Mineralization of England and Wales

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Chapter 4

South Pennine Orefield:

Cheshire, Leicestershire and Shropshire

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INTRODUCTION

The sites described in this chapter are geographically dispersed around the Midlands of England, and range in geological age from Precambrian to Triassic. They have in common a history of exploitation, as mines and quarries, which in some cases extends back many centuries. Alongside commercial activity, they have attracted the attention of scientists by virtue of their geological characteristics, which include the type locations for certain (rare) minerals, and the occurrence of hydrocarbons within mineralized rocks. Many of these locations have played a very significant role in the historical development of the Earth sciences, and whilst interest in them may now be dormant, they have achieved international exposure through their past contributions to our understanding of mineralizing processes. Although some of the locations no longer show features that were recorded in the past, the bibliography recorded here is guite substantial and allows them to be placed into context.

Four GCR sites in Leicestershire (see Figure 4.1) are related spatially to the Precambrian-Lower Palaeozoic basement rocks and their uncomformably overlying Triassic sediments. At the Newhurst Quarry GCR site, near Shepshed, the unconformity between granodiorites intruded into a Charnian hornfels and overlying Mercia Mudstone Group (Keuper) marls carries distinctive mineralization. High-temperature copper sulphides occur within veins within the basement granodiorite, whilst native copper and secondary copper-vanadium minerals occur within the basal Triassic or along fractures close to the unconformity. Similarly, the unconformity between basement and Triassic rocks is exposed at the Croft Quarry GCR site (an isolated inlier of dioritic rock, 10 km south-west of Leicester). Here, alteration of the diorite has led to the formation of a suite of zeolites including analcime, and unconformity-associated mineralization within the overlying Mercia Mudstone Group includes manganese minerals. At Warren Quarry, the unconformity was exposed in the past during quarrying, and this is the only British locality that shows formation of palygorskite (Mg₂Si₈Al₂O₂₀(OH)₆.4H₂O) during weathering in the Triassic. Granodiorite from basement rocks is exposed at the Castle Hill Quarry GCR site, at Mountsorrel near Loughborough, where it contains mineral veins carrying a hightemperature assemblage including molybdenite and topaz. Here, Carboniferous dolerite dykes carry bitumens in association with a lowtemperature hydrothermal suite of minerals, including dolomite. The spatial association of bitumens with igneous rocks at this location was used in the 1970s as evidence for an abiogenic origin for hydrocarbons, and so contributed significantly to debates concerning the origin of life and the possible development of life in extraterrestrial systems.

Farther from the unconformity, the Keuper sediments at **Gipsy Lane Brick Pit** (north-east of Leicester) contain uranium and vanadium minerals in association with bitumens, within gypsum.

Evidence of deep mantle systems is afforded by the occurrence at the Calton Hill GCR site near Buxton, in Derbyshire (see Figure 4.1) of Lower Carboniferous volcanic rocks that contain olivine nodules. These originated deep beneath the Earth's crust and represent the only known examples found in England. The Calton Hill volcano is believed to have produced the Miller's Dale volcanic rocks which provide a control on the distribution of mineralization in the Carboniferous sequence of the Peak District. At the Masson Hill Mines GCR site (south-west of Matlock), mineralization within the Carboniferous succession is clearly controlled by the distribution of the volcanic rocks and by dolomitization of the limestones. Here pipes and other, planar, replacement fluorite(-galena) orebodies occur within dolomitized limestone sandwiched between two volcanic horizons.

The South Pennine Orefield is important as an example of Mississippi Valley-type mineralization within the British Isles. One of the best examples of vein mineralization in this area is seen at the Dirtlow Rake and Pindale GCR site, located to the south of Castleton, in Derbyshire (see Figure 4.1), which is a major hydrothermal fissure-vein that can be traced for over 6 km in a general ENE-WSW direction. Between 3 m and 12 m in width, it carries fluorite and galena mineralization, and shows extensive silicification of the host limestones. This vein has played a major role in the development of our understanding of the mineralization processes that have taken place within the zoned orefield, in which high-temperature lead (galena)-fluorite veins are surrounded by lower-temperature



Figure 4.1 Map of the geological sites reported in this chapter showing simplified major geological boundaries and faults. 1 – Castle Hill Quarry; 2 – Croft Quarry; 3 – Newhurst Quarry; 4 – Warren Quarry; 5 – Gipsy Lane Brick Pit; 6 – Calton Hill; 7 – Masson Hill Mines; 8 – Dirtlow Rake and Pindale; 9 – Bage Mine; 10 – Fall Hill Quarry; 11 – Treak Cliff; 12 – Windy Knoll; 13 – Portway Gravel Pits; 14 – Kirkham's Silica Sandpits; 15 – Ecton Copper Mines; 16 – Alderley Edge District; 17 – Snailbeach Mine; 18 – Huglith Mine.

barite-bearing veins. On exposure of these mineral veins to the surface, secondary minerals form by weathering of primary sulphides; these commonly include sulphates and carbonates. The **Bage Mine** GCR site, at Cromford, near Matlock (Figure 4.1) contains a remarkable assemblage of secondary minerals, and is the type locality for the lead chloride minerals cromfordite (properly known as 'phosgenite': Pb₂CO₃Cl₂) and matlockite (PbFCl).

Importantly, the South Pennine Orefield is hosted by anticlinal features of which the largest is the Derbyshire Dome. Peripheral smaller anticlinal structures have created inliers of Carboniferous limestone surrounded by younger, clastic-dominated Carboniferous rocks. Although scales vary, the occurrence of hydrothermal mineralization at the crests of anticlinal structures is an important constraint on models of their genesis. In many cases, crestal mineralization is accompanied by hydrocarbons, leading to conceptual overlaps with models of petroleum migration into structural traps. The **Fall Hill Quarry** GCR site at Ashover (Figure 4.1) exposes part of the Ashover Anticline, which is an example of a microcosm of the Derbyshire mineralization story. Here, fluorite veins cutting limestone carry small amounts of sphalerite and nickel and cadmium sulphides, including millerite, greenockite and hawleyite. Hydrocarbons occur within the fluorite, suggesting a link with petroleum hosted farther to the east, in similar buried structures.

On a much larger scale, the 'crest' of the Derbyshire Dome contains fluorite mineralization, as seen at the **Treak Cliff** and **Windy Knoll** GCR sites (Figure 4.1). Treak Cliff is host to the unique deposits of Blue John fluorite that occur within a boulder bed at the contact between the Carboniferous limestone reef and overlapping

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Namurian mudstones. At Windy Knoll, at the crest of the reef structure, fluorite mineralization is accompanied by the occurrence of a variety of solid bitumens. As in the case of the **Croft Quarry** GCR site examples, the Windy Knoll bitumens have been used as evidence for abiological hydrocarbon formation by virtue of their spatial association with mineral deposits.

Geographically located on the summit of the Derbyshire Dome and close to Dirtlow Rake, the **Portway Gravel Pits** GCR site shows evidence of the collapse of a pipe structure with barite mineralization, and the later infill by Pleistocene sediments. Farther south in Derbyshire, the **Kirkham's Silica Sandpits** GCR site has a Pliocence–Pleistocene sedimentary fill, with the clay mineral metahalloysite $(Al_2Si_2O_5(OH)_4)$. Importantly, the Pliocene–Pleistocene fill at these locations provides evidence of uplift and erosion of the South Pennines and adjacent areas, by up to 450 m in 2 million years.

To the west of the Derbyshire Dome, a flanking anticlinal structure at the Ecton Copper Mines GCR site (Figure 4.1) introduces mineralization dominated by copper sulphides. Again, hydrocarbons are present. These deposits are unique in the United Kingdom, as they are the only copper deposits that were mined from within Carboniferous limestones. They occur on the flank of the Cheshire Basin, within which the Triassic sandstones contain a number of occurrences of copper mineralization. At the Alderley Edge District GCR site (Figure 4.1), copper mining has taken place over several centuries, recovering copper from an assemblage of secondary minerals (principally copper carbonates) associated with faulting within Triassic sandstones. These deposits also contain vanadium and cobalt minerals, and were the source of the material used by Roscoe (1876), who discovered vanadium. The geological relationships of the copper and associated barite mineralization at Alderley Edge are typical of those associated with clastic petroleum reservoirs.

The mineralization of the West Shropshire Orefield is represented by the **Snailbeach Mine** GCR site, which was the largest lead-zinc mine in the orefield, dating back to Roman times. The lead-zinc veins occur within Ordovician rocks, with a clear stratigraphical control. A further association between copper and barite mineralization is found at the **Huglith Mine** GCR site, near Habberley in Shropshire (Figure 4.1). Here vein mineralization occurs in basement (Neoproterozoic) quartzites. The characteristics of the vein mineralization suggest an origin from basinal brines, probably during early Carboniferous times.

The locations described in this chapter share a number of common features. With the exception of Calton Hill and Kirkham's Silica Sandpits, they all describe hydrothermal mineral deposits associated with geological boundaries between basement or host-rocks and unconformably overlying impermeable strata. Without exception, all locations have made significant contributions to geological knowledge during a long history of study, extending back to the early 1800s in some cases. The story they tell is one of migration of ore-bearing fluids into fractured rocks within which precipitation takes place, followed by uplift, erosion and modern exposure to the atmosphere which has generated suites of secondary minerals. The occurrence of bitumens in spatial association with igneous or hydrothermal rocks within many of the localities has been used in the past as evidence of an abiological origin for hydrocarbons, and comparisons have been made between these materials and organic matter from extraterrestrial sources, with a view to supporting models for the origin of life. However, as geochemical analysis has become more sophisticated, combined with improved understanding of petroleum migration and biodegradation, reexamination of hydrocarbons from these locations now favours a secondary, petroleumrelated origin. Thus the mineral deposits of the Midlands region form part of a much larger story of the evolution of sedimentary basins and how they interact with basement highs.

In this context, the individual descriptions that follow provide a view of the historical record of the geological investigations of each site. Each has been studied at different times with different geological paradigms in mind, and so individual descriptions vary greatly in the quality and quantity of work that is available. With these limitations in mind, the site reports provide an opportunity not only to focus on the individual merits of each site, but to consider more broadly the contribution that all of the sites, taken together, can make in the future to our understanding of the geological evolution of the Midlands region, and hence to similar geological environments elsewhere.

CASTLE HILL QUARRY (MOUNTSORREL GRANITE QUARRY), LEICESTERSHIRE (SK 577 148)

Introduction

Castle Hill Quarry occupies the exposed and north-eastern limits of the pluton of the Caledonian (Caradoc) 'Mountsorrel Complex' (Lowe, 1926; Meneisy and Miller, 1963; Le Bas, 1968, 1972), cropping out as part of the Midlands Microcraton, described in the *Caledonian Igneous Rocks of Great Britain* GCR volume (Stephenson *et al.*, 1999), and is closely related to the *Buddon Hill* GCR site, described in that volume. This GCR site is situated in the village of Mountsorrel, 7 km south-east of Loughborough, Leicestershire (see Figure 4.2). Early work at Mountsorrel (Hill and Bonney, 1878; Lowe, 1926; Taylor, 1934) showed that the principal rock-type, granodiorite, is increasingly hybridized in a westerly direction until gabbroic rocks occur at the contact with possibly Tremadocian hornfelsed sedimentary rocks. This area is adjacent to the Soar Valley Fault, which drops down the eastern limits of the igneous mass below the younger sedimentary rocks.

Miller and Podmore (1961), and Pidgeon and Aftalion (1978) established the age of the Mountsorrel Complex to correspond to the Caledonian Orogeny, forming as part of Ordovician subduction-related magmatism.

This site (see Figure 4.3) represents a fine example of granite-related high-temperature mineralization characterized by molybdenite,



Figure 4.2 Location map of the Castle Hill Quarry GCR site.



Figure 4.3 Outcrop at Castle Hill Quarry. (Photo: M.L. White.)

allanite and topaz, with later modification by dolomite, sulphides and recrystallized chlorites (King, 1959). Late-stage igneous rocks include swarms of aplite dykes and a rare pegmatitic facies. Hercynian tectonic movements in the complex have produced faults subsequently occupied by olivine-dolerite dykes. The latter carry a unique mineral assemblage characterized by asphaltite, dolomite-calcite and pyrite. This occurrence of fracture-bound asphaltite (bitumen) was described by Pering (1973).

It is believed that Castle Hill Quarry was worked for building materials by the Romans. Industrial quarrying has taken place at Mountsorrel since the late 18th century. The quarrying industry grew rapidly, having between 500 and 600 employees by 1870. During the industrial revolution, this area represented the nearest source of hard rock to London. Consequentially, Mountsorrel 'granite' can be found throughout many Roman sites and in the buildings of London. Quarrying ceased at Castle Hill Quarry in 1964. Tipping of waste has taken place at Castle Hill Quarry since the 1960s. Landfill operations have now ceased, preserving key aspects of the site as a Site of Special Scientific Interest (SSSI).

Description

The granodiorite at Mountsorrel is represented by a series of isolated outcrops, situated approximately 10 km north of Leicester (Miller and Podmore, 1961). These exposures are part of a large intrusive boss more than 1.5 km in diameter.

Many characteristics of granitic and granodioritic igneous rocks have been recorded at Castle Hill Quarry. Two varieties of coarsely crystalline granodioritic rock exist and are distinguished by their pink and grey feldspars (Miller and Podmore, 1961). Hill and Bonney (1878) first characterized the 'microscopic structure' of the 'red' and 'grey' varieties of the Mountsorrel Complex. They described the mineral assemblage to consist of: quartz, feldspar (mostly orthoclase with some plagioclase), biotite, hornblende (replaced by epidote) and magnetite, with minor amounts of apatite. They suggested that a section of the rock had been melted to form a distinct assemblage rather than co-formation of the two from separate magma types. Hill and Bonney (1878) reported a 20 cm-thick dyke of 'compact pinkishred felstone' or rhyolite, striking north-east and dipping at 60° to the eastern side, located to the west of the principal quarry at Mountsorrel.

In addition to the principal minerals listed above, accessory minerals present within the granodiorite at Castle Hill Quarry were observed by Taylor (1934) to include zircon, titanite, pyrrhotite, magnetite, illmenite and orthite (allanite). Taylor (1934) noted that zircon is 'abundant, varied and extremely interesting' in most of the Mountsorrel rocks. Other accessory minerals include chlorite and epidote, and also two 'pneumatolytic' accessory minerals, anatase and rutile (Taylor, 1934). Hydrothermal mineralization related to granitic processes ranges from a high-temperature suite of minerals, with molybdenite, topaz and allanite, to a mesothermal suite, characterized by dolomite, sulphides and epidote.

Tectonic movements in the complex have produced faults subsequently occupied by olivine-dolerite dykes. These dykes are host to a unique asphaltite hydrocarbon compound mixture, and a dolomite-calcite and pyrite mineral assemblage. The hydrocarbons occur particularly in calcite-dolomite veins, at the margin of cross-cutting dolerite dykes, and as vein-like masses within the dolerite (Parnell, 1988a). A similar association of hydrocarbons with mineralization is seen at the **Windy Knoll** GCR site, in Derbyshire.

Interpretation

The Mountsorrel Complex is older than the overlying Triassic sandstones, and is cross-cut by dolerite dykes of Carboniferous age. It is therefore pre-Carboniferous, while Miller and Podmore (1961) determined it to be younger than some of the Precambrian rocks of Charnwood Forest. Its age has been determined more accurately by Pidgeon and Aftalion (1978), who used U-Pb data collected from zircons to obtain a date for the Mountsorrel granodiorite and the surrounding plutons of 452 ± 5 Ma (Caradoc).

Taylor (1934) suggested that the granodiorite originated through the action of acid magma on basic rock (hybridization) rather than being a straightforward differentiate from a gabbroic magma. The abundant igneous inclusions in the granodiorite are generally acidic quartzmica-diorite. It is uncertain whether the material added to the initial acid magma was gabbro, diorite or a mixture or both. A general increase in basicity westwards has been determined, noted by an increase in the proportion of mafic minerals and the presence of xenocrysts (Sylvester-Bradley and Ford, 1968).

Changes in mineralogy during the latest stages of magma crystallization (deuteric mineralization effects) included varying degrees of sericitization, with reddening of the feldspars (especially orthoclase), decomposition of biotite, and minor epidotization. The reddening or 'pinking' of feldspar occurs in the form of dyke-like bodies which are often more than 300 m thick (Sylvester-Bradley and Ford, 1968).

Hercynian orogenic (Late Devonian– Carboniferous) tectonic movements induced faults within the complex. These were subsequently occupied by olivine-dolerite dykes. The source of the hydrocarbons within these dolerite dykes has been investigated by several researchers.

The simplest explanation for the origin of fracture-bound hydrocarbons is that they derived from Carboniferous rocks which once covered the pluton. King (1959), and Ford (1968) suggested that hydrocarbons migrated from the overlying Namurian shales during a stage of hydrothermal mineralization, and argued for an abiological origin. Other researchers (Sylvester-Bradley and King, 1963; Sylvester-Bradley, 1964; Ponnamperuma and Pering, 1966; Pering, 1973) suggested a biogenic source for the hydrocarbons. The carbon isotope ratio of the Mountsorrel hydrocarbons is similar to that of petroleum samples (Pering and Ponnamperuma, 1969). Morerecent GC-MS analyses of the alkane fraction and the pyrolysate of the asphaltene fraction have yielded abundant biomarkers (Xuemin et al., 1987). It seems clear that after some controversy during the early years of understanding the origin of hydrocarbons within igneous rocks, the Mountsorrel hydrocarbons originated from sedimentary petroleum and migrated into their present host.

Conclusions

Castle Hill Quarry is important historically for its contribution to studies of the origin of organic geological materials, and for its unusual high-temperature granodiorite-associated mineralization.

CROFT QUARRY, LEICESTERSHIRE (SP 510 964)

Introduction

Croft Quarry is one of Leicestershire's 'superquarries', generating over 2 million tons of aggregate per annum. This and the adjacent Huncote Quarry (currently not in use, see Figure 4.4 for location map) expose an outcrop of the 'South Leicestershire diorites' (Le Bas, 1968), which forms an arcuate shape trending roughly north-south to north-east-south-west. The rocks were emplaced on the margin of the Midland Microcraton, south-west of Leicester, described in the Caledonian Igneous Rocks of Great Britain GCR volume (Stephenson et al., 1999), and specifically in the Croft Hill GCR site report, which identified the Croft pluton as being tonalitic rather than dioritic in composition.

