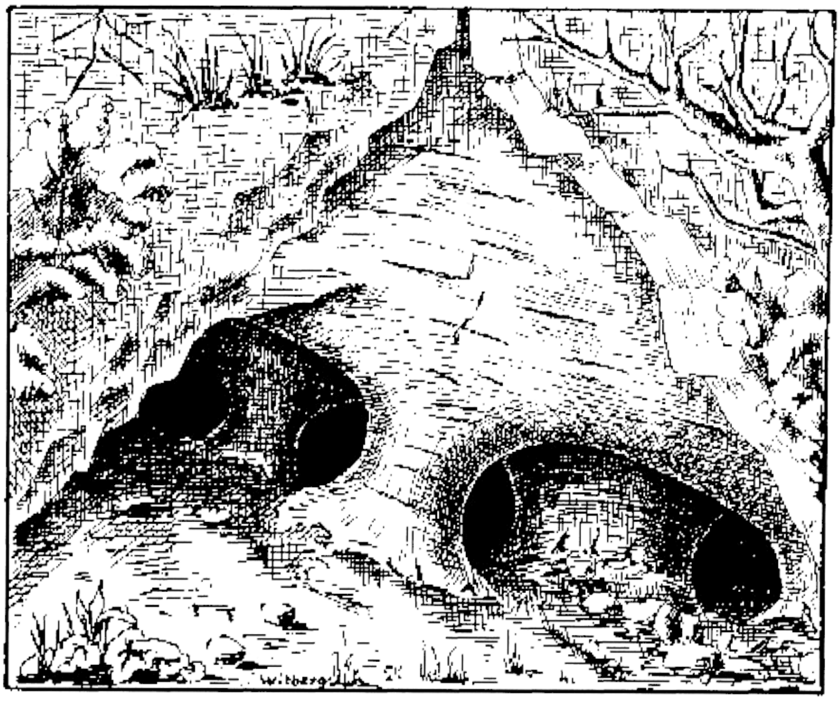

Fig. 6 : *View of the prehistoric copper mine at El Aramo in Spain (ANDREE, 1922 : fig. 25).*

Wooden buckets could have been used to pour water on the hot rock after firesetting or to bring the water out of the mine.

The oldest winch, with crossed bars ever found also comes from the Mitterberg mines (fig. 3) and might have been used to haul leather bags full of water to the surface, or sending logs into, or bringing ore out of the mine [60].

Recent research in the area of Schwaz/Austria led to the discovery of more than 40 prehistoric copper mines from the Early and Late Bronze Age. They were all cut by firesetting, some of them have really large chambers. [61]

Other European prehistoric copper mines also show traces of firesetting, such as the Irish Mt. Gabriel mines [62] or those in Wales [63] or in southern France [64]. Firesetting is claimed for the mines at Rudna Glava in former Yugoslavia [65], but this is neither proved by the shape of the mines, nor by the small quantities of charcoal, which probably may come from lightening branches. Possibly the limestone may not have required firesetting. However, at the Chalcolithic mines (4th/3rd millennium BC) of Aramo near Mieres-Oviedo (Asturia), firesetting and hammerstones are clearly reported (fig. 6), as they are for the mines of Milagro [66].

60. KLOSE, 1918.
61. RIESER und SCHRATTENTHALER, 1998/1999.
62. O'BRIEN, 1994; WEISGERBER and PERNICKA, 1995.
63. TIMBERLAKE, 1990a; WEISGERBER and PERNICKA, 1995.
64. AMBERT, 1990-1991; WEISGERBER and PERNICKA, 1995.
65. JOVANOVIC, 1982.

COPPER MINES AT VESHNOVEH / IRAN

The best and most impressive example for early firesetting as an effective technique of mineral excavation is found in the mines of Veshnoveh near Qom in Iran [67]. They probably date to the 4th millennium BC. In three areas of activities, Mezrajeh, Chale Ghar, and Laghe Morad, at an altitude of ca. 2 000 m, more than 70 mines of various sizes and shapes were opened. The shape of the walls, however, is that uniform that probably they were made in the same time range (pl. X : 2-3 et pl. XI : 1-3). No traces of the use of metal tools could be observed. At Laghe Morad, hammerstones of andesitic rock, brought to the mines, were manufactured on the site. The mines followed the oxidic copper ores and sulphide mineralisations, which were mostly visible as vertical green malachite bands in the rock. Every mine was opened by adits on the mountain slopes and never by shafts. Sections and views of the walls of drifts, headings, and mining chambers clearly indicate the use of firesetting and stone hammering.

66. ANDREE, 1922 : 44.
67. HOLZER and MOMENZADEH, 1971.

During spring 2000, the German Mining Museum expedition (Bochum) made a further observation. At several mines, the typical smooth wall surfaces left by firesetting and hammering had either fallen off or were in the progress of exfoliating. The interpretation is that the heat affected the rock deeper than necessary; and it was cracked additionally by annual frost during the winter seasons (pl. XI : 2-3). It illustrates the potential for very heavy hammering after firesetting, which was presumably not realised at the time the work took place.