Hill and Bonney (1878), Harrison (1885), and Fox-Strangeways (1900, 1903) carried out much



Figure 4.4 Location map of Croft Quarry. After Le Bas (1968).

of the initial work on these intrusive rocks in the later quarter of the 19th century, and Eastwood *et al.* (1923) provided a summary of the geology of south Leicestershire. A more up-to-date review of the igneous rocks of the area is given by Worssam and Old (1988). Other local exposures of the South Leicestershire diorites crop out north-east of Croft and Huncote, at Enderby and Narborough, and to the south-west at Stoney Stanton and Sapcote, most of which are also quarry sites that were mapped by Bosworth (1912).

The age of the South Leicestershire diorites remained unconstrained for some time; their protrusion as monadnocks (like Croft Hill) through a covering of Triassic rocks (Le Bas, 1968) confirmed their age simply as pre-Triassic. Hill and Bonney (1878) compared slates found enclosed within the igneous rocks at nearby Enderby to the slates of Billa Barrow (part of the Brand Group of the Neoproterozoic III, Charnian Supergroup). Bonney (1895) later correlated the Enderby slates with those exposed at Brazil Wood into which the Caledonian rocks of Mountsorrel are intruded, suggesting that the South Leicestershire diorites were Precambrian. Harrison (1885), and later Lowe (in Bennett et al., 1928), and Butterley and Mitchell (1946) suggested that the slate was Cambrian and related to the Stockingford Shale Group of Nuneaton, implying that the south Leicestershire igneous rocks were Cambrian to early Ordovician. The tonalitic Croft pluton was suggested by Snowball (1952) to be post-Cambrian and Caledonian in age. This has been confirmed by Pidgeon and Aftalion (1978), who determined a radiometric age of 452 ± 5 Ma (Caradoc, corresponding to Ordovician Stage 5).

The tonalite is cut by E-W-trending and NE-SW-trending joint-systems that are reported to dip both to the north and south (Eastwood et al., 1923). Associated with the joint systems, alteration of the tonalites is evident; fresh unaltered grey surfaces are observed to grade into dirty-pink altered rock that shows varying degrees of decomposition, from early sercitization of feldspars to their entire kaolinization. Altered rock zones are also characterized by the replacement of mafic minerals with epidote. End stages of alteration of the rock are characterized by the formation of 'rammel' rock; this comprises completely disaggregated minerals (usually breakdown products and residual quartz and feldspar) and resembles coarse sand (Le Bas,

1968). By analogy with alteration of the Southwest England granites, the 'rammel' rock may originate through surface weathering (cf. Worssam and Old, 1988), prior to deposition of the overlying Triassic sequence. Some of the rammel units are up to 12 m thick, and in the past were used for footpath gravel. Vein structures are commonly recognized within the centre of the thicker rammel units; these are dominated by white analcime, which stains pink when in close proximity to hematite or other associated iron oxides. Other minerals of interest associated with the vein analcime include chabazite, quartz, rhombic calcite, chalcopyrite, galena, pyrite, fluorite, goethite, pyrolusite and quartz (and also laumontite at nearby Huncote) (Le Bas, 1968). Rarer members of this assemblage include prehnite, datolite, dolomite and molybdenite. The presence of molybdenite in close association with analcime in the vein system renders interpretation difficult, as molybdenite is thought to belong to a high-temperature environment, whereas analcime belongs to mesothermal and lower environments. It has been suggested that the partial substitution of sodium by potassium may stabilize analcime in a hydrothermal environment and may possibly be a reversion and an inversion process, with leucite as an end member (Le Bas, 1968).

Description

The rocks at Croft Quarry (and other nearby localities such as Huncote, Sapcote and Stoney Stanton in south Leicestershire) were classed incorrectly as syenites as part of the Charnwood Forest Group, and they are referred to as this on the Geological Survey of Great Britain one-inch sheets 155 (1932), and 156 (1903), respectively. Eastwood et al. (1923), however, observed that the rocks at Croft and the other sites showed a distinct mineralogical resemblance to basic marginal modifications of the nearby Mountsorrel granites. This likeness is apparent in the predominance of feldspars and their range in composition, in the dominance of hornblende rather than augite as the principal ferromagnesian minerals and the general absence of granophyric groundmass in the rocks at Croft, when these are characteristic of the 'Southern Syenites' of Charnwood Forest (Eastwood et al., 1923). Jones (1934), and Snowball (1952) also later suggested that the

South Leicestershire 'granites' were in fact diorites; Jones and Langley (1931) had stated that the rocks at Croft were probably the most siliceous members of the dioriteporphyries which protruded from the Triassic rocks in south Leicestershire. The classification of the rocks at Croft was later refined to hornblende-tonalite by Le Bas (1968), then to quartz diorite (Worssam and Old, 1988), and finally to tonalite by Carney and Pharaoh (in Stephenson *et al.*, 1999).

Fresh surfaces of the rocks at Croft are grey; plagioclase phenocrysts are evident (approximately 2 mm in diameter) and some show zoning throughout from andesine to oligoclase, with occasional albite at the grain margin (Le Bas, 1968). These rocks are notably more porphyritic than those to the south at Sapcote, which are part of the same intrusive complex (Eastwood et al., 1923). The groundmass comprises laths of more calcic plagioclase compared to the phenocrysts (Eastwood et al., 1923). Hornblende is also present as greenyellow and pale-brown crystals (approximately 1 mm in diameter) enclosing clear colourless augite in the fresh rocks at Croft Quarry. Hornblende comprises around 10% of the rock, and grains are pleochroic and occasionally twinned and euhedral (Le Bas, 1968). Biotite is also present in the Croft rocks, although in lesser quantities compared to the hornblende. Perthitic orthoclase mantling plagioclase is evident; perthite comprises up to 5% of the rock, and interstitial quartz is also common, forming between 15% and 20% of the rock volume. Opaque minerals, apatite and titanite, are present as the normal accessory minerals (Le Bas, 1968).

In the altered varieties of the tonalite the mafic minerals are chloritized, the feldspar shows signs of sericitization and kaolinization, and secondary epidote is abundant. Also present in the quarry exposure are pegmatites, consisting of large albite-oligoclase crystals which show albite twinning and which are slightly sericitized (Le Bas, 1968). Occasional inclusions of optically continuous quartz are evident in the rock, which has a granophyric texture. Large crystals of interstitial quartz are present, and intergrowths of quartz together with fine-grained orthoclase are found enclosing plagioclase. Epidote and apatite are present together with cavity-filled chlorite rosettes (Le Bas, 1968). Numerous small xenoliths of augite-

Croft Quarry

microdiorite occur in the tonalite at Croft Quarry. Most of the microdiorite (75%) comprises sericitized and zoned oligoclase, colourless augite, pale-green hornblende, opaque mineral grains and a little quartz (Le Bas, 1968).

The vein-style mineralization at Croft Quarry (see Figure 4.5) is controlled by joint sets. The joint-sets trend east-west and north-east-southwest, and are generally less regular than those exposed in the Sapcote quartz diorites to the south of Croft (Eastwood et al., 1923). A large single vein rises vertically from below the quarry floor level, splits into two and then fans out into a great number of thinner veins (Le Bas, 1968). These take the form of shallow arcs which pinch out laterally and appear to follow an irregular joint pattern. The altered country rock affected by the mineralization has been of economic importance in the past, and its characteristic dirty-pink staining contrasts with the unaltered 'clean' igneous rocks which are a bluish-grey colour. The degree of alteration of the country rocks appears to be controlled by the proximity and thickness of the veins carrying the mineralization (Le Bas, 1968).

The earliest description of the occurrence of zeolites at Croft Quarry is that of Jones and Langley (1931). Zeolites (chabazite) were first found in a widened joint-cavity (50 cm in length and 15 cm wide), and were initially mistaken for quartz or calcite crystals. The cavity appears to be some 25 m deep into the rock, and is associated with a low-angle red stringer beyond the cavity. Closer inspection of this cavity shows that analcime is the dominant infill (crystals have been measured at diameters of 1 cm) and appears colourless, milky-white and also orangeor red-tinged, due to iron oxide staining (Jones and Langley, 1931). The chabazite is opaque white and translucent on fracture surfaces, and appears as only small fragments (Jones and Langley, 1931).

Interpretation

Despite early dispute over the age of the granodiorites, the rocks at Croft and Huncote are believed to be Ordovician in age. The Triassic Mercia Mudstone Group (MMG) rocks (Le Bas, 1968) unconformably overlie the intrusive rocks, and consist of deep-red loams, sandy marls and 'skerry' sandstone beds that were deposited as a wadi infill. Pre-Triassic palaeovalleys are exposed in the faces of Croft Quarry into which the lowest MMG units dip (namely the skerry bands) at an angle conforming to the slope of the valley sides (Eastwood *et al.*, 1923). These units are truncated by the unconformity surface, consistent with deposi-



Figure 4.5 The Croft Quarry GCR site. (Photo: M.L. White.)

tion on an irregular eroded landscape. What appears to be the lowest unit of exposed MMG rocks is a grit-bed, which comprises angular fragments of the underlying granodiorite cemented by a calcareous material, with a breccia-like appearance (Eastwood et al., 1923). This unit varies in thickness and is probably the local basement-bed of the MMG (although without interstratified marl units this cannot be confirmed; Eastwood et al., 1923). The relations of the MMG rocks to the underlying igneous rocks at Croft Quarry are similar to those at Stoney Stanton (approximately 2 km south-west of Croft), which exhibits similar stratigraphical relationships. The development of a thick manganese-rich crust on the unconformity surface is consistent with a long-lived episode of desert varnish formation prior to deposition of the Mercia Mudstone Group.

Textural relationships indicate that the analcime crystallized before the chabazite (Jones and Langley, 1931). The igneous rocks at Croft Quarry are regarded as probably the most siliceous members of the South Leicestershire diorites; accordingly, the occurrence of analcime and chabazite is unexpected (Jones and Langley, 1931), as these minerals are normally associated with alkali (soda-rich) basic rocks (Jones and Langley, 1931) and their appearance in the calcalkaline rocks at Croft is therefore unusual.

Conclusions

Croft Quarry contains an Ordovician tonalite with an unusual occurrence of zeolites. The unconformity with the overlying Triassic sequence is marked by manganese mineralization. Alteration within the tonalite may be related to ancient surface weathering processes prior to the deposition of the Triassic Mercia Mudstone Group.

NEWHURST QUARRY, LEICESTERSHIRE (SK 486 180)

Introduction

Newhurst Quarry is located 1 km south-east of Shepshed in Leicestershire (see Figure 4.6). The northern part of the site comprises mineralized quarry faces and exposures of diorite. The mineralization includes quartz veins with



Figure 4.6 Location map of Newhurst Quarry.

carbonates (including pink dolomite) and sulphides (namely pyrite), which are both An unconformity between the abundant. Charnian Supergroup (Neoproterozoic III) and Triassic rocks is particularly well-exposed in the deep palaeowadi at the western end of the quarry. Rich copper mineralization can be found here; this takes the form of native copper with malachite and rare azurite (King and Ford, 1968). The copper mineralization commonly appears to be associated with dolomite and rhombic calcite. Newhurst Quarry is of particular geological significance as the first know occurrence of the vanadium mineral vésigniéite, Cu3Ba(VO4)2(OH)2. More recently, Ince (2005) has provided an extensive review of the mineralogy of Newhurst Quarry and described the presence of additional vanadate minerals, including mottramite and vanadinite, as well as the molydate mineral wulfenite. Ince (2005) also discredited the account of coulsonite from Newhurst Quarry.

Description

Mineralization in Newhurst Quarry (see Figure 4.7) tends to occur on the unconformity surface between the (Neoproterozoic III) Charnian Supergroup and the overlying Triassic mudstones, and within the basal beds of the Triassic sedimentary rocks up to 0.6 m from the unconformity surface, particularly in the breccias. Mineralization is characterized by copper carbonates, namely malachite and azurite. Copper sulphides are also present and occur at this locality predominantly as chalcocite veinlets



Figure 4.7 The Newhurst Quarry GCR site. (Photo: Midland Quarry Products.)

within the Charnian joint-system, immediately below the unconformity. The veinlets are commonly surrounded by oxidation products and associated with goethite.

Occasionally the chalcocite occurs as earthy deposits within geodes of dolomite crystals that are present in the basal beds of the Triassic sandstones (Sylvester-Bradley and Ford, 1968). This form of mineral development is well displayed at Newhurst Quarry, although nodular chalcocite can also be observed at the nearby western (No. 2) quarry of Redland Roadstone Ltd at Groby. The nodules are frequently surrounded by oxidation products and similarly associated with dolomite, calcite and goethite (Sylvester-Bradley and Ford, 1968). Other types of copper mineralization associated with the unconformity in the region and that can be observed at Newhurst Quarry, take the form of native copper, together with cuprite, azurite, and malachite. These occur as nodular masses within the basal beds of the Triassic sandstones and may be up to 20 cm in diameter, weighing up to 1 kg. Native copper commonly takes a thin, sheet-like form which occurs on joint surfaces, and at Newhurst Quarry one occurrence was estimated to measure

approximately 10 m by 15 m in area, on a surface immediately below the Triassic unconformity (Sylvester-Bradley and Ford, 1968).

Towards the north-eastern face of Newhurst Quarry a number of hypogene copper-rich quartz-carbonate veins have been exposed. These are confined to one of the three large NW-trending shear zones that are associated with late movements in the Long Cliff Reversed Fault System (Watts, 1947). The veins cut intrusive granophyric diorite (Snowball, 1952) and fine-grained hornfelsed volcanic tuffs of the Blackbrook Group, which is part of the Charnian Supergroup (Watts, 1947).

Primary copper minerals in the veins consist of an intimate association of bornite, chalcocite and chalcopyrite. Mineralogical zonation within individual veins is also apparent in the form of an upper bornite-chalcocite zone, giving way to a chalcopyrite zone below, with a lower zone of galena at the base, and with quartz and ferroan dolomite as gangue (King and Wilson, 1976). The upper portions of these veins (the bornitechalcocite association) show evidence of extensive supergene alteration, and a boxwork structure of oxidized copper salts and goethite with relic sulphides is commonly all that remains of the original bornite-chalcocite association.

In the cavities of the oxidized bornitechalcocite veins, tiny rosettes (up to 2.4 mm in diameter) of thin tabular crystals in sub-parallel orientation, yellowish-green in colour, of vésigniéite (Cu₃Ba(VO₄)₂(OH)₂) are found dispersed on the corroded surfaces. Maximum crystal plate width observed was 2.1 mm, and the crystal thicknesses were up to 0.4 mm (King and Wilson, 1976). Ince (2005) described an extensive supergene mineral assemblage occurring in vertically orientated oxidized sphalerite-chalcopyrite-galena veins located 5-10 m below the Neoproterozoic-Triassic unconformity, containing the vanadate minerals mottramite and vanadinite, and the molybdate mineral wulfenite.

Interpretation

exceptional mineralization the The in Charnwood Forest area may be a result of limited chemical activity associated with the Charnian Supergroup (Neoproterozoic)-Triassic unconformity (Sylvester-Bradley and Ford, 1968). The Charnwood Forest rocks appear to have been less susceptible to chemical reaction with percolating mineral solutions than the Carboniferous strata that underlies the mineralized Permo-Triassic unconformity in the Nuneaton area, which is also associated with copper mineralization (Sylvester-Bradley and Ford, 1968). This is because mineralizing fluids descending below the unconformity into the Charnian sequence appear to have been restricted to vein-like bodies which occupy joint planes, and no major wall-rock alteration has occurred.

The supergene alteration/modification may have occurred during late Triassic times, as the veins have been planed off below a visible thickness of 7.2 m of unconformably overlying sandstones and mudstones of the Mercia Mudstone Group (Warrington, 1970). There is also evidence of recycling and reprecipitation of copper salts at the unconformity and below it in the form of mineralized pipe-like bodies, within the underlying igneous and metavolcanic rocks, filled with Charnian and Triassic debris (King and Wilson, 1976).

King and Wilson (1976) suggested that the overlying sedimentary rocks of the Tarporley Siltstone Formation of the Mercia Mudstone Group are the likely source of both barium and vanadium; barite is present as cement in certain sandstone units, while dispersions of wad (manganese oxides/hydroxides) carrying traces of vanadium frequently coat the upper surfaces of mudstone units in the same formation. High concentrations of wad also occur below the unconformity in the pipe-like bodies.

A similar vanadium-rich cuprite deposit is located in Triassic sedimentary rocks at Bardon Hill, 5.5 km to the south-west of Newhurst Quarry (King, 1967).

Conclusions

The mineralization at Newhurst Quarry is an excellent example of supergene alteration of copper sulphide minerals, and hosts an assemblage containg the rare vanadate minerals vésigniéite, mottramite and vanadinite, and the molybdate mineral wulfenite.

WARREN QUARRY, LEICESTERSHIRE (SK 542 001)

Introduction

Also known as 'Warren Hill Quarry' and 'Enderby Stone Quarry', Warren Quarry worked a Caledonian hornblende tonalite within the Charnwood Forest inlier of Lower Palaeozoic and Precambrian rocks (Sylvester-Bradley and Ford, 1968). The hornblende tonalite is overlain by Triassic rocks of the Mercia Mudstone Group, forming a wadi complex that historically was well exposed in the eastern faces of the quarry. The location is unique because of the occurrence of the clay mineral palygorskite (also known as 'attapulgite') in association with the Triassic unconformity (Evans and King, 1962; Tien, 1973; Pearson and Jeffrey, 1997; Jeans, 2006). At the time of writing (2008), the quarry (Figure 4.8) hosts a landfill site and associated waste handling facilities.

Description

The hornblende tonalite is composed of up to 60% plagioclase, occurring as phenocrysts (2 mm) and groundmass, with 10% hornblende, 5% orthoclase and 15–20% quartz; accessory minerals include iron oxides, apatite and titanite (Le Bas, 1968).