LEAD AND SILVER MINES

On the western shore of the Gulf of Suez, the peninsula of Gebel Zeit is located opposite the edge of Sinai. There, a mineralisation of galena occurs in synsedimentary depositions in Miocene limestones. The mineralisation occurs either in vertical veins (< m) or in stratiform layers which almost reach a thickness of three meters. The galena is extremely poor in silver. As the Egyptians made no special use of lead except for alloying copper for casting, galena may have been used mainly as black pigment for cosmetic purposes. Mining took place between 1 900 and 1 300 BC. Dwellings of the miners and a temple of Hathor were discovered nearby and excavated [68].

Firesetting took place in both kinds of mineralisations. The rounded shape of sections and shafts should be sufficient proof. Many roofs are intensively sooty and are sometimes covered by real soot incrustations, especially at the entrance where smoke escaped. Mine 14 had sponge-like hard crusts at the roof. The problem of fuel in this desert remains unsolved : massive wooden props are still in place between the vertical walls. This timber and the fuel probably had to be brought to the site from a longer distance – one of the remarkable logistical achievements of the ancient Egyptians. Details of how firesetting was handled there are not yet available. The illustration shows the effect of these activities at the rock (pl. XII : 1).

At the large lead/silver mines of Lavrion in Greece, a Bronze Age exploitation using hammerstones could be observed but, as on the island of Thasos, activities date mainly to Classical times (4th and 3rd centuries BC) [69]. At both sites no firesetting could be observed. This may partly be due to the nature of the stratiform ore bodies. But they are mainly the results of the use of iron/steel tools, which were at that time available; these tools are the reason why fine rectangular-sectioned drifts could be constructed. The mines of the Island of Siphnos in the Aegean Sea are dated to the Early Bronze Age (1st half of 3rd millennium BC). In contrast, these passage sections are rounded or oval and there is charcoal on the floors. Among all the classical and 19th century mining debris, several pebbles of foreign origin with marks of hammering were collected [70]. This indicates that the firesetting combined with hammering was applied.

In Central Asia silver mining was an economic factor during the Islamic period for the production of silver coins. These were an over regional silver supply, even for Viking ornaments. A famous mine in Ilak was Altyntopkan. Starting at the outcrop of the ore deposit at the summit of a steep mountain, at an altitude of 2 000 m, ore veins with high silver contents were exploited by a vertical shaft. Additionally, an inclined (45°) shaft, 2 x 2 m wide and 30 m deep, was dug in the metamorphic limestone using firesetting. Several high and large chambers were made in the same way. Another 20 m deep vertical shaft enhanced ventilation. During a 1992 visit to the mine 108, the rounded rock faces, the general shape of the mine, and the soot clearly indicated intensive use of firesetting techniques (pl. XII : 2). Today scarce juniper trees grow on the slopes and in the area. They probably indicate the fuel that was used more than 1 000 years ago by the miners.

TIN MINING

Prehistoric tin mines and their infrastructure in Uzbekistan and Tajikistan were recently studied by a joint research of the German Mining Museum, the Eurasien-Institut of the German Archaeological Institute in Berlin and the University of Freiberg/Saxon together with the Academies of Science of both countries [71]. Work was concentrated on the mines at Karnab in the steppe south of Bokhara and Samarkand. These mines were dug (as it seems today) by open cuts in granitic host rock into more or less vertical quartz veins, which contain cassiterite (SnO_2). They could reach a depth of more than 15 m, a level where our excavations were stopped by the ground water (pl. XII : 3). The mines are deeper but they are drowned today and remained inaccessible. Vertical stopes are very narrow because only the relatively thin veins were worked out. Wider veins sometimes have shaft like dipping headings. The hundreds of mines we found belong to the Late

68. CASTEL and SOUKASSIAN, 1990.
69. WAGNER und WEISGERBER, 1988.
70. WAGNER und WEISGERBER, 1985.
71. ALIMOV *et al.*, 1998; WEISGERBER und CIERNY, 1999.

Bronze Age. ^{14}C dates ranging from cal. 1 600-800 BC. According to the pottery found, the mining activities are due to "nomadic" people of the Andronovo culture. The mines must have had an enormous economic importance : calculations based on the quality of ores in remaining safety pillars show that a single mine, 30 m long and 15 m deep, produced a minimum of 1 ton of tin. As only a hand-full of mines could be studied, there is a possibility that older mines also occur. At this period, the tin of the Near East might come from these mines or from others in a wider area.

These mines in Central Asia were dug by hammerstones and firesetting. Millions of marks of hammer stones cover walls, floors, and roofs. As there are no pebbles in the loess steppe, the thousands of hammerstones were produced out of quarried hard limestone of the area. They have hafting grooves only on three sides, as it is often the case. As there are no trees in the steppe, except where some water occurs, the supply of fuel for firesetting remains a problem. J. Cierny demonstrated in a 1999 experiment that firesetting works with the available wormwood shrubs that cover the area. It burns quickly, gives sufficient heat, and leaves no charcoal but a whitish grey ash. Faces and walls indicate the use of firesetting by their rounded, lanceolate or willow leaf-shape. The problem remains that in a vertical open cut the effect of the fire mainly had to be towards the bottom. The heat of quick burning shrubs, however, is directed in the opposite direction. Inclined entries (instead of vertical shafts) might thus have been the first operation to open a mine in order to get room for firesetting that affects the hanging wall.