Figure 4.8 The face at the Warren Quarry GCR site, showing the weathered surface of the tonalite. (Photo: J. Aumônier.)

The hydrothermal alteration of the tonalite at Warren Quarry involves the formation of a number of secondary minerals, including analcime, clearly associated with veining (King and Ford, 1968; Pearson and Jeffrey, 1997). Early alteration includes the sericitization and kaolinization of the feldspars, chloritization of mafic minerals, and the formation of secondary epidote. As alteration progressed, layers known as 'rammel' were formed. These are composed of the breakdown products described above, with residual quartz and feldspar. At the centre of the rammel 'beds' veins occur, dominated by the presence of the zeolite analcime, with quartz and calcite.

The tonalite at Warren Quarry represents the bedrock exposed during late Triassic times, when desert conditions prevailed. A number of wadi systems were formed in the Charnwood Forest area, and one of these is located at Warren Quarry (although not currently exposed). According to King and Ford (1968), the mineral palygorskite typically occurs within the Mercia Mudstone Group, and at Warren Quarry it occurs up to 36 m below the base of the wadi, as well as in the overlying mudstones itself. Within the tonalite itself, palygorskite occurs on joint faces, where it sometimes occurred as 'mountain leather', a parchment-like habit (Evans and King, 1962; Tien, 1973).

Palygorskite (otherwise known as 'attapulgite') is a fibrous clay mineral that is highly absorbent. Tien (1973) gave a detailed description of palygorskite from Warren Quarry, including beautiful transmission electron microscope images. The palygorskite fibres resemble those of a coarse textured paper, up to 10 mm long in some cases. Occurring in bundles, individual fibres are up to 0.1 mm across. Tien (1973) reported that the palygorskite is close to the magnesium end member composition Mg₂Si₈Al₂O₂₀(OH)₆.4H₂O.

Interpretation

The origin of the palygorskite is undoubtedly related to the unconformity and to weathering that took place under desert conditions in late Triassic times (Pearson and Jeffrey, 1997). Wright and Sadler (1994) draw parallels with modern examples in Australian inland drainage basins, where alkaline (pH 8–10) groundwater discharges into shallow playalakes with strong evaporation. In these circumstances, carbonate minerals and palygorskite both precipitate. Although the details of the late Triassic palaeogeography at Warren Quarry are unknown, the principle that the present is the key to the past suggests that it shared many characteristics with parts of present-day Australia.

Conclusions

Warren Quarry demonstrates the complexities of geological processes that take place at unconformities, where a combination of hydrological, hydrogeological and lithological factors influence the mineralogical composition of the rocks at the location. It provides evidence of specific weathering conditions during late Triassic times, when the climate was hot and semi-arid.

GIPSY (GYPSY) LANE BRICK PIT, LEICESTERSHIRE (SK 619 071)

Introduction

Gipsy Lane Brick Pit (see Figure 4.9) is located north-east of Leicester, in the Rushey Mead district. Works at the site have focused on quarrying the calcareous mudstones of the Mercia Mudstone Group for clay extraction (Faithfull and Hubbard, 1988). Brick and tile manufacture has dominated the works at this site and other local quarries for many years, with production peaking during the turn of the last century (Fox-Strangeways, 1903). Faithfull and Hubbard (1988) reported the pit was still being worked at the time of their study at the site. Gypsum has also been quarried from Gipsy Lane



Figure 4.9 Location map of Gipsy Lane Brick Pit.

predominantly for use in plaster and construction materials, and gypsum beds and nodules are well exposed at this site. The site is of particular interest to mineralogists as it exposes an upper stratigraphical section of the Mercia Mudstone Group containing carbonate, evaporite, sulphide and silicate minerals (King, 1967), and also the basal shale beds of the Westbury Formation (Warrington et al., 1980). At least three iron-rich gypsum beds interbedded with the marls are exposed (Faithfull and Hubbard, 1988). Sections of these beds have been stockpiled, as they are of little commercial value due to the extensive oxidation of sulphide minerals which has resulted in iron-staining. Secondary copper carbonates (malachite and occasionally azurite) are also present. Siltstone and sandstone lenses within the calcareous mudstones are commonly dolomite-rich (Faithfull and Hubbard, 1988), and show striking halite pseudomorphs within them. Faithfull and Hubbard (1988) provided evidence for the existence of the uranium silicate coffinite exposed during opencast mining works at the site, and this is detailed in their comprehensive study. Other rare or unusual minerals observed at the site include celestine, erythrite, lavendulan and djurleite (Faithfull and Hubbard, 1988).

Description

Gipsy Lane Brick Pit (see Figure 4.10) exposes lower and upper sections of the Upper Triassic Mercia Mudstone Group (previously known as the 'Keuper Marl'). The lower exposed beds of the Mercia Mudstone Group comprise brown gypsiferous mudstones (Bosworth, 1912) of the Glen Parva Formation (Warrington et al., 1980), interbedded with thin lenses or irregular masses of dolomitized sandstone and siltstone towards the top of the unit. Celestine has been found in one such dolomite-rich siltstone layer within the mudstones towards the top of the unit, in the form of coarsely crystalline pink masses (Faithfull and Hubbard, 1988). Sedimentary structures within the siltstone and sandstone lenses are common and include currentbedding structures such as ripple marks and halite pseudomorphs. Conformably overlying the gypsiferous mudstones are marls of the Blue Anchor Formation (formerly known as the 'Tea Green and Grey Marls'), which is the highest stratigraphical unit of the Mercia Mudstone Group and which is gypsum-free. Sulphides



Figure 4.10 Gipsy Lane Brick Pit. (Photo: M.L.White.)

such as pyrite and galena are common in these beds and especially when associated with the abundant sandstone and siltstone lenses ('skerry bands'). An erosive base and abrupt change in colour and lithology marks the unconformable boundary between the Mercia Mudstone Group units and the thinly bedded black shales of the Westbury Formation, which is the basal unit of the Penarth Group. An intermittent sandy fish bone bed marks the base of the Westbury Formation.

At least three substantial gypsum beds are exposed (approximately 0.2-1 m in thickness). The gypsum is nodular and forms irregular upper and lower contacts with the marl. Green staining can be observed on the upper surfaces of exposed gypsum beds within the pit, which is attributed to the presence of the copper carbonate mineral malachite (Faithfull and Hubbard, 1988). Bornite and djurleite ($Cu_{31}S_{16}$) have also been observed as metallic lustrous films overlying the upper surfaces of gypsum beds (Anon, 1973), although these have not been observed in subsequent studies. The principal gypsum beds show considerable lateral continuity where exposed; however thinner discontinuous beds of nodular gypsum are present elsewhere at the locality (Faithfull and Hubbard, 1988).

The gypsum beds contain small sub-spherical black masses, up to 8 mm in diameter, particularly in the upper gypsum beds. These sub-spheroids can be observed in a variety of environments, namely: (a) on the top surfaces of beds; (b) in green-stained clay films within nodular gypsum (sometimes partially enclosed in gypsum); (c) enclosed entirely within massive gypsum in the outer sections of nodules; and (d) occasionally in green-stained clay proximal (several millimetres) to gypsum nodules (Faithfull and Hubbard, 1988). Commonly malachite, erythrite and occasionally lavendulan (NaCaCu₅(AsO₄)₄Cl.5H₂O), form encrustations around, or associations with, the sub-spheroids, while a rare deep-blue efflorescence may be due to the presence of azurite (Faithfull and Hubbard, 1988), although only one of these minerals is usually observed on any one spheroid.

In the Blue Anchor Formation, sulphides are present and include pyrite in the form of aggregates of cubes dispersed among the greycoloured mudstones, and galena in association with small plates of barite in the skerry bands. Black vanadium-rich spots also occur scattered sporadically throughout the marl, but never associated with, and having a different appearance and mode of occurrence to, the black spheroids in the gypsum beds. The spots are up to 1 cm in diameter, with diffuse outer boundaries encircled with green reduction zones; these are the result of ferric iron (contained in the marl) reduction by the organic-rich vanadium deposits (Faithfull and Hubbard, 1988).

Interpretation

The black sub-spherical masses in the gypsum were first identified as djurleite (Cu31S16) and later as chernovite (YAsO₄) (Embrey, 1978) on the basis of X-ray diffraction (XRD) and chemical analysis using spectrographic methods. However, following further XRD and energy dispersive analysis, the likely constituent of the spheroids was identified as being similar to the mineral coffinite $(U(SiO_4)_{1-x}(OH)_{4x})$ (Faithfull and Hubbard, 1988). This conclusion was backed up by X-ray fluorescence analysis. Yttrium forms a minor component of the coffinite, and also detected during analysis were lead and/or sulphur, and aluminium as minor constituents. The spheroids are only moderately radioactive which implies that they are not pure coffinite, and based on the results of combustion experiments and polished thin-section analysis it seems likely that the coffinite is homogeneously dispersed on a fine-scale within an organic matrix. Three other mineral phases which constitute the spheroids have not been conclusively identified, but include a grey copper sulphide, a pink nickel arsenide and a grey/white cobalt-nickel-copperarsenide-sulphide, which may constitute up to 50% volume. The enclosure of the coffinite and arsenide spheroids within massive nodular gypsum suggests that the spheroids are an early The gypsum is thought to have feature. precipitated in the sediment interstices in interand supra-tidal sabkha flats around the Triassic shoreline. If diagenetic oxidation was occurring simultaneously with gypsum formation, it is possible that organic material present (e.g. disaggregated algal mats) would scavenge elements such as U, Co, Ni, Cu and As prior to envelopment by the growing gypsum nodules.

Other occurrences of coffinite together with Cu-Co-Ni-As mineralization have been reported from the Triassic at Budleigh Salterton in Devon (Harrison, 1975). Pb-Cu-Co-Ni-As-V mineralization without uranium is recognized in the Triassic sandstones at the **Alderley Edge District** GCR site in Cheshire (Ixer and Vaughan, 1982).

Conclusions

The Triassic succession exposed at Gipsy Lane contains a suite of uranium and vanadium minerals associated with organic matter within gypsum. It demonstrates an unusual association of elements that reflect specific circumstances at the time of origin, in which U, V and other elements entered an evaporitic environment, were scavenged by organic matter and subsequently preserved within gypsum.

CALTON HILL, DERBYSHIRE (SK 119 715)

Introduction

The Lower Carboniferous volcanic complex at Calton Hill, Derbyshire (see Figure 4.11), provides exposures of fresh basanitic rocks containing relatively abundant nodules of spinel-bearing lherzolite and harzburgite, more generally termed 'olivine nodules'. Derbyshire Stone Ltd and Tarmac Roadstone Holdings formerly quarried this site, 5 km south-east of Buxton, before it became a landfill site. Part of this quarry site is preserved as a SSSI and is also described in the *Carboniferous and Permian Igneous Rocks of Great Britain* GCR volume (Stephenson *et al.*, 2003).

Calton Hill is the location of a 330-340 Ma volcanic vent (Piper et al., 1991) associated



Figure 4.11 Location map of Calton Hill Quarry.

spatially with the younger Upper Miller's Dale Lava Member (belonging to the Monsal Dale Limestone Formation of Brigantian age) and the Lower Miller's Dale Lava Member (Walters and Ineson, 1981; MacDonald et al., 1984; Waters in Stephenson et al., 2003). Although much of the vent has been quarried, critical geological features including examples of the spinel-bearing lherzolite and harzburgite nodules have been preserved. These originated from the Earth's upper mantle, from depths of 45-48 km according to Donaldson (1978), and represent the only known examples of mantle-derived nodules found in England. Investigation of the site is of interest historically, as it has attracted the attention of investigators who have contributed significantly to the study of Carboniferous igneous activity in Great Britain.

Description

The Calton Hill basanites (see Figure 4.12) are heterogeneous, and descriptions from reports dating back over 100 years reflect the availability of material at the time of investigation. Detailed summary descriptions are given by Aitkenhead *et al.* (1985), and geochemical data have been published by Donaldson (1978), and MacDonald *et al.* (1984). Waters (in Stephenson *et al.*, 2003) summarized the igneous mineralogy and mineral chemistry of the ultamafic lavas and host lava.

First described by Arnold-Bemrose (1894, 1910), the basanite is grey-black, fine-grained and vesicular in texture, with a blocky appearance, and appears to be largely unaltered, although chloritic alteration has been recorded by Sarjeant (1967). It was believed originally to have erupted from a small vent, now exposed as a highly altered and brecciated rock (Donaldson, 1978; MacDonald *et al.*, 1984), although an intrusive origin as a sill has been proposed by Aitkenhead *et al.* (1985).

The ultramafic nodules (0.2–4 cm in diameter) are restricted to the southern side of the basanite intrusion. Hamad (1963) described the nodules as randomly distributed and oval-rounded in form, while Donaldson (1978) reported them to be elongate, tabular in form and angular in section. The nodules have a sharp boundary with the basanite host. In thin-section, enstatite, diopside and spinel have been identified, as well as olivine, together with secondary dark-green chlorite and pinkish-white analcime.

In the host basanite, Hamad (1963) described the presence of augite phenocrysts (bordering olivine crystals) embedded in a groundmass of



Figure 4.12 The exposure at the Calton Hill GCR site. (Photo: C. Hughes.)

labradoritic feldspar laths, and crystalline aggregates of idiomorphic augite, magnetite, analcime and calcite, along with traces of limonite. Chlorite occurs as fibrous spherulites (Tomkeieff, 1926; Sarjeant, 1967). Augite is associated with large analcime grains, which occur as spherules and as irregular greyish turbid patches (Hamad, 1963). The outer sections of the analcime grains are bordered by microlites of feldspar and augite. Vesicles within the basalt are also filled with sparry calcite that is also observed in cross-cutting veins, whilst more recently Dyer *et al.* (2001) reported the presence of natrolite as fibrous, radiating crystalline masses filling vesicles up to 10 mm across.

Prismatic jointing is well developed in the centre of the quarry, with more irregular sheetjoints at the margins of the vent. Above these sheet joints, the rock is present as broken 'rubble', suggesting formation by explosive eruption.

Interpretation

Arnold-Bemrose (1910) concluded that the ultramafic nodules were segregations from the host magma rather than enclosures of older rocks. Tomkeieff (1928) studied the volcanic complex as a whole, and suggested that two types of augite exist within the nodules (a normal and a hydrous type) that are possibly members of a continuous series of pyroxenes. The Mg-rich, angular nature of the nodules suggested that they are fragments of a pre-existing peridotite formed under plutonic conditions (Tomkeieff, 1928). The relatively large size of individual mineral grains and the high chromium content of the spinels and clinopyroxenes imply that they did not derive from a basaltic magma. The nodule structure indicates they have been subjected to orogenic stress implying a 'deep-seated peridotite source' for the fragments (Hamad, 1963). Some of the olivine crystals are surrounded by orthopyroxene grains and have convex borders towards them, suggesting that olivine was the first mineral to crystallize. Interstitial finegrained aggregates of clinopyroxene along the margins of the olivines are thought to have developed from magmatic reaction.

Although direct genetic links between the Calton Hill complex and spatially associated volcanic rocks are not clear, it is believed that volcanic activity in Derbyshire included both submarine and subaerial extrusion (Aitkenhead *et al.*, 1985).

After emplacement, the basanites and lapilli tuffs experienced hydrothermal alteration. The first phase of this resulted in the infilling of the vesicles with calcite, analcime, natrolite and chlorite. Subsequent hydrothermal activity resulted in highly siliceous fluids in the centre of the complex. In the centre of the intrusion occur veins, some 20 cm wide, containing hematite within quartz crystals.

Donaldson (1978) investigated the 'suite of protogranular to porphyroclastic-textured spinels' found at this site, and outlined the petrogenetic history of the lherzolites and harzburgites, based on compositional data. The results indicated the nodules were 'accidental' xenoliths derived from a source at a depth of 45 km, at a temperature of 950°C. Their petrogenetic history involved: (1) formation as residues; (2) admixing with pyroxenite; (3) a complex series of metamorphic cycles of mineral reaction and exsolution, deformation, recrystallization and annealing; and (4) incorporation into the basanite.

Conclusions

The Lower Carboniferous volcanic complex at Calton Hill, Derbyshire, represents a site of international importance, providing exposures of fresh basanitic rocks containing relatively abundant ultramafic nodules, derived from the Earth's mantle. These spinel-bearing lherzolites and harzburgites represent the only known examples of mantle-derived rocks found in England.

MASSON HILL MINES, DERBYSHIRE (SK 290 587)

Introduction

The mines and caverns at the Masson Hill Mines GCR site (see Figure 4.13), belonging to the South Pennine Orefield, are located around a complex anticline structure (over 2 km in length), which comprises interlayered limestones (part of which are dolomitized) and basaltic lava sheets ('toadstone'), folded over a volcanic vent (Ford, 2002). The majority of the mineralization is in the Monsal Dale Limestone Formation and in particular, in the lowest limestones of this group (formerly the 'Lower Matlock Limestone'), although there is a limited



Masson Hill Mines

Figure 4.13 Location and geological map of the Masson Hill Mines and surrounding area.

amount of mineralization in the overlying Eyam Limestone Formation (formerly 'Cawdor Limestone'). Two main lava-flows, the Lower Matlock Lava Member and the Upper Matlock Lava Member (also of the Monsal Dale Limestone Formation), extended from the volcanic vent, and these can be seen in the entrance passage to Rutland Cavern (Ford, 2002). The mineralization takes the form of rakes, pipes, flats and scrins (Warriner *et al.*, 1981), and contains fluorite, barite, calcite, bravoite, pyrite,

marcasite, chalcopyrite, sphalerite and galena (Ixer, 1974). Mining for lead has taken place at Masson Hill since Roman times, and has largely focused on working a series of pipe-veins along an east–west axis across the summit of Masson Hill, within the 'Lower Matlock Limestone' (Ford, 1967a). Significant fluorite flats have been worked both underground on the east slope of Masson Hill, and in large opencuts on the summit of Masson Hill. The fluorite body lies in the basal 'Lower Matlock Limestone' immediately above the Lower Matlock Lava Member (Lower Toadstone unit) (Sylvester-Bradley and Ford, 1968; Ixer, 1978b), and trends north-westsouth-east along the strike of the limestone (Ford, 1967a).

Description

Ford (2001) reviewed the mines of the Matlock area, including Masson Hill, placing them into an overall context and providing many photographs of underground and surface workings. The geological sequence related to the mineralization at Masson Hill consists of the Lower Matlock Lava Member (78 m), intervening Monsal Dale Limestone (36 m) the Upper Matlock Lava Member (21.5 m), the upper part of the Monsal Dale Limestone, and the Eyam Limestone Formation (formerly 'Cawdor Limestone') (Ixer, 1975, 1978b; Warriner et al., 1981). The mineralization is restricted to two horizons, the Monsal Dale Limestone between the two lava horizons and the Eyam Limestone Formation, with the former being the most significant (Warriner et al., 1981). The Monsal Dale Limestone contains four 'wayboards' (volcanic clay horizons or bentonites) up to 0.3 m thick; between wayboards 1 and 2 in the southern area of the Masson Hill Flat lies the Little Toadstone (0.80 m), which is also a volcanic clay horizon. Dolomitization is sporadic throughout the limestone and decreases towards the north-west where it is absent (Ixer, 1978b). In the opencast quarry and along the 'main rake' dolomitization is extensive, and only the basal 5.5 m of the Monsal Dale Limestone, lying above the Lower Matlock Lava Member, remains undolomitized. The boundary between the limestone and dolomite coincides with the Little Toadstone in the southern area of the Masson Hill Mine flats and at the equivalent stratigraphical level in the opencast quarry (Ixer, 1978b).

The limestones of the Monsal Dale Limestone Formation vary from fine-grained and porcellanous to coarse-grained and bioclastic. Jointing is poor in the limestone in relation to the overlying dolomites. The junction between the limestone and the dolomite is very sharp, with the change from pure limestone to pure dolomite typically occurring within 15 mm (Ixer, 1978b). This sharp change is also observed immediately above wayboards 2–4, where the amount of dolomitization is substantially reduced in a zone of up to 0.5 m away from them. The Lower Matlock Lava Member is a darkgreen calcitized, chloritized, amygdaloidal olivine-basalt, the top portion (0.5 m) of which has been weathered to a grey clay with red or brown streaks and mottling (Ixer, 1975; Warriner *et al.*, 1981). X-ray diffraction analysis has shown the clay to be a mixture of kaolinite, mixed illite-montmorillonite and mixed chloritemontmorillonite (Ixer, 1975).

Ixer (1975) provided a detailed examination of the sedimentary and volcanic rock succession of the Masson Hill ore deposit area. Bedding dips at between 20° and 25° towards the northeast, and with the angle of slope greater than this dip the youngest units are exposed to the east, at the bottom of Masson Hill (Ford, 1967a). The main Masson Hill Fault Zone trends northwest-south-east, and the faults are downthrown to the south-west with typical throws of less than 10 m. These faults are filled with clay-gouge, probably sourced from the altered basalts and wayboards, which has made them effectively impermeable barriers (Ixer, 1978b). Both the mineralized and the barren joints occur as a conjugate set, trending north-west-south-east and north-east-south-west. The master joints (314°) trend parallel to the main Masson Hill Fault Zone, with the subordinate joints trending 049°.

The orebody consists of a series of intermittent flats and pipes along a 2 km transect parallel to the Masson Hill Fault. The largest pipe is in Masson opencast quarry (largely extracted), which is 500 m long, and 240 m wide. The main orebody is in the basal 6 m of undolomitized limestone of the Monsal Dale Limestone Formation (Ixer, 1978b), where extensive flats have developed. The flats possibly represent the metasomatic alteration of limestone during mineralization, and the infilling of palaeokarstic channels and cavities (Ford and Worley, 1977; Ixer, 1978b). The bulk mineralogy of the main ore was determined by Ixer (1978b) and consists of 60% fluorite, 20% quartz, 15% calcite, and less than 5% barite. The main sulphide minerals present are bravoite, pyrite, marcasite, chalcopyrite, sphalerite and galena. There is also a wide range of secondary ore minerals in the oxidation zone of the deposit, including smithsonite, rosasite, hemimorphite, cerussite and cinnabar (Ford, 1967a). A detailed description of mineralogy and paragenesis of the fluorite flat at Masson Hill is provided in Ixer (1974).

Masson Hill Mines

Post-mineralization karstification at Masson Hill occurred by solutional enlargement of voids left by the hydrothermal fluids, and these then acted as pathways for groundwater movement. This phase is thought to have initiated during late Tertiary or early Pleistocene times when incision of the Derwent Gorge commenced and the necessary hydraulic gradients became established (Ford and Worley, 1977). Some of these solution features were infilled with sediments of both surface inwashed glacial clays and sands, and also galena and fluorite from the orebodies. Noel et al. (1984) measured the palaeomagnetism of the glacial sediments in Old Jant Mine, at Masson Hill and determined that the earliest sediments may date from the Brunhes/Matuyama reversal event of 730 000 years ago.

Interpretation

The fluorite mineralization at Masson Hill represents the eastern extent of a pyritic-fluoritic zone that characterizes the south-eastern region of the South Pennine Orefield (Sylvester-Bradley and Ford, 1968). The mineralization is largely hosted within the Monsal Dale Limestone Formation of Lower Carboniferous age. The location and extent of the ore deposit is controlled by the distribution of replaceable limestone, dolomites, basaltic lavas and ash bands ('wayboards') which controlled the lateral movement of the ore fluids, whilst the faulting and jointing controlled vertical migrations (Ixer, 1978b). The major orebodies are in the coarse-grained limestone at the base of the Monsal Dale Limestone Formation, where the mineralizing fluids were trapped above the thick, impermeable, Lower Matlock Lava Member, and below the 'Little Toadstone' wayboard. The clay-sealed faults of the Masson Hill Fault Zone prevented the mineralizing fluids from migrating further up-dip. The mineralization of the dolomites is largely in the form of porosity infilling, reflecting the increased porosity resulting from the dolomitization. The ore was probably emplaced as a result of both metasomatic replacement and infilling of premineralization karstic solution features (Ixer, 1978b). The mode of occurrence and the mineralogy is consistent with a low-temperature hydrothermal origin. The texture is consistent with a single long-term primary mineralization followed by extensive oxidation by meteoric waters (Ixer, 1974).

As most of the boundaries between the limestone and dolomites are parallel or subparallel to the bedding, it is likely that the intensity of the dolomitization reflects the primary texture or chemistry of the original limestone beds (Ixer, 1978b). The cause of the dolomitization has been speculated as being derived from the downward circulation of brines associated with the Permian Zechstein Sea (Ford, 1967a). However, Weaver (1974) suggested that the jointing is related to late Carboniferous, Variscan ground movements, and as the jointing varies between the limestones and dolomites, Ixer (1978b) deduced that the dolomitization must pre-date the jointing and therefore be of Carboniferous age.

Ixer (1978b) proposed a five-stage sequence for the formation of the Masson Hill mineral deposits, namely:

- 1. Deposition of coarse-grained limestone and intermittent volcanic ash bands and emplacement of two main lava-flows.
- 2. Groundwater circulation producing cavities by dissolution of limestone adjacent to limestone–volcanic rock junctions.
- 3. Dolomitization of coarse-grained limestone by magnesium-rich fluids following established bedding and lithological horizons. Dolomitization controlled by the grain-size and chemistry of the limestones and by proximity to the volcanic rocks. The volume change during dolomitization increased porosity.
- 4. Formation of the Matlock Anticline and Masson Hill Fault Zone during the Variscan Orogeny, leading to the north-easterly dip of the limestone/lava sequence. Establishment of good vertical pathways within the welljointed dolomites and the loss of dolomite/ clay wayboard junctions as effective horizontal barriers/pathways.
- 5. Ingress of silica-rich fluids following all the vertical and horizontal pathways, locally silicifying limestone and dolomite.

Hot, dense, mineralizing fluids moved up the Masson Anticline until they reached the clayfilled Masson Hill Fault Zone. The fluids followed established pathways. Metasomatic mineralization occurred when calcite was passed (particularly at limestone/dolomite junctions), or where fluids ponded. Void development also took place, with a greater amount in the more porous and jointed dolomite.

Conclusions

The Masson Hill mineralization is a good example of a Mississippi Valley-type deposit hosted in a mixed limestone/dolomite sequence with interbedded and bounding basalt and volcanic ash horizons. The mineralization in the limestone is mostly in the form of flats, which probably formed by a combination of metasomatic replacement by the mineral fluids and infilling of palaeokarstic features. The mineralization of the dolomite is mostly in the form of infilling of the secondary porosity associated with the dolomitization.

DIRTLOW RAKE AND PINDALE, DERBYSHIRE (SK 152 818)

Introduction

The Dirtlow Rake and Pindale area, south of Castleton in Derbyshire (see Figure 4.14), is a GCR site for the well-exposed range of mineralization features found there. Included in the site are the Dirtlow Rake itself, which is a major fissure-vein complex; the Pindale limestone quarry, which contains a transition from limestone to metasomatic quartz rock; and the Dirtlow Rake fluorite-barite orebody, which is hosted in limestone breccia.

Dirtlow Rake is one of the major hydrothermal fissure-veins of the South Pennine Orefield, and can be traced for over 6 km in a general ENE-WSW direction. It varies considerably in width (between 3 m and 12 m) and mineral composition. Old workings can be found over a distance of 2 km in and above Pindale, from SK 144 815 to SK 157 823, where they run at the north-east end into Pindale limestone quarry. The numerous small opencasts demonstrate the complex structural relationships better than anywhere else in the Peak District. Additionally, sections through the veins in these opencuts clearly show the multi-phase character of the mineral paragenesis. At Pindale Quarry (now disused) fluorite scrins (mineralized joints) and pipes can be observed at the south-west end, in Visean lensoid reef limestones. Adjacent crags farther south-west (SK 156 820) show the transition from unaltered limestone to quartz rock. More recently (in 1984), a fluorite-barite orebody was discovered hosted in limestone breccias adjacent to Dirtlow Rake, 1.5 km SSW of Castleton. It has been worked as an open pit. The host rock is a shelf carbonate sequence, within which collapse-breccia domes have formed.

The fluorite-barite deposits of the South Pennine Orefield have been described by numerous authors, including Dunham (1952, 1983), Ford and Ineson (1971), Ford (1976), Ineson and Ford (1982), and Ixer and Vaughan



Figure 4.14 Sketch map of the Dirtlow Rake and Pindale area.

Dirtlow Rake and Pindale

(1993). Genetic models proposed in the literature have been re-evaluated by Plant and Jones (1989), and Jones *et al.* (1991, 1994). Mineral deposits occur in veins and pipe complexes, many of which were originally worked for their lead mineralization, whereas other fluorite-barite deposits in the area are hosted in replacement flats and breccias, and have not been so extensively worked. As part of the intensively investigated mineralized area south of Castleton, the Dirtlow Rake and the Pindale deposits include examples of all the deposit types listed above, providing an opportunity to study the relationships between them.

The most detailed descriptions of the Dirtlow Rake area are those by Stevenson and Gaunt (1971), Carlon (1975), Butcher and Hedges (1987), and Jeffrey (1997). It has been a key location in the development of theoretical models explaining orebody genesis as well as models used as predictive tools for exploration.

Description

Dirtlow Rake Vein

The Dirtlow Rake Vein (see Figure 4.15) displays a multi-phase history of mineral deposition linked to fault movement and the concomitant dilatancy. On the vein walls, well-preserved horizontal slickensides can be seen, indicating principally strike-slip movement during the final major dilatant phase. During this final phase, the dominant columnar calcite fill was precipitated. Near the vein margins there are dark calcite bands with minor white barite and galena stringers. Towards the vein centre, cavities containing well-preserved scalenohedral calcite crystals have developed, often with manganese dioxide coatings. Cusps and ribs of fluorite and barite with minor galena are preserved near the vein walls, and are interpreted as earlier mineral phases (for example by Jeffrey, 1997).

The Dirtlow Rake Vein is dominantly a dextral shear with the strike-slip component estimated to be 100 m from evidence of displacement of the reef belt and the Namurian shale contact to the east (Jeffrey, 1997). The main limestone lithological units reveal dip-slip movement of approximately 25–30 m down to the south; however, a full structural interpretation of the deposit is lacking. In the vicinity of the breccia-hosted ore-zone, the Dirtlow Rake Vein is a simple structure trending 060° and dipping between 80° and 90°



Figure 4.15 The Dirtlow Rake Vein. (Photo: M.L. White.)

south. To the west it forms a more complex structure, a splay zone, at the junction with Oxlow Rake. To the east the vein becomes involved in an extensional duplex connecting it to the Pindale Fault, with further splay terminations to the north.

Breccia domes

Mineralized breccia domes are contained within the stratigraphical unit called the 'Monsal Dale Limestone Formation', of the Peak Limestone Group, largely below the Upper Girvanella Band and above a major volcanic horizon which has been correlated with the Upper Miller's Dale Lava Member of the Monsal Dale Limestone Formation (Butcher and Hedges, 1987). The limestones comprise a series of predominantly light-coloured biosparites, locally with shell banks, and chert both in bands and as isolated nodules. Lowermost in the exposure is a massively bedded limestone unit, which is overlain by progressively thinner-bedded units on the north side of Dirtlow Rake Vein. To the south the uppermost unit is a darker, mediumbedded limestone that forms a roof to the breccia zone. Although most of the units are parallelbedded, some channelled and cross-bedded units are also present. The greatest development of mineralized breccia is within the lower, massive, pale limestones with an apparent lithological control to the southern dome roof. Facies transitions in the limestone, from lagoonal through to a reef belt, may be observed in the nearby Hope and Pindale quarries, and are documented from the Cavedale and Winnats Pass (Parkinson, 1965; Stevenson and Gaunt, 1971).

Breccia domes are present on either side of the Dirtlow Rake Vein, with the central cores and upper reaches of the domes comprising the fluorite-barite ore-zone. The broad character of the northern breccia-zone was described by Butcher and Hedges (1987). The two domes are both elongate, partially dissected, bell-like structures, but the dome south of the vein is 25-30 m deeper. In detail the shapes of the two domes are different (see description by Jeffrey, 1997). Breccia blocks range in diameter from 1 cm to several metres, and in the upper portion of the dome the differences in bed thicknesses within the horizons intersected are reflected in the shapes of the breccia blocks. The degree of brecciation, disarticulation and rotation of the breccia blocks on the two sides of the vein is similar, and near the top of the dome the blocks can be shown to have moved only by small vertical distances with little rotation (Jeffrey, 1997).

The breccia is clast-supported, with fluorite and barite filling the interstices. At the contacts between mineral fill and limestone blocks, a range of alteration, crustification and replacement textures have developed. Most commonly, the blocks are relatively unaltered with a crustiform growth of goethite. In other cases the blocks are silicified, and fluorite has subsequently infilled the cavities or porous matrix. Some smaller blocks have been completely replaced by fluorite, with the outline of the block preserved as an iron-rich band formed from goethite and residual chert.

Jeffrey (1997), stated that 'doubt must remain over whether the breccia domes represent a single unit or two separate structures, especially in the light of the early dome formation and subsequent lateral movement on the main vein'.

Replacement 'bow ties'

Structurally controlled wedges of mineralization ('bow tie' deposits) are found at bedding-plane– fracture intersections in the dome roof, within the uppermost 20 m of the massively bedded unit, on the northern upthrown side of the vein, dying out at the boundary with the thinnerbedded unit above. The fractures are a set of minor shears, which splay off the main fault. 'Bow tie' deposits host the full suite of minerals seen in the dome deposits, with the focus of replacement in the acute angle between the two planes. This was the site of increased permeability due to high fracture density or localized brecciation (see Jeffrey, 1997, for detailed diagrams and description).

Pervasive replacement

Adjacent to the vein, on the north wall, silicified and fluoritized limestones occur in the dome roof-zone. The silicification is well developed in a competent, relatively fine-grained, unfractured unit; it has resulted in a highly porous, but not vuggy, rock with some preservation of limestone structures. Post-silicification fluoritization by purple fluorite is widespread. Examples of silicified limestone hosting well-preserved goethite pseudomorphs after marcasite can be found, the same as those seen overgrown by the earliest fluorite elsewhere in the deposit (Jeffrey, 1997).

Pipe mineralization

There are a small number of pipes exposed on prominent bedding-planes at the top of the silicified wall-zone. The pipe cores consist of white fluorite above a floor zone comprising a purple fluorite replacement front in silicified limestone. Drilling has indicated that pipes may be present in the floor zone of the domes; it is suggested by Jeffrey (1997) that a concentration of these structures could have caused the instability needed to trigger the collapse of the dome.

Interpretation

The paragenesis of mineralization at Dirtlow Rake is detailed by Jeffrey (1997), who stated that it is consistent with the general paragenesis of the South Pennine Orefield proposed by Ixer (1986), and also with a number of deposits examined by Quirk (1987). Silicification was the first stage in the mineralization, and the pores and vugs created in the process prepared the ground for further mineralization: fluoritization of unaltered limestone is not seen. The Bage Mine

occurrences of limestone silicification around Dirtlow Rake and Pindale have been described by Ford (1967b), with the best example being the Pindale quartz rock, found 300 m to the north-west of the Dirtlow Rake open-pit next to the southern vein wall. It is a vuggy, occasionally hydraulically brecciated, silicified limestone with yellow and purple fluorite cavity infill. Orme (1974) showed from a detailed petrographic study of the Pindale quartz rock that the fluorite post-dated the major silicification event. Jeffrey (1997) interpreted the 'silica rock' occurrences as the root zones of subsequently eroded domal structures or failed dome precursors.

Development of the domes

The breccia domes are inferred to have formed due to collapse of the rocks above zones of intense dissolution and silicification. These zones were located directly above the boundary with the Upper Miller's Dale Lava Member, where the mineralizing fluids ponded due to the The earliest fluids permeability contrast. deposited chalcedony and/or quartz, marcasite and traces of calcite. At this stage, Dirtlow Rake Vein was a minor fracture, filled by calcite and small amounts of barite and fluorite (Butcher and Hedges, 1987). The fracture (fault) appears to have acted as the primary channel for fluids into the area.