Kestel in southern Anatolia in the foothills of the Taurus Mountains offers many examples of the use of hammering assisted by firesetting [72]. The bulk of the very low-grade cas siterite deposit, associated with haematite, is found in limestone metamorphosed to marble as elliptical vugs or anastomosing veinlets. The earliest exploitation (ca. cal. 2 900 BC) utilised firesetting with only limited use of stone hammers, producing sub-circular passages ca. 70 cm diameter, leading to chambers where sufficient ore was found. An underground shaft was deepened for 5 m in a steep angle. Excavation at its bottom showed that the base was a smooth walled hemisphere, but though it was sunk along a joint, this had hardly any effect on the morphology. Ca. cal. 2 200 BC, these earlier workings had been worked again by opencasting and a combination of underground firesetting and very heavy hammering as well, that produce large amounts of mechanically broken debris. One chamber alone would have required the breaking of between 3 000 and 7 000 tons of rock. The low grade ore, which required fine (down to flour size) grinding using crushing and grinding tools was clearly a laborious task. This heavy procedure, and the small size of the deposits in the area were probably the cause of the end of the life of the mine as soon as alternative ore sources became available.

The deepest parts of the mine may relate to a later, perhaps Late Bronze Age exploitation, which economically was clearly unsuccessful; these parts are located within a pegmatite-filled fault zone in which the wall rock consists of a heavily shattered quartzite. Limonitic clay within a portion of the fault is soft enough to be excavated with a bone; once a free face was obtained, then the rock was often that much shattered that it was possible to break it down with one of the several stone mauls left there. However, it is clear from scattered fire remains that firesetting has been carried-out too. This was probably necessary to break up large resistant pieces of the quartzite rock or, possibly, to open up existing joints within it.

CONCLUSIONS

Rocks containing quartz is usually highly susceptible to firesetting; rocks with quantities of feldspars, micas, olivine, and a substantial number of other ferromagnesium minerals, are moderately affected. This covers the great variety of igneous rocks and many metamorphic ones which, otherwise, would be amongst the toughest to be tackled in mining.

It is clear, that disintegration of minerals or rocks by firesetting sets in at far lower temperature than might be imagined; some effects can be detected at temperatures just above ca. that of boiling water; substantial effects are observable for many rocks around 300 °C, and nearly all rocks are severely damaged by temperatures between 400 °C and 600 °C. These are temperatures which are readily attained in a wood fire, though higher temperatures would usually have even greater effect.

Firesetting has been in limited use since Neolithic times when hard host rock of flint nodules had to be broken. All over Europe, the Near, Middle and Far East, firesetting was common at least from the Early Bronze Age in mines of metal ores. It was widely used for copper and lead/silver/zinc mines. In the Anatolian limestone and the Central Asian mines in hard granite it was even more essential for tin. Miners have proved extremely versatile in devising ways of using firesetting to meet their specific problems. It has been possible to use it within very small and confined passages, as well as

72. WILLIES, 1991 ; YENER, 2000.

within very large scale mining works. It could be combined with mechanical methods of breaking rock, either with the predominance of firesetting, or using it only to tackle specific problems. It might also have beneficial effects in reducing the amount of energy required for comminution, in giving a better light, and possibly also in improving ventilation.

Firesetting is one element in the technological and economic environment in which mining takes place. In a very small mine, such as the workings at Mount Gabriel in Ireland described by O'Brien[73] or by Rieser[74] at Schwaz, the requirements were 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, possible on-site smelting, and distribution 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. In the mines at Veshnoveh/ Iran as in the mineral-bearing areas in desert Rajasthan, this might have been different, not only because of their distant situation in the mountains but also because of the amazing size of some of the workings.

Considerable problems occurred in larger mines, but there is rarely sufficient information available to understand prehistoric organisational framework. A major problem is to calculate the duration of exploitation. Were works done within a short time or as single workings over many years ? In the Roman or ancient Egyptian substantial mines the state played a considerable role. Were the mines at Kestel in Turkey worked and managed by the local inhabitants or were the miners recruited from distant areas ? Were the works there and in such areas as the Sinai desert seasonal or performed throughout the year ? Moreover, how did the enormous number of tin mines in Central Asia came to be worked by the nomadic Andronovo people ?

Gerd WEISGERBER
Deutsches Bergbau-Museum
Am Bergbaumuseum 28
D-44791 Bochum
Germany
weisgerber@lb.dmt.de

Lynn WILLIES
Peak District Mining Museum
Matlock Bath
Derbyshire. DE4 3NR
United Kingdom
lynnwillies@hotmail.com

73. O'BRIEN, 1994.
74. RIESER und SCHRATTENTHALER, 1998/1999.

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