The collapse of the dome formed a small void at its top. This now has an upper, relatively open breccia-zone with a more compact, silicified rubble floor. White fluorite infilled much of the void space provided at higher levels, whereas replacement of partially silicified breccia clasts was more prevalent towards the bottom of the collapse structure.

The onset of calcite mineralization occurred at a significantly later stage, associated with both dilation and re-activation of the fault. Minor phases of white barite and galena are persistent, and the latter was in sufficient abundance to have been worked by the old lead miners.

Relationship of replacement styles

It is rare to see such a wide range of replacement mineral types well-exposed in a single deposit. The following general conclusions about their relationships were drawn by Jeffrey (1997). In easily replaced horizons (with respect to silica and fluorite) the residence time and geochemistry of the fluids dictated the form of the final deposit. Abundant fluid access without ponding resulted in diffusion-driven pervasive replacement. Where fluid-rock contact was prolonged (due to ponding), dissolution and replacement continued further until collapse and breccia dome formation occurred. Conversely, in unfavourable lithologies, replacement only occurred with the aid of strong structural controls: poorly mineralized fractures locally formed 'bow tie' structures where there was adjacent brecciation. Where little structural disruption was present, other than bedding or unconformity surfaces, pipe formation dominated, as mineralization was again restricted to the plane that permitted fluid access.

Conclusions

The Dirtlow Rake and Pindale area is within the South Pennine Orefield, and contains fluoritebarite deposits displaying a wide range of mineralization styles. It is rare to see such a range of replacement mineral types wellexposed in a single deposit, and the locality therefore provides an opportunity to study the relationships between them. The numerous small disused opencasts created by lead and early fluorite-barite mining in this area are perhaps the best exposures in the Peak District for the demonstration and study of the complex structural relationships and the multi-phase character of the mineral paragenesis. Such studies have led to improvements in the understanding of the orefield genesis (Jeffrey, 1997), and to the development of useful prospecting models (Butcher and Hedges, 1987).

BAGE MINE, DERBYSHIRE (SK 292 549)

Introduction

Bage Mine is a long-disused lead mine (see Figure 4.16 for location map). Burr (1994) noted that deep mining at Bage ceased in 1907, but later attempts were made to work the mine at shallow depths. The mine is of international geological importance as the only British source of the very rare mineral matlockite (PbFCl), and is the type locality for that mineral (the type specimen is in the Natural History Museum, registered specimen BM89055). Phosgenite



Figure 4.16 Location map of Bage Mine.

(Pb₂CO₃Cl₂) is also known from the mine, and was previously called 'cromfordite' on the basis of specimens from Bage Mine. The first sample of phosgenite, a relatively rare mineral worldwide, is believed to have been collected in approximately 1785 from 'the district of mines intended to be unwatered by the Cromford level' (Chenevix, 1801; Burr, 1992), although phosgenite had been collected previously elsewhere. The first confirmed discovery from Bage Mine was in 1851 (Greg, 1851), when some specimens of 'phosgenite and an unknown mineral' (matlockite) were found in the debris of an old mine shaft belonging to part of the Bage Mine and Cromford level workings. The main mineshaft to Bage Mine was re-opened in 1980, and some 2740 m of levels to a maximum depth of 115 m have been explored (Warriner, 1982). Only a few minute crystals of the rare minerals were found (not *in situ*), but as the exact site of the original discovery is unknown, a more thorough search and excavation, particularly of the lower levels of the mine, may reveal it. Surviving specimens in 19th century collections show some of the finest crystals known of these minerals.

Bage Mine lies on the eastern margin of the Dinantian, Carboniferous Limestone Supergroup, platform of Derbyshire, close to the contact with the overlying Namurian Millstone Grit Group; it also lies on the boundary between the barite and fluorite 'zones' of the Derbyshire orefield (Dunham, 1952). At the time of the most recent published research on Bage Mine, the accessible workings of the mine and their surveys represented only a part of the original extent of Bage Mine (Burr, 1994). Most of the accessible workings now show barite veins, but little galena. There is little to be seen on the surface and the GCR interest is entirely underground.

Description

The present entrance to Bage Mine is the 92 m former main engine shaft, the Hard End Shaft, (see Figure 4.17) (SK 2915 5499) of the mine (Warriner, 1982), situated in the village of Bolehill on the western edge of Cromford Moor, 1.6 km south of Cromford and 1.6 km south-east of Middleton-by-Wirksworth (Burr, 1992) (see Figure 4.16 for location map). The mine consists of workings on three levels: the 58-m, 72-m and 92-m levels. The presently accessible workings trend in a generally north-south direction, extending about 1 km towards Cromford. Workings associated with the 58-m levels were apparently active as early as 1752. The mine levels were driven entirely in the Visean Evam Limestone and Monsal Dale Limestone formations, and in the 72-m and 92-m levels the courses of intercepted natural watercourses were adopted where suitable. The limestones vary from a white crinoidal limestone to a hard buff-coloured limestone with discontinuous bands of black chert. Solution cavities in the limestone contain scalenohedral crystals of calcite, varying in size up to 30 cm long (Jones, 1982). Most of the workings were in the Butler, Bage and Wallclose veins (Warriner, 1982). Warriner (1982) described the re-opening of Bage Mine using the former main engine shaft, Hard End Shaft (SK 2915 5499), for an

Bage Mine



Figure 4.17 Bage Mine entrance (at the former main engine shaft). (Photo: M.L. White.)

exploration of the mine down to a maximum final depth of 115 m.

Burr (1992), and Bridges and Smith (1983) provide full accounts of the occurrence of phosgenite ('cromfordite') and matlockite in the Bage Mine area. The term 'cromfordite' was introduced as a mineral name for phosgenite after it had already been described elsewhere (Warriner, 1982). Historical research suggests that phosgenite was the first mineral to be discovered at Bage Mine, probably around 1785 (Chenevix, 1801; Burr, 1992, 1994), from workings connected to Cromford Sough. At this time it appears that a local 'petrifactioner' collected specimens, most probably including phosgenite, for Sir Charles Greville, whose mineral collection was acquired by the Government on his death and is now a part of the Natural History Museum collections. The first chemical analysis of phosgenite was undertaken by Chenevix (1801), who described it as a lead chloro-carbonate, although its precise formula was not determined (Burr, 1992). Mawe's 'Mineralogy of Derbyshire' (Mawe, 1802) described a sample of what was probably phosgenite incorrectly as 'muriate of lead in

perfect crystals of a beautiful transparent yellow colour'; a source location for this mineral was not given.

Matlockite was first discovered in 1851 by Bryce Wright in 'the debris of an old shaft belonging to the old Bage Mine and Cromford level workings' (Greg, 1851; Burr, 1992). Although the initial analysis suggested that it was a lead oxychloride (Greg, 1851), it is a lead fluoro-chloride. Later in 1851, Bryce Wright found samples containing both phosgenite and matlockite underground in 'one of the old shafts' of Bage Mine (Greg 1851; Burr, 1992, 1994). Rieuwerts (1982) used old mining records to trace the likely source of these rare minerals. A branch of Cromford Sough at approximately 92 m depth below Bage Mine was driven south along Wallclose Vein between 1777 and 1800, reaching its intersection with Butler Vein in about 1800, 34 m below the presently accessible workings on the 58-m level (Jones, 1982). The Bage branch of Cromford Sough was not driven until the 1807-1826 period and therefore did not exist at the time of the first discovery in the area of phosgenite in 1785. The original site of the discovery is therefore likely to have been in workings on Wallclose Vein (or associated sub-parallel- or cross-veins) near the junction with Butler Vein, and just below the level of Cromford Sough (Rieuwerts, 1982; Burr, 1992).

The samples of phosgenite and matlockite from Bage Mine are most characteristically associated with galena, barite and fluorite, with lesser amounts of cerussite, sphalerite, marcasite and/or pyrite present (Burr, 1992). Bannister (1934) found that in addition to galena and barite the specimens were also associated with anglesite, which is identical to the occurrence of matlockite crystals from Arizona (Abdul-Samad *et al.*, 1982). Some samples also show both matlockite and phosgenite separately enclosing crystals of clear fluorite. There are only a few samples of phosgenite and matlockite in direct association (Burr, 1992).

Jones (1982) described the veins present at Bage Mine. The Butler Vein courses approximately north-south, while Bage Vein courses north-west-south-east and is intersected by a number of smaller east-west veins and scrins. The Wallclose Vein crosses the Butler and Bage veins on a WNW-ESE orientation.

The workings on the lowest, 92-m level, south of the main shaft, are thought to be on Butler

Vein. The vein here is rich in sphalerite but poor in galena. This is in contrast to most of the upper two levels of the mine, where galena is the dominant ore mineral and most primary sphalerite has been oxidized and undergone replacement to hemimorphite (Jones, 1982). At places within the Butler Vein, shales, possibly from the overlying Bowland Shale Formation, have been incorporated into the vein, which has formed a loose breccia with barite.

In the 58-m level the veins are poorly exposed, although there is one good exposure of the Bage Vein close to the entrance shaft. The vein here is 110 mm thick and consists of an outer 1 mm layer of calcite, a 3 mm barite string which contains some galena, followed by 20 mm intermixed barite and fluorite which contains most galena, and at the centre of the vein, calcite up to 50 mm thick which is barren of ore. At its northern extremity, Bage Vein splits into numerous 20 mm-wide scrins, most of which contain galena.

Barite is the main ore-bearing mineral in the mine, and it usually has a vuggy texture which accommodated the precipitation of galena, sphalerite and small clusters of white cockscomb crystals associated with small transparent cubic fluorite crystals. Other minerals found in the mine include hemimorphite, which occurs in crusts of brown sheaf-like crystal aggregates in barite, anglesite and malachite. Selenite and hydrozincite have been identified as secondary minerals that have formed since the cessation of mining (Jones, 1982). Selenite commonly forms stellate groups of lustrous transparent crystals, up to 30 mm long, encrusting the sides and roofs of the passages, particularly where shale is present in the higher parts of the 58-m level. A pale-green form of hydrozincite, an oxidation product of sphalerite, is located in the 92-m level. This mineral usually forms pure-white crystals, but in this case impurities of copper have altered its colour.

Interpretation

Bage Mine is in most aspects an example of a typical South Pennine Orefield mineral deposit. However, it is the presence of the rare minerals matlockite and phosgenite which makes the mine of considerable interest. The study of formation of these minerals is significantly hampered by the absence of any currently accessible in-situ deposits and the vagueness of

the descriptions of minerals collected in the 18th and 19th centuries. Most of the existing research has therefore focused on the mineralogy and attempting to locate the most likely sources of the minerals within the mines.

Burr (1992) determined that the likely source of the matlockite and phosgenite is on the Wallclose Vein close to the junction with the Butler Vein in the north of Bage Mine. Although this general area of the mine is now accessible, all of the workings below the level of Cromford Sough are now flooded. Investigations of the accessible mines in this area have yet to find any in-situ matlockite or phosgenite. During explorations in 1981 a small single specimen of phosgenite was found in an old 'kibble' or tub, high up in a stope above the 58-m level (Jones, 1982). The crystal was found within small cavities in a sample of galena which also contained anglesite. No other samples of phosgenite, matlockite or anglesite were found in the upper area of the mine adjacent to this location (Jones, 1982). Burr (1992) believes that, as most of the original specimens from Bage Mine are associated with small amounts of marcasite and pyrite, they are most likely to have been sourced from the less-oxidized, lower, parts of the mine. However, two of the Bage Mine specimens of matlockite, and phosgenite have matrices of galena which exhibit smooth water-worn faces coated with layers of greywhite cerussite (Burr, 1992). This suggests that they could have come from the upper 58-m and 72-m level workings, which Jones (1982) identified as being driven partly along natural karstic water-courses.

The Bage Mine deposits lie at the boundary between the barite and fluorite zones of the orefield, close to the boundary with the overlying shales. It is not evident how this may have contributed to the formation of phosgenite or matlockite.

Conclusions

The present evidence suggests that the rare minerals matlockite and phosgenite occur at Bage Mine, although no current in-situ deposits are known. However, Bage Mine is the recognized type locality for matlockite, with the type specimen preserved in the Natural History Museum. Burr (1992) concluded that the locality where phosgenite and matlockite were originally collected in the Bage Mine was in a Fall Hill Quarry

part of the Wallclose Vein (or associated subparallel- or cross-veins), probably near its junction with the Butler Vein and just below the level of Cromford Sough. The possibility of these minerals having been found in the higher mineworkings, however, cannot be discounted. Continued exploration of the mines may well result in the discovery of further examples of matlockite and phosgenite. The mode of formation of the minerals has not been determined.

FALL HILL QUARRY, DERBYSHIRE (SK 355 624)

Introduction

Fall Hill is situated on the crest of a small Visean inlier within the Namurian Bowland Shale Formation (formerly 'Edale Shales') and Ashover Grit (see Figure 4.18 for location and geological map). The inlier is composed of the Eyam Limestone Formation (formerly the 'Cawdor Limestone') and the Fallgate Volcanic Formation, with the latter in the core of an anticlinal feature. Most of the mineralization is located in the Eyam Limestone Formation (Ewbank, 1992). A mineralized fault, the Ashover Old Vein, has been worked for fluorite in Fall Hill Quarry, and contains minerals such as greenockite (CdS) and its cubic dimorph hawleyite (only known in Great Britain from this locality; see Smith, 1982). The Ashover Anticline has long been known as a classic teaching area of British geology (Himus and Sweeting, 1951). At its north-west end, the vein known as 'New Butts' has been worked for fluorite, but the wallrock is highly silicified (Kanaris-Sotiriou et al., 1986) and the high silica content of the ore caused extraction difficulties (Ford and Ineson. 1971). At the Fall Hill end, a large opencast along the vein was worked for fluorite during the 1960s and early 1970s. The opencast has been partly backfilled, and the area between the backfill and the eastern end is now flooded to some depth. At the western end, a backfill of limestone boulders extends down a ramp to water level. Many of these boulders contain fluorite, calcite and sulphide mineralization. A large proportion of the wall-rock surfaces are stained green due to the oxidation of sulphide mineralization. A large fluorite-lined vug is present on the north-east face, but is now submerged. On the opposite face at this point calcite veining is evident in the toadstone, and the primary calcite vein was mined for nickel minerals. The adits in the north-west of the quarry represent the remains of the former underground workings on the vein. The area has much dump material, and the best remnants of mineralization are in the dumps between the quarry and the road at the top of the backfill (see Figure 4.19).



Figure 4.18 Location and geological map of Fall Hill Quarry. After Ford and Ineson (1971).

South Pennine Orefield: Cheshire, Leicestershire and Shropshire



Figure 4.19 Fall Hill Quarry. (Photo: M.L. White.)

Description

The Ashover Old Vein is a mineralized reverse fault, downthrown and dipping at 80° to the north-east. Smith (1982) described the geology of Fall Hill Quarry. The mineralized fault trends north-west-south-east along the crest of the Ashover Anticline. This fault has been worked at Fall Hill Quarry where the footwall is in basaltic pyroclastics (toadstone) and the hangingwall in limestone. The vein is mineralized with fluorite, galena and sphalerite. Calcite veinlets running into the pyroclastics also contain pyrite (FeS₂), millerite (NiS) and chalcopyrite (CuFeS₂). The vein runs the length of the anticline from Butts in the north-west to Fall Hill in the south-east. Fluorite cubes, from vugs in the vein, attain dimensions of up to 75 mm. These were coated with the iron oxyhydroxides limonite and goethite in the upper levels and carry inclusions of zoned marcasite near the quarry bottom (Smith, 1982).

Smithsonite (ZnCO₃) encrusts fluorite, while galena from higher parts of the quarry is encrusted with cerussite (PbCO₃) and pyromorphite (Pb₅(PO₄)₃Cl). Barite (BaSO₄) occurs as cockscomb rosettes associated with fluorite, and at times encloses small pyrite crystals. Most of the pyrite present is associated with toadstone, through which it is disseminated, particularly near calcite veining. This calcite encloses bright brassy metallic filaments of millerite, associated with small granules of chalcopyrite. A green staining of these minerals may represent both nickel and copper secondary minerals, although specific mineral species have not been identified. These nickel and copper minerals are not seen in the main vein. Quartz occurs as euhedral crystals in vugs in the limestones and in the central part of the main vein, where pyrite is also present. Hydrocarbons are usually associated with fluorite (Ewbank et al., 1993, 1995) and in one instance were enclosed by marcasite (Smith, 1982).

In the southern section of the inlier lies the E–W-trending Gregory Rake. This is a major rake vein up to 6.5 m wide, relatively high in fluorite but worked only for galena underground, which splits up into a number of 'scrins' in the southwest. In contrast to the main Ashover Old Vein there is an elevated concentration of nickel in this vein, chiefly associated with marcasite (Ixer and Townley, 1979).

Fall Hill Quarry

Interpretation

Fall Hill Quarry demonstrates the control of lithology on mineral chemistry in the South Pennine Orefield. The Fallgate Volcanic Formation in the centre of the anticline was thought to be laterally equivalent to the Upper Matlock Lava Member. However, British Geological Survey boreholes in the anticline centre proved over 100 m of pyroclastic rocks and lavas, on the site of what is interpreted as a vent complex (Kelman, 1980). It is not known whether limestone-hosted mineralization continues at depth within the anticline (beneath the volcanic sequence), although the Gregory Rake was worked down to toadstone in the area to the south-west.

Smith (1982) described the ore mineral assemblage, but no detailed paragenesis has been determined. A sequence across the Ashover Old Vein from both walls to the centre, of calcitesphalerite-smithsonite-calcite-galena-quartz, was established by Smith (1982). The Ni content of the marcasite has not been determined, although this mineral from the Gregory Rake was nickeliferous (Ixer and Townley, 1979). The formation of greenockite and hawleyite is likely to be a result of the alteration of cadmium-rich sphalerite to smithsonite. Sphalerite in the adjacent Milltown Quarry (SK 354 622) does not contain unusual amounts of cadmium, and greenockite and hawleyite are absent. This quarry is more renowned for the presence of the three polymorphs of Zn(OH)₂, ashoverite, sweetite, and wülfingite, being the type locality for the first two listed species. Canary-yellow greenockite coatings at Fall Hill Quarry, along with its cubic dimorph hawleyite, on both sphalerite and fluorite indicate oxidation of the upper part of the orebody. The close association at the adjacent Fallgate Quarry (SK 355 623) of sphalerite with fluorite is similar to that observed at Fall Hill.

The nickel-copper mineralization in the toadstones is distinct from the fluorite-baritesphalerite-galena mineralization in the main vein. It reflects remobilization of nickel and copper as a consequence of hydrothermal alteration (which may or may not be associated with the South Pennine Orefield mineralization activity) of the volcanic rocks.

Thick shales overlie the limestones, while a thick volcanic pile underlies it. Both would have represented effective barriers to ore-fluid vertical migration. If the major Ashover–Crich fold is pre-Zechstein in age, it would have formed a physical barrier to the westward progress up-dip of laterally migrating mineralizing solutions. As a result, a local concentration of mineralization in the crest of the anticline beneath the shales might have occurred. In such circumstances, hydrocarbon accumulations would also have been likely to occur. Dolomitization is absent at Fall Hill, suggesting that the shale cover was intact during mineralization. The presence of a central quartz area in the vein is unusual and may be the result of silica transport from the underlying volcanic rocks. As at the Odin Mine and the Windy Knoll GCR site, both near Castleton (Derbyshire), hydrocarbons are evident just below the Bowland Shale Formation unconformity.

The main concentration of mineralization at Ashover occurs in the south-western section of the Carboniferous limestones, where the large east-west Gregory Rake splits up into a number of scrins. This is where mineralization would be expected if solutions had broken through the volcanic rocks below, along a deep major structure. The Gregory Rake in this area does contain nickeliferous marcasite. If Gregory Rake continues across the crest of the Ashover Anticline to the east, it can be suggested that mineralization has migrated laterally up-dip into this area from an easterly direction. Alternatively, it would have had to break through volcanic rocks below the Gregory Rake before moving laterally through the limestone in the crest of the anticline.

Conclusions

Mineralization at Fall Hill Quarry consists of a limestone-hosted assemblage and a toadstone (basaltic lavas and pyroclastic rocks)-hosted assemblage. The limestone assemblage is free of nickel minerals which are present in the toadstone, absent of accompanying dolomitization and carries hydrocarbons. This strongly suggests that the mineralization of the limestones is largely a result of regional mineralization processes, and that a cover of the Bowland Shale Formation was still present at the time of this mineralization. An origin to the east in the deep Carboniferous basin is likely for the mineralizing fluids. The mineralization in the toadstone is likely to have resulted from the result of a lowtemperature re-distribution of metals and sulphur already present in the lava and tuff. More intense mineralization along the Gregory

Rake to the south-west may have resulted from the lateral migration of ore fluids from an Eorientated feeder vein or may have originated by vertical migration of higher-temperature orefluids from depth through the basaltic lavas and pyroclastics.

TREAK CLIFF, DERBYSHIRE (SK 134 831)

Introduction

Treak Cliff hill and caves are famous for the unique banded variety of fluorite (CaF₂) known as 'Blue John'. This rare mineral variety is found only at this location, although fluorite of a similar colour (but not the same banding pattern) is known from the Ashover and Matlock areas in Derbyshire, and at sites in the USA (Nevada), Iran, and China (Ford, 1994). The name 'Blue John' may derive from the French Bleu Jaune (blue-yellow), although there is no documentary evidence to support this (Ford, 1994). The unique blue-purple and whiteyellow banded variety of fluorite has been mined and used for ornamental purposes since the 18th century. The deposits have been worked in open pits and shallow mines scattered over the hill of which Treak Cliff is the most prominent point, but the main sources at present are the two show caves of Treak Cliff Cavern and Blue John Cavern. The mineralization belongs to the South Pennine Orefield.

Description

The Treak Cliff GCR site lies 800 m west of Castleton in Derbyshire, at the northern edge of a large inlier (about 400 km²) of Lower Carboniferous Dinantian rocks (see Figure 4.20 for location and geological map). Most of the limestones present belong to the Asbian Bee Low Limestone Formation. Treak Cliff marks the transition between the shallow lagoonal limestones to the south and deep-water basin deposits to the north and east, and is chiefly composed of a massive reef limestone with a fore-reef slope on the basinward face (Broadhurst and Simpson, 1967, 1973; Stevenson and Gaunt, 1971; Aitkenhead and Chisholm, 1982). Broadhurst and Simpson (1967) were able to use the dip of sediment fills in fossils and cavities to show that

the limestones at Treak Cliff were deposited on a steep slope with a contemporary dip of approximately 27°.

The contemporary deep-water basin sedimentary rocks are not exposed, although mine dumps at nearby Odin Mine do contain some fine-grained dark limestone fragments that may be part of this facies. Prior to the subsequent deposition of the Namurian Bowland Shale Formation (formerly the 'Edale Shales'), the limestone platform was exposed and some karstification occurred. As a result of this emergence, a boulder bed (up to 12 m thick) formed on the fore-reef slope which coincides very closely with the present surface topography of Treak Cliff (Simpson and Broadhurst, 1969). The karstification and boulder-bed formation continued into the early stages of deposition of the Bowland Shale Formation (Ford, 1969; Simpson and Broadhurst, 1969). The entire area of Treak Cliff was then completely covered by the Bowland Shale Formation and subsequent Namurian and Westphalian sediments.

The Blue John mineralization is an almost monomineralic fluorite deposit, with minor amounts of calcite, quartz, and barite, and a little galena. The mineralization is not restricted to any one facies and it has been found in the following situations (Ford, 1969; Simpson and Broadhurst, 1969): in voids between the boulders in the boulder bed just below the Bowland Shale Formation (particularly important in Treak Cliff Mine); as pipe-veins below wellfissured limestone in karstic solution of bedding planes (particularly important in Blue John Cavern); as small veins in joints in the underlying fissured limestone (see Figure 4.21); as metasomatic replacement of limestone boulders and solid rock (particularly porous shelly limestone); and locally as scattered cubes in the Bowland Shale Formation. The bestknown and largest deposits of Blue John are those that formed in the voids and palaeokarstic solution cavities (up to 3 m in diameter) in the boulder beds (Ford, 1994). The basal part of the boulder bed, with some large cavities can be seen in the Witches Cave of Treak Cliff Cavern (SK 136 832).

Ford (1955, 2000) provided extensive descriptions of the mineralogy and texture of Blue John at Treak Cliff. The mineral is found to occur in spheroidal nodular masses with a



Figure 4.20 Treak Cliff location and geological map. After Ford and Rieuwarts (1976).

radiating crystalline structure containing blue bands of varying intensity and number, arranged concentrically, parallel to the nodular surface. In between these bands are colourless, yellow or pale-blue bands. The nodular surfaces are made up of large numbers of interpenetrating cubic crystals. The highest traces of blue fluorspar are found in the shale and crinoid-debris matrix of the upper parts of the boulder bed. Near Odin Mine (at the northern end of Treak Cliff), these small cavities also contain glauconite and hydrocarbons (Young et al., 1968). In the larger cavities of the boulder bed (~1 m or 2-3 m in diameter), where the shale matrix did not penetrate, nodular radiating crystalline Blue John with typical colour-banding is found (Ford, 1969). A fine-grained horizontally bedded quartz rock deposit is present at some cavity floors. These are horizontally bedded when unaffected by solution collapse. Blue fluorspar cubes have been observed occurring within these quartz layers, and appear to have precipitated from mineralizing fluids at successive intervals (Ford, 1969). Above the quartz layers, the remainder of the cavity is lined with Blue John, sometimes encrusted with calcite scalenohedra. Rare occurrences of galena encrustation of Blue John are also reported.

Ford (1969) postulated that the quartz needles were an authigenic replacement of calcite rhombic accumulations, into which fluorite cubes had precipitated. Some re-distribution of the fluorite was noted, indicated by overgrowths on the cubes, some of which enclose the quartz needles. The margins of some limestone blocks in the boulder bed also show silicification in the form of chalcedony or quartz needles of authigenic aspect. Ford (1969) suggested that silicification and fluoritization occurred close together, and in places overlapped chronologically. Metasomatic replacement of limestone by blue fluorspar is sporadically developed in the more porous shelly limestone, whether in boulders or in the more fissured limestone beneath. Relatively resistant fossils are now surrounded by blue fluorspar.

South Pennine Orefield: Cheshire, Leicestershire and Shropshire



Figure 4.21 The Blue John veins in Carboniferous limestone found within Treak Cliff Cavern, Castleton. (Photo: Phil Sturges, Natural England.)

Interpretation

The mineralization at Treak Cliff is part of the Mississippi Valley-type orefield of the South Pennines. Generally this is a lead, zinc, barium, calcium and fluorine deposit sourced from dewatering of Carboniferous basins to the east (Ford, 1994), but here it is largely dominated by fluorite. The boulder-bed cavities would have provided a series of channels for the migration of mineralizing fluids and hydrocarbons which would have then been trapped by the overlying Bowland Shale Formation. What is not clear, however, is why the Treak Cliff deposit is almost entirely dominated by fluorite, despite extensive galena deposits in Odin Mine, just to the north of Treak Cliff. Fluid-inclusion data suggest that the mineral fluids were very saline at temperatures of between 80° and 180°C, and the likely timing of mineral emplacement was in late Carboniferous to Permian times (Ford, 1994).

A number of theories have been developed for the differing colours of the fluorite but none of them have been confirmed. The possibilities have been summarized by Ford (1994). The presence of manganese has been disproved by analysis, and although present in the fluorite, the hydrocarbon concentrations are low (Ewbank et al., 1993, 1995), and have no relationship to the different colours. Other possibilities are that it forms as a result of colloidal calcium trapped within the fluorite, or molecular lattice distortion caused by uranium absorbed on hydrocarbons. More research is needed to establish the definite cause of the various colours of the Blue John fluorite. There is a similar lack of consensus on the cause of the varied banding of the Blue John in Treak Cliff and the formation of this banding has not been studied. Ford (1994), however, has described the most reasonable explanation as involving a complex system of flow variations and changes in fluid pressure in the palaeokarst and boulder-bed void systems. Repeated, irregular flushes of hot solution would then give potential for the different coloured bands. Periods of steady flow would give rise to a clear band, while frequent interruptions would yield the coloured bands. Slow growths of crystals with absorbed uranium and dislocations could give rise to intensely coloured bands.

Conclusions

The Treak Cliff Blue John mineralization contains a rare, coloured fluorite deposit which exhibits a pattern that may well be unique. Blue John has been used in jewellery manufacture and in many decorative ornaments. It formed as part of the mineralization of the South Pennine Orefield but the deposit consists almost entirely of fluorite. The structural setting of the Blue John fluorite has been studied in detail, but the cause of the colouration and the banding of the Blue John deposit has yet to be definitively determined.

WINDY KNOLL, DERBYSHIRE (SK 127 829)

Introduction

Windy Knoll forms a small culmination on a ridge crest composed of the Carboniferous (Visean) Bee Low Limestone Formation, that was previously a reef completely top- and side-sealed by the Namurian Bowland Shale Formation (formerly the 'Edale Shales'. The quarry is on National Trust land, to the west of Castleton, in Derbyshire (see Figure 4.20).

At Windy Knoll, a small, disused limestone quarry is famed for its bitumen deposits (see Figure 4.22). The quarry face displays 'neptunian dykes' (or fossil grikes) at the contact of the eroded Carboniferous limestones and the overlying shales. These neptunian dykes are variously filled with mixtures of limestone boulders and shales, and include heavy hydrocarbons, including elaterite (a rubbery bituminous material).

The bitumen deposits of Windy Knoll are regarded as a heavy residue of a former oil accumulation. Inorganic minerals are present within the bituminous materials and can be released through the use of solvents. They include galena, sphalerite, marcasite, bravoite, fluorite, barite, calcite and quartz, and typically form small, euhedral, perfectly formed crystals. Marcasite coats rod-like nodules of a hard, green waxy hydrocarbon.

Description

The stratigraphical position of the mineralization at Windy Knoll is almost identical to that at the nearby Odin Mine. A substantial boulder bed occurs between a reef knoll and the overlying Bowland Shale Formation. Quarrying in the mid-19th century opened this up, although the quarries are now mainly infilled and overgrown. The main area of exposure is in the south-west face of the quarry, which is mapped as a boulder bed. However, the limestone appears to be fairly solid, although broken up into large units by neptunian dykes filled with limestone and shale, and containing solidified hydrocarbons and metalliferous minerals. There appears to be a transition from south-east to north-west, from solid limestone, to limestone with increasing neptunian dykes, to boulder bed. This implies a passage through a regolith zone, which is in keeping with the northerly regional dip of the strata. Stromatolite mats, crinoids and corals are among the fossils found in this exposure.

At the south-eastern end of the quarry there is a small cavern, in the walls of which the 'oily and rubbery' hydrocarbons are clearly visible, seeping out of the limestone (Ford, 2002). Some hydrocarbons may be observed occurring as shiny, black nodules, while others are present in 'sticky, brown' seepages. Polymerization on exposure to air causes these seepages to become elastic and rubbery; as such they are described under the general name 'elaterite'. Pering and Ponnamperuma (1969) described the hydrocarbons as ranging from 'brittle, black chunks and brown chunks and brown rods showing concoidal features, to dark grey-green elastic Nooner et al. (1973) classified the gums'. hydrocarbons at the Windy Knoll deposit into four main types based on their aliphatic, aromatic, and asphaltic distributions, termed 'Types A-D'.

In addition to occurrences in neptunian dykes and in joints in the limestone, bitumens also occur within hydrothermal veins in the Lower Carboniferous (Visean) Bee Low Limestone Formation (Mueller, 1954, 1970). These hydrothermal veins within the Windy Knoll area terminate along the boundary of the overlying impermeable Namurian Bowland Shale Formation. The bitumens are in some cases associated with fluorite-rich veins.

Interpretation

The abundance and variety of bitumens in the Castleton area suggest that before the removal of the Namurian cover the shelf-margin crest and South Pennine Orefield: Cheshire, Leicestershire and Shropshire



Figure 4.22 The limestone quarry face (left) at Windy Knoll with the residual petroleum 'elaterite' deposits in the foreground. The black tarry material forms the matrix to pale fragmented limestone. (Photo: J. Poll, Natural England.)

the northwardly-inclined shelf margin of the Visean limestone succession could have hosted a significant oil accumulation.

It has been hypothesized that the boulder-bed formation resulted from either (1) the widening of solution joints into neptunian dykes in a karstic environment, and then a break-up of the karst in the zone of wave action during Bowland Shale Formation deposition; or (2) the neptunian dykes represent the collapse of overlying strata into voids during replacement of limestone by mineralization, beneath a cap-rock of shale, i.e. collapse into a replacement flat of Northern Pennine-type.

The role of hydrocarbons in the process of orefield paragenesis at Windy Knoll has been the topic of extensive research (for example Mueller, 1954; Pering and Ponnamperuma, 1969; Worley and Ford, 1977). Polymerization causes the brown hydrocarbon seepages to become elastic and rubbery. Dunham (1967) noted the intimate association between the hydrocarbons and gangue minerals such as pyrite, marcasite, quartz, calcite and fluorite. This association implies that hydrocarbon deposition may be related to the genesis of once economically important lead, zinc and barite deposits in the area. A similar link between hydrocarbons and mineralization is seen at the **Castle Hill Quarry** GCR site, in Leicestershire.

Mueller (1951, 1954, 1969, 1970) suggested the bitumens were derived from biogenic organic matter distilled from surrounding sediments by hot (250°-350°C) ore-bearing Sylvester-Bradley and King (1963) fluids. reported evidence that these may be either biogenic or abiogenic in origin. Pering (1971) proposed that the bitumens formed from organic material collected in a topographical high during two-stage migration from parent sediments. Pering and Ponnamperuma (1969), and Pering (1971, 1973) detected isoprenoid hydrocarbons in the bitumens, again supporting evidence of a biogenic origin. Nooner et al. (1973) identified four distinct bitumen types (Types A-D) in the Windy Knoll deposit, and Khavari-Khorosani and Murchison (1978) concluded that the bitumen forming the base

Portway Gravel Pits

of the Windy Knoll deposit (a Type-D 'black bitumen') is a product of thermal metamorphism. More modern work (Xuemin *et al.*, 1987; Ewbank *et al.*, 1993, 1995) has shown that the bitumens at Windy Knoll represent the biodegraded residue of an oil accumulation. Moser *et al.* (1992) determined a direct link between the fluid-inclusion populations in fluorite at Windy Knoll, the outcropping bitumens, and fluorite deposition. A two-stage deposition of the fluorite was determined from the fluid-inclusion data, with an early, highsalinity fluid at a temperature of 69° -100°C, and a later, lower-salinity fluid at a temperature of 112° -150°C (Moser *et al.*, 1992).

The base of the elaterite may define a residual oil–water contact. Bitumen impregnation in limestone breccias below the oil–water contact may indicate the charge pathway. These breccias were found by Peacock and Taylor (1966) to contain uraniferous collophane. If the bitumen and uranium are genetically associated, an indication of the area formerly open to oil migration is provided by Peacock and Taylor's map of surface uranium anomalies. Radioactive anomalies occupy the entire 6000 m-long, 500 m-wide and 150 m-high exposed portion of the slope to the south of Windy Knoll.

Conclusions

The Windy Knoll GCR site provides an excellent location to study the inter-relationship between lead-zinc-fluorite mineralization and hydrocarbons in the South Pennine Orefield. In contrast to most of the mineralized sites in the orefield it contains a large bitumen deposit which contains both solid and liquid hydrocarbons. Prior to the erosion of the overlying Bowland Shale Formation, the Windy Knoll area would have formed an ideal structural-trap for a significant hydrocarbon deposit. The site also contains a very good example of a palaeokarst surface.

PORTWAY GRAVEL PITS, DERBYSHIRE (SK 128 812)

Introduction

The excavation at Portway Gravel Pits has exposed a chaotic blocky infill of a hollow in the Carboniferous Limestone, adjacent to a mineral vein system, which was formed as a result of the collapse of a solution cavity some distance below the surface (Figures 4.23 and 4.24).



Figure 4.23 Portway Gravel Pits. (Photo: J. Aumônier.)



Figure 4.24 Geological map of the Portway Gravel Pits GCR site. After Ford (1967b).

Description

Many of the blocks within the subsidence feature show excellent examples of pipe-vein mineralization. Examination of the blocks shows that ancient cavities in the rock were lined with barite which developed in multiple layers, showing a variety of forms and colours. This form of barite consists of finely crystalline layers of varying shades of yellow and red, with the youngest layer often showing euhedral barite crystal forms. Yellow fluorite occurs inter-

Kirkham's Silica Sandpits

banded with the barite, and the centres of the cavities often show large corroded calcite crystals in the form of scalenohedra. Juxtaposed with the barite blocks are blocks of quartz rock, reflecting metasomatic replacement of the limestone, and the available evidence suggests that this replacement occurred at an earlier stage than the bulk of the mineralization.

The precise age of the collapse structure is difficult to determine, but is at least partly Pleistocene in age, as loess clays, which blanket the deposit, have also penetrated downwards and form the final infill of barite-lined cavities.

The site lies on mineral veins that form part of the Dirtlow Rake system (Stevenson and Gaunt, 1971), one of the major lead-bearing veins in north Derbyshire (Figure 4.24). Galena, calcite, barite and fluorite are reported to occur here. The country rock is of the Asbian Bee Low Limestone Formation, which is characteristically composed of massive limestones with occasional coral bands (Stevenson and Gaunt, 1971).

In detail, the geology of the site is complex. Ford (1967b) described the site at a time when barite mining was active, exploiting the Old Wham Vein, and compares his observations with those made by Arnold-Bemrose in 1898. The fact that the quartz rock encloses coral fossils and is mineralized, containing fluorite and barite, suggests that it is the product of alteration of the limestone as a consequence of mineralization. Ford (1967b) noted that the quartz rock is cut by (and hence pre-dates) at least some of the faulting associated with Dirtlow Rake.

Interpretation

In the Pleistocene, collapse of a cavern within the Old Wham Vein occurred. The resulting collapse feature is of the order of 30 m in diameter and at least 4 m deep, with vertical limestone walls, and is filled with blocks of limestone and quartz rock. Ford described a soil sequence at the top of the faces exposed in the 1960s, which includes a loess (Pigott, 1962). Although at the same stratigraphical level as the solution features of south Derbyshire (e.g. **Kirkham's Silica Sandpits**, see GCR site report, this chapter) there are differences; the host rock at Portway is limestone, not dolomite, and the pit lacks the fill of refractory sands and clays that typically occur in the pits of southern Derbyshire. On the basis that erratics are lacking, Ford (1967b) suggested that the Portway feature may represent an unglaciated enclave, not covered by flowing ice.

Conclusions

In addition to the occurrence there of barite in various forms, the Portway Gravel Pits GCR site provides evidence of Pleistocene landscape development in the South Pennines, with solution-related collapse features that preserve a lithologically distinct quartz rock.

KIRKHAM'S SILICA SANDPITS, DERBYSHIRE (SK 216 542)

Introduction

The Kirkham's Silica Sandpits GCR site mined (until recently) silica sands of the Miocene– Pliocene Brassington Formation, which occurs in karstic 'pocket deposits' located largely within dolomitized limestones of the Carboniferous Asbian Bee Low Limestone Formation (Walsh *et al.*, 1972; see Figure 4.25).

The Brassington Formation was well exposed in a number of pits in the vicinity of the Kirkham's Silica Sandpits site. The formation includes silica sand that was of commercial value as a raw material for the manufacture of refractories. In addition to quartz-rich sands, the deposits contain kaolinitic clays, also valuable for ceramic purposes (Figure 4.26). From a scientific point of view, the Brassington Formation is important as it provides evidence for uplift since its deposition by perhaps as much as 450 m relative to the Trent Valley (Ford and Jones, 2007) to form the South Pennines, i.e. within the last 2 million years (Walsh et al., 1980, 1999). The deposits exposed in the sandpits provide valuable evidence of the development of late Tertiary palaeogeography (Gibbard and Lewin, 2003), which in turn played a key role in the development of groundwater circulation systems responsible for the Derbyshire thermal waters (Brassington, 2007).

Description

Exposures in Kirkham's Silica Sandpits that were accessible in the 1970s are described in detail by Walsh *et al.* (1972, 1980). The Brassington

South Pennine Orefield: Cheshire, Leicestershire and Shropshire



Figure 4.25 Kirkham's Silica Sandpits, Derbyshire. (Photo: J. Aumônier.)



Figure 4.26 Kaolinitic sand from Kirkham's Silica Sandpits, Derbyshire. (Photo: Photo: J. Aumônier.)

Formation is divided into the lower Kirkham Member, overlain by the Bees Nest Member and then the Kenslow Member (Boulter *et al.*, 1971). Although its type locality is at Kirkham's Silica Sandpits, the Kirkham Member occurs widely in subsidence features throughout east Derbyshire.

The deposits at Kirkham's Silica Sandpits rest on Namurian mudstones (Chisholm *et al.*, 1988), and are dominated by fine- to medium-grained quartz sands, with angular–subangular grains and little sorting according to grain size (Walsh *et al.*, 1980). This suggests rapid deposition. Gravel horizons also occur, clearly with pebbles derived from the Sherwood Sandstone Group (Figure 4.27). A dominant source from the south-east is clearly demonstrated from crossbedding measurements, with supply also from the south and ESE. Pebble orientations are consistent, predominantly north–south and ESE (Walsh *et al.*, 1980).

Kirkham's Silica Sandpits is also important for the occurrence within them of the clay mineral metahalloysite ($Al_2Si_2O_5(OH)_4$; Ford, 1963), which is less hydrated than the mineral halloysite ($Al_2Si_2O_5(OH)_4$.xH₂O). Chemically Ecton Copper Mines



Figure 4.27 Pebbly horizon within the Brassington Formation at Kirkham's Silica Sandpits, Derbyshire. (Photo: Photo: J. Aumônier.)

similar to kaolinite, the clay sheets in the halloysite family of minerals are characteristically coiled up (like a brandysnap biscuit; these are well illustrated by Robertson and Eggleton, 1991). In the sand pits, metahalloysite was observed by Ford (1963) to occur as bright white nodules, up to 30 cm in diameter, within a matrix of a strongly sheared red clay that occupies fissures within the Kirkham Member sediments. The metahalloysite nodules are reported as often encrusted with black manganese oxide ('wad'; Ford, 1963). The origin of the metahalloysite at this location is problematical. Weathering of kaolinite or illitic clay minerals derived from the Sherwood Sandstone Group is most likely (cf. Robertson and Eggleton, 1991), but would be expected to be associated with low-pH acidic waters. Ford (1963) suggested that these might have arisen as a consequence of weathering of sulphide mineral ores, given the close proximity of these. How metahalloysite then came to form nodules within a weathered clay matrix has not been resolved.

Interpretation

Although the Derbyshire pocket deposits are disconnected and patchy, they provide evidence of a large Pliocene (within the interval 5.33–1.81 Ma) river system, draining the Triassic Sherwood Sandstone Group to the south and east of the present-day Derbyshire hills. An origin from the Sherwood Sandstone Group is also favoured by the quartz-grain morphology, which shows evidence of quartz overgrowths like those observed in Sherwood Sandstone Formation sandstones (Walsh *et al.*, 1980).

The occurrence of metahalloysite reflects the specific conditions of weathering during the development of the pocket deposits, although the occurrence of metahalloysite as nodules within sheared mudstone means that its origin is not entirely clear.

Conclusions

The Kirkham's Silica Sandpits GCR site provides insight into the geomorphological development of the South Pennines, combined with mineralogical evidence of chemical processes associated with weathering conditions at the Miocene–Pliocene unconformity.

ECTON COPPER MINES, DERBYSHIRE (SK 099 579)

Introduction

The copper ore deposits at Ecton, with nearby Mixon, form the western extremity of the South Pennine Orefield (see Figure 4.28 for location map). The Ecton orefield occupies the western edge of the Derbyshire Dome, which lies at the extreme southern end of the Pennine Hills (Pattrick and Polya, 1993). The Ecton mines penetrate copper deposits within folded Dinantian limestones, namely the Milldale Limestone and Ecton Limestone formations (Critchley, 1979), which form the NNW-SSE-trending Ecton Anticline at the northern end of the Manifold Valley gorge, in east Staffordshire. Namurian mudstones and sandstones unconformably overlie the limestones, which now form an inlier of high relief, surrounded by low-relief Namurian terrain (Aitkenhead et al., 1985).



Figure 4.28 Location map of Ecton Copper Mines.

The mineralization at Ecton is unique in being the only deposit substantially mined for copper in the Carboniferous Limestone of England. Records suggest that Ecton was mined during the Roman occupation of Britain (c. 50 BC) (Dunham, 1983) and periodically since then. The most significant ore yields were produced during the 18th and early 19th centuries (Kirkham and Ford, 1967). Mining operations ceased in 1891 (Robey and Porter, 1972), but throughout the most prolific mining period mining records state that Ecton yielded a number of copper-bearing ores including (in order of abundance) chalcopyrite, bornite, chalcocite, cuprite, tenorite, malachite and azurite (Sarjeant, 1956; Kirkham and Ford, 1967). Of these minerals, chalcopyrite was the most abundant and exploited sulphide, followed by lesser amounts of galena (Masheder and Rankin, 1988). Pyrite also figured as one of the dominant hypogene sulphides, although was never exploited as an ore. Calcite is evident as the major gangue mineral, together with barite and minor fluorite (Pattrick and Polya, 1993), and hydrocarbons also occur (Ewbank *et al.*, 1993, 1995). It is estimated that between 100 000 and 150 000 tons of ore in total were extracted from the Ecton mines, with grades of around 15% copper (Robey and Porter, 1970) during the most prolific mining period. Associations are frequently made with the mining area of Mixon, several kilometres west of Ecton, where mineralization occupies a similar geological setting. The Mixon mines, although covering a smaller area, were also known for the high quality of their copper and lead ores, albeit occurring in lesser quantities (Robey and Porter, 1970).

The predominance of copper over lead and zinc sulphides in the Ecton and Mixon areas is atypical of the South Pennine Orefield as a whole, where lead-zinc-fluorite-barite mineralization dominates. The South Pennine Orefield has been described as a classic carbonate-hosted Mississippi Valley-type deposit by Mostaghel (1985b), and as a fluoritic subtype of the Mississippi Valley-type lead-zinc deposits by Dunham (1983). In contrast, Masheder and Rankin (1988) proposed that the predominance of copper over lead and zinc sulphides at Ecton may indicate a different origin to that assumed for the South Pennine Orefield.

Description

The Ecton orebody is thought to be bell-shaped, increasing in volume with depth and dominated by vein-style mineralization in the form of vertical pipe-like void-infilling and metasomatic replacement bodies (Ixer and Vaughan, 1993). The mining works at Ecton focused mainly on the irregular pipe-like bodies within the uppermost 300 m of the Asbian and Brigantian limestone sequences, which underlie the now eroded basal Namurian Edale Shales aquiclude (Pattrick and Polya, 1993). The mineralization within these pipe-like bodies is suggested to have occurred as the result of open-cavity filling (Masheder and Rankin, 1988), and the Ecton Pipe is the largest, with a vertical extent of several hundred metres. Copper ores were found to be most prolific in the lower levels of the orebody, and the worked lead ores, principally galena and barite stringers, were generally found to exist as discrete deposits in the higher Namurian sandstones in the immediate vicinity of the larger pipes (Kirkham and Ford, 1967; Masheder and Rankin, 1988). Secondary

Ecton Copper Mines

enrichment of the copper ores is considered to be the likely cause of both the higher grade of ore in the upper levels of the deposit, which yielded around 15% copper between the years 1776 and 1817 (compared to poorer-grade ore in the lower levels), and the existence of galena and sphalerite as alteration products in the upper orebody. As the chief ore of copper, chalcopyrite was frequently found associated with calcite, fluorite and barite, where calcite was the predominant gangue mineral existing in the form of large (> 10 cm) transparent crystals lining cavity walls within the main Ecton Pipe (Masheder and Rankin, 1988). Particularly characteristic of the location is the occurrence of chalcopyrite as small crystals (1 mm or less) within massive grey sparry calcite.

Sporadic occurrences of celestine (strontium sulphate) in calcite veinlets in the south-east mine-workings are also thought to be the product of secondary mineralization, together with the copper-zinc minerals aurichalcite, rosasite and rare chalcanthite (Ford and Sarjeant, 1964). Other reported secondary carbonate minerals include cerussite (lead carbonate) and smithsonite (zinc carbonate), and these are probably the result of oxidation of primary lead and zinc sulphides (Ixer and Vaughan, 1993). Associated gangue minerals include hydrozincite, limonite, 'wad' (manganese oxyhydroxides), pyrite and arsenopyrite (Ford and Sarjeant, 1964). Rust (1995a) described a wide range of supergene minerals from the Waterbank dumps surrounding Shaft (SK 102 576), which included rare species such as namuwite, ramsbeckite and schulenbergite, as well as two minerals which could not be matched to known species. One of these has subsequently been identified as the first British record of the rare lead sulphate selenate mineral olsacherite (Rust and Green, 2005).

Several fault-/joint-sets dominate the main South Pennine Orefield (Weaver, 1974; Quirk, 1988), and the same structural regime is observed in the Ecton orebody. The earliest and most common faults trend north-west-southeast and are 1–2 km-long straight vertical faults coinciding with master joints. These are often associated with pre-mineralization solution cavities, which are syn-sedimentary features (Pattrick and Polya, 1993). Minor fault-sets are normally sinuous and 2–5 km long, but reaching up to 8 km in some cases. These are wrench faults trending east-west or ENE–WSW, and often show horizontal slickensides on their wallrocks with little vertical displacement. Most of the large rake deposits belong to this set. Other minor faults comprise a series of north-eastsouth-west extensional structures (Weaver, 1974; Quirk, 1988), which are probably of late Carboniferous age.

Some 12 mines with 70-80 associated shafts (Porter, 1970) penetrate the vein system to depths of at least 300 m (Kirkham and Ford, 1967). The principal NW-SE-trending veins can be observed along the ridge that forms the north-west-southeast axis of the Ecton Anticline and on the NEfacing hillside. The south-east plunge of the anticline allows best exposure of worked veins at the shafts and pits sunk into the northern region of the anticline. Principal worked E-Wtrending veins can be observed to dip to the south within the limestone strata at the disused workings at Clayton Mine (see Figure 4.29), Stone Quarry Mine and Fly Mine, but the workings are overgrown. Other smaller exploited pipes trend ENE-WSW.

A detailed description of the Ecton area, from which much of the following is drawn, is presented in Braithwaite (1991). Many of the lower mine-workings are now flooded at adit level. Several of the major adits remain in the south-west at the base of Ecton Hill, and continue to drain water from the old shafts. This is the case with respect to Deep Ecton Adit, Clayton Adit, Birches (Hurts) Adit, and the remains of Salts Level that are preserved, although the associated building works (which include old smelters, mills, smiths' forges, waterways and a tramway) are either ruined or have been demolished and mixed with tipped mine waste. Few of the original buildings remain and these are now mostly residential properties. The remains of a worked quarry (formerly known as 'Apes Tor Quarry' (SK 100 585)) are also visible on the western extent of Ecton Hill in close proximity to the main adits. Above this quarry and halfway up the W-facing flank of Ecton Hill are the remains of the engine house, shafts, several adits and the spoil heap of Dutchman's Mine. These disused works are behind a stabilizing barrier of conifers, planted to prevent slope failure of the mine spoil. Inspection of this spoil heap reveals discarded lumps of blocky pink barite with distinctive spots of lustrous chalcopyrite and green malachite interspersed throughout orange-weathered, 'honeycomb'texture limestone. Large red-brown grains of South Pennine Orefield: Cheshire, Leicestershire and Shropshire



Figure 4.29 The remains of mineralization within Clayton Mine. (Photo: H. Townley, Natural England.)

hematite are also evident in the spoil, together with veinlets of calcite and dark cubes of galena and lustrous grains of sphalerite.

There are a number of other ruined buildings and works associated with the Ecton mines, and many of these can be seen from public footpaths. Old shafts and trial pits however are frequently backfilled, and the remains of worked veins are only exposed at a few locations on the hill.

Interpretation

The copper-rich mineralization at Ecton, along with other significant lead-zinc-iron-rich deposits in the Pennines, Cornubia, Cumbria and the Bristol Channel are the result of post-Carboniferous episodes of low-temperature hydrothermal activity, largely hosted by Lower Carboniferous carbonate rocks, so-called Mississippi Valley-type (Pattrick and Polya, 1993).

Fluid-inclusion studies have aided greatly in determining the age and source of the mineralizing fluids responsible for the Ecton mineralization. Masheder and Rankin (1988) obtained notably lower mean homogenization temperature data from primary and secondary inclusions within calcite and fluorite gangue from Ecton than those generated in previous studies from the South Pennine district (Rogers, 1977). Consequently, genetic models for this mineralized region have been refined, for example those models proposed by Dunham (1983), and Mostaghel and Ford (1986).

Basin dewatering has been one of the most popular models proposed to identify the source of the mineralizing fluids responsible for the Ecton ore deposits. Such a model involves the expulsion of metalliferous brines derived from surrounding sedimentary basins into ore structures within the Derbyshire Dome. Mostaghel and Ford (1986) suggested that eastward-moving fluids expelled from the Cheshire-Irish Sea Basin to the west of Ecton were responsible for the copper and associated mineralization in the area. Davidson (1966) speculated that the ores of Ecton and the South Pennine Orefield were telethermal, and deposited by interstitial brines derived diagenetically from evaporates, the brines being capable of concentrating metals from sediments through which they had migrated.

Ecton Copper Mines

The presence of sulphate-rich groundwater in the sub-surface Carboniferous limestones beneath Nottinghamshire has been established by Downing (1967). Metals were transported in porewaters but only precipitated when mixed with brines, or sulphate and bacteriogenic sulphide. Further to this, Allen (1982) has suggested that sandstone-hosted stratabound copper deposits at the margins of Triassic basins in Cheshire and Staffordshire may be associated with the copper mineralization at Ecton.

As may be expected, in addition to a source of mineralizing fluids from the Cheshire Basin, sedimentary basins to the east of the Derbyshire Platform (probably related to the northern and southern North Sea basins) have also been considered as a source for mineralizing fluids responsible for the lead-zinc-fluorite mineralization present in the eastern and central parts of the South Pennine Orefield. Ford (1976) envisaged the North Sea Basin as a possible source for the Ecton mineralization, whilst a derivation from the basinal sediments of the Gainsborough, Edale and Widmerpool gulfs was considered possible by Rogers (1977), and Ineson and Ford (1982). However, Ixer and Townley (1979), in their description of the mineralogy and paragenesis of the South Pennine Orefield, concluded that the Ecton copper mineralization is anomalous and should not be considered to be part of the main orefield at all.

With this in mind, fluid-inclusion data obtained by Masheder and Rankin (1988) indicate that, irrespective of source, the leadand zinc-rich fluids responsible for the mineralization in the South Pennines differed only slightly in their physico-chemical properties from the eastward-moving, copper-enriched fluids believed to be derived from the Cheshire Basin. The latter were also thought to be cooler, while K:Na ratio data suggest that the Ecton fluids were also more enriched in potassium than the lead-zinc-fluorite fluids that sourced the rest of the South Pennine Orefield. A possible explanation for the lower temperatures of the Ecton fluids is a shallower depth of origin within the Cheshire Basin, compared with the other more easterly sedimentary basins, rather than lower regional geothermal gradients (Masheder and Rankin, 1988). The higher potassium levels of the Ecton ore-fluids may be explained through the high abundance of evaporites in the Cheshire Basin than in other sedimentary basins elsewhere in the area (Masheder and Rankin, 1988). Potassium enrichments of ore fluids through interaction with evaporites is not a new concept and has been suggested by various authors to explain high K:Na ratios, and evidence from sulphur isotopic studies has indicated that sabkha-type fluids may be involved in ore formation. The abundance of calcite gangue is also consistent with the basinal brine model in explaining the Ecton ore genesis, based on fluid compositions of modern-day basinal brines (Carpenter *et al.*, 1974).

Conclusions

Based on the mineralization characteristics at Ecton, models of episodic basin dewatering, as proposed by Cathles and Smith (1983), can be applied to explain the copper mineralization at this site, where local basin evolution was responsible for controlling the flow of brines derived in this fashion (Pattrick and Polya, 1993). Periods of active rifting, thermal subsidence and basin inversion that were ongoing during late Carboniferous to early Permian times would have been conducive to fluid expulsion from rapidly buried sediments. Crustal extension, which occurred later in Permian times would have facilitated fluid movement, together with fault activity on basin margins (Pattrick and Polya, 1993). The Carboniferous Ecton Limestone and Milldale Limestone formations would have provided an ideal permeable aquifer within which to contain basinal fluids. Shale units within the limestones, as beneath Ecton and Mixon, would have acted as impermeable barriers but also as sources of sulphur.

The orebody at Ecton represents a unique type of copper mineralization, which shares a similar genetic model to the Pb-Zn mineralization of the South Pennine Orefield. Whereas the latter is classed as a typical carbonate-hosted Mississippi Valley-type deposit, Ecton may be classed as a copper subtype of this type of deposit. The most popular genetic theories for the formation of the Ecton orebody, like the South Pennine Orefield, incorporate a basinal brine model with respect to fluid derivation, and post-Carboniferous extensional tectonics as a mode of fluid migration prior to the mineralization. The literature suggests that although the majority of the South Pennine Orefield was sourced from fluids derived from basins to the east of the Derbyshire Platform, the Ecton

mineral deposit brines were likely to have been sourced from a more westerly source that differed only slightly in terms of their chemical and physical properties from the South Pennine Orefield fluids. Marginal evaporitic fluids from the Cheshire Basin represent a possible fluid source for the Ecton mineralization, although a number of minor rift-basins present within the Carboniferous may also have provided a suitable source. Although much work has been conducted with respect to the larger economically important orefields in this area of Derbyshire, there still remains some lack of clarity with respect to the constraints on the genesis of the ore deposits at Ecton.

ALDERLEY EDGE DISTRICT, CHESHIRE (SJ 84 77–SJ 86 77, SJ 87 78)

G. Warrington

Introduction

Alderley Edge lies some 20 km south of Manchester, in the north-eastern part of the Cheshire Basin (Figure 4.1), an asymmetric halfgraben or rift that underlies most of Cheshire and north Shropshire. The basin is bounded to the east by the Red Rock Fault, part of the Wem–Bridgemere–Red Rock Fault System (Chadwick *et al.*, 1999), and is occupied by rocks of Permian, Triassic and Jurassic age (Warrington *et al.*, 1999).

Sandstones form the lower part of the Triassic succession and host a widespread barite mineralization, and, at scattered localities in north Shropshire, at Bickerton (west Cheshire), and in the Alderley district, a copper-dominated polymetallic mineralization (Dewey and Eastwood, 1925; Warrington, 1980a, 1995; Carlon, 1981; Plant et al., 1999a). The Alderley mining district encompasses extensive workings on Alderley Edge and a small mine at Mottram St Andrew (Figure 4.30). It is the largest occurrence of sediment-hosted polymetallic mineralization in the Cheshire Basin, with a long mining history and the greatest known output; it is also the most extensively studied and documented. The influence of sedimentary host-rocks of different facies, and of structure, on the nature and distribution of the polymetallic ores and the

form of the orebodies can be examined in threedimensions in unweathered sections in more than 15 km of shallow, disused mine-workings that underlie an area of some 1.5 km² on Alderley Edge. Over 30 elements are present in a mineral assemblage comprising over 60 species. These factors render the site of unique importance in Britain, and farther afield, for scientific and educational purposes; appropriately, it is a geological SSSI. Entrances to mines on Alderley Edge are on National Trust property. Access is administered by the Derbyshire Caving Club (DCC) by arrangement with the National Trust; DCC members monitor conditions underground and have improved and extended access by clearing blocked shafts and tunnels.

Description

Alderley Edge is a topographical feature that rises to 197 m, as much as 100 m above the surrounding glacial drift-covered Cheshire plain. It comprises an abrupt N-facing scarp and a gently sloping southern side. It lies on a 3 kmwide horst of rocks uplifted between two major N-S-trending faults; the Alderley Fault to the west, and the Kirkleyditch Fault to the east (Warrington, 1980b, fig. 1). Rocks to the west and east of these faults respectively have been downthrown relative to those in the horst by several hundred metres. Faults with smaller displacements occur within the horst; these include important WNW-ESE-trending structures, and others with north-west-south-east and northsouth trends (Figure 4.30). The stratigraphy and structure of the area has been described by Taylor et al. (1963), Mohr (1964a), Warrington (1965), Warrington and Thompson (1971), Carlon (1979), Warrington (1980b), Thompson (1991), Rowe and Burley (1997), Chadwick et al. (1999), and Plant et al. (1999a).

Alderley Edge was not included in the GCR volume on Permian and Triassic red-beds (Benton *et al.*, 2002), and therefore the stratigraphy and characters of the rock units that host the mineralization are summarized here.

Rocks exposed in the horst comprise two formations of the Sherwood Sandstone Group; the Wilmslow Sandstone Formation, of Early Triassic (probably Olenekian) age, between c 250 Ma and 246 Ma, and the succeeding Helsby Sandstone Formation, of early Mid-Triassic (Anisian) age (c. 242 Ma). The dip of Alderley Edge District



Figure 4.30 The Alderley Edge mining district: simplified solid geology with distribution of mine sites and workings. After Warrington (1965, maps 1, 2; 1980b, fig. 2), incorporating more-recent underground observations.

these beds, south-west at 10° – 15° , is slightly steeper than the slope of the land surface, resulting in progressively younger units in the Helsby Sandstone cropping-out in that direction. The succeeding Mercia Mudstone Group, the lower formations of which are also of Anisian age (Warrington *et al.*, 1999), crops out to the south, beneath glacial deposits; it formerly capped the Helsby Sandstone across the horst (Taylor *et al.*, 1963; Warrington, 1980b, fig. 1), but has been removed by erosion.

The Wilmslow Sandstone Formation is exposed on the scarp face of Alderley Edge where it is capped by the lowest, erosion-resistant, member of the Helsby Sandstone Formation. It is encountered underground in a long adit that runs from the base of the scarp near Stormy Point, southwards, to Engine Vein Mine (Figure 4.30) and continues farther south-west, then WNW, connecting with other mines (Warrington, 1965, map 2). It consists of soft, orange- to redbrown sandstones that lack pebbles and have few interbedded mudstones. Large-scale crossbedding of aeolian-dune-type occurs and indicates wind transport from an easterly direction. It is an example of the 'soft sandstone' facies of Thompson (1970a), interpreted by him as a largely aeolian continental deposit with some fluvial interbeds.

The Helsby Sandstone Formation overlies the Wilmslow Sandstone Formation unconformably. It comprises an alternating succession of the 'soft' and 'red-pebbly' sandstone facies of Thompson (1970a). The 'red-pebbly' facies, of fluvial origin, was deposited in a N- to NW-flowing river system (Thompson, 1970b, fig. 3.12; Warrington and Ivimey-Cook, 1992, map Tr1b). It comprises fining-upward sedimentary cycles which, in their lower part, consist of red-brown, cross-bedded, conglomeratic or pebbly sandstones that rest on an uneven surface created when a migrating river channel eroded underlying sediment. These beds pass upwards into finer sandstones and siltstones. If a cycle is complete, the highest bed is a mudstone; this was, however, usually partly eroded, or even completely removed, before the start of the next cycle, the basal bed of which contains the eroded mudstone debris (Thompson, 1970b, figs 7, 8).

The Helsby Sandstone Formation comprises five members, the lowest of which, the Engine Vein Conglomerate, is a representative of the 'red-pebbly sandstone' facies. It is exposed principally along the top of the scarp face of Alderley Edge, but is also encountered in quarries and other excavations between Stormy Point and Engine Vein (Figure 4.30) where it is seen in the openworks (Carlon, 1979, pl. 21; 1981, pl. II) and underground (Warrington, 1965, map 4). The other members are, in ascending order, the Beacon Lodge Sandstone, Wood Mine Conglomerate, West Mine Sandstone and Nether Alderley Sandstone; the first and third of these are 'soft' sandstones and the others are 'red-pebbly' facies.

On Alderley Edge rocks of both the 'soft' and the 'red-pebbly' sandstone facies host a geographically and stratigraphically widespread barite mineralization. The polymetallic mineralization is more localized. It occurs almost exclusively in the topmost Wilmslow Sandstone Formation and the succeeding Engine Vein Conglomerate Member, and in the Wood Mine Conglomerate and West Mine Sandstone members of the Helsby Sandstone Formation, and is visible in mine workings that, from east to west, display the different character of the mineralization and host rocks at these three successive levels (Warrington, 1965, map 2). Cobalt ore may occur in the Beacon Lodge Sandstone Member (Timberlake and Mills, 2003.)

Mineralization in the Wilmslow Sandstone Formation and the Engine Vein Conglomerate Member is seen in the east (Figure 4.30), around Stormy Point and at Engine Vein (Warrington, 1965; Pickin, 1974), where it is closely associated with WNW–ESE-trending normal faults (e.g. Carlon, 1979, pl. 4) that downthrow north-east. Mines here were worked mainly for lead ores, remnants of which remain in the fault-breccia at Engine Vein (Rowe and Burley, 1997, fig. 9a,b). Disseminations of copper ore in the Wilmslow Sandstone and Engine Vein Conglomerate were worked in the footwall on the upthrow side of the Engine Vein Fault (Warrington, 1965, map 4).

The next highest host-rock unit, the Wood Mine Conglomerate Member, crops out farther west and is seen in Wood Mine (Figure 4.30) where mineralization occurs in a succession of eight or nine fining-upwards sedimentary cycles and is more extensive and stratiform in appearance, and less clearly fault-related, than that in the lower beds farther east (Warrington, 1965, map 3). A mudstone at the top of a cycle near the middle of the succession is traceable

throughout the central part of the mine. One in a higher cycle is traceable in the southern workings but was completely eroded farther north, where, like those at other levels throughout the mine, it is represented only by mudstone debris at the base of the overlying cycle. The mine is bounded to the north by a WNW extension of the fault seen at Engine Vein, and to the south by a parallel normal fault that also downthrows north-east; beds immediately north and south of these faults respectively are not ore-bearing. The main produce of this mine was copper ore; some lead mineralization is associated with the faults at the north and south boundaries of the mine and a NW-SE-trending fault in the middle of the workings (Warrington, 1965, figs 1D, 2A; Rowe and Burley, 1997, fig. 9c,d,f.). A large stope in the northern part of the mine represents a N-Strending orebody that terminated against the northern fault; in the southern part of the mine large, flat stopes represent orebodies that extended up-dip from the southern fault (Warrington, 1965, map 3; Plant et al., 1999a, fig. 136b).

The highest host-rock unit, the West Mine Sandstone Member, crops out farther west and south-west and is seen principally in West Mine. Here, the largest bodies of copper ore in the Alderley district are represented by very extensive workings in aeolian sandstone with very few mudstone intercalations (Figure 4.30; Warrington, 1965, map 2). The south-west side of the mine is bounded by a NW-SE-trending normal fault that downthrows to the north-east, and the workings are intersected by several north-south normal faults that downthrow to the east. Mining was initially in a large opencast pit (Carlon, 1979, fig. 9, pl. 11), but progressed underground to the WNW, creating a very large stope (Carlon, 1979, pl. 7) from which an incline (Carlon, 1979, pl. 6) was driven south-west, down-dip, and intersected other large orebodies (Carlon, 1979, pl. 10). Immediately west of these, the underlying Wood Mine Conglomerate Member is exposed in the footwall of a northsouth fault (Plant et al., 1999a, fig. 136c). Farther west, long, continuous stopes at three levels in the hangingwall of the south-west boundary fault (Milodowski et al., 1999, fig. 93) are aligned parallel to that fault (Figure 4.31), to the south-west of which no orebodies were proved.

Other accessible mines on Alderley Edge include one worked for cobalt ore (Johnson, 1984a; Timberlake and Mills, 2003) and one in Brynlow Valley (Johnson, 1984b) (Figure 4.30). Alderley Edge District



Figure 4.31 Fault in the West Mine Sandstone Member at the south-west boundary of West Mine, Alderley Edge, looking south-east. The fault is normal and downthrows to the north-east (left). Ground stoped for copper ore is to the left, in the hangingwall; rock in the footwall is barren. The fault is silicified and has fractures containing a mineral assemblage that includes argentite and cinnabar (Milodowski *et al.*, 1999, fig. 93). (Photo: G. Warrington, 1979).

The Mottram St Andrew Mine is adjacent to the Alderley Horst, on the eastern (downthrow) side of the Kirkleyditch Fault (Figure 4.30). Orebodies there appear to be hosted by beds equivalent to those seen at Stormy Point and Engine Vein. The workings may be similar in character to those at Engine Vein but are poorly known. Carlon (1979) reviewed the then available information about this site; Ward (1982), and Rowe and Burley (1997, p. 331) reported underground observations.

Braithwaite (1994) assessed previous records of minerals from the Alderley district and confirmed the presence of 52 species (Table 4.1), 48 of which comprise the polymetallic assemblage; the others are barite and gypsum (common), sulphur (common?), and calcite (rare?). The polymetallic assemblage is dominated by copper minerals but includes lesser quantities of those containing lead, cobalt, nickel, manganese, zinc, arsenic, molybdenum, vanadium and other elements; multi-element complexes, some including copper, are common. Primary minerals, other than barite, are scarce and are mostly sulphides; most of the species recorded are secondary carbonates, sulphates, oxides, hydroxides and hydrous complexes.

Records of caledonite, cobaltite, connellite, cyanotrichite, enargite, heterogenite, lavendulan, libethenite, liroconite, massicot, scorodite, siderite, vanadinite and witherite were considered doubtful or were unconfirmed (Braithwaite (1994). The record of heterogenite has been discredited (Ryback *et al.*, 1998).

The following have been recorded since Braithwaite's survey: enargite (copper-arsenic sulphide) (Ixer and Budd, 1998); the cobaltnickel-arsenic sulphides cobaltite (Milodowski *et al.*, 1999, pls 25, 27) and possibly siegenite (Milodowski *et al.*, 1999, pl. 26), and a leadchloro-phosphate with arsenic (mimetite) (Milodowski *et al.*, 1999, pl. 28, fig. 93); silver sulphide (acanthite, as 'argentite'), mercury sulphide (cinnabar), a hydrated copper silicate (dioptase), a lead carbonate (hydrocerrusite), hydrated iron oxide (goethite) and manganese-

	COMMON	UNCOMMON	RARE	VERY RARE
MAIN COPPER MINERALS				
Carbonates (hydrated)	Azurite Malachite			
Silicates (hydrated)	Chrysocolla			Plancheite
Sulphides	Covelline Djurleite	Chalcocite	Spionkopite	
Cu-Fe sulphides	Bornite Chalcopyrite		Idaite	
Sulphates (hydrated)		Brochantite	Langite	Antlerite Posnjakite
Cu			Native copper	
Oxide			Cuprite	
Arsenates (hydrated)				Olivenite Tyrolite (sulphatian)
MAIN LEAD MINERALS				
Carbonate	Cerrusite			
Sulphide	Galena			
Chloro-phosphate + As	Pyromorphite			
Sulphate			Anglesite	
Pb-Cu-Fe-Al sulphate (hydrated)			Beaverite	
Pb-Fe-As sulphate (hydrated)	1 2 2 1			Beudantite
Sulphato-carbonate (hydrated)				Leadhillite
Oxide	rom cust to w	Sundston	Member, crops o	Minium
Molybdate	a near the sum the	petra a restant and su	ne West Auge Sandan	Wulfenite
MAIN ZINC MINERALS	all Mineral Mobile		AND	
Sulphide	a set for the produce by	Sphalerite	Contraction of the second second	
Silicate (hydrated)	and the second state		a survey of the second strength	Hemimorphite
Carbonate	and a second		and the second second	Smithsonite
OTHER SPECIES		and a second	a second and a second second	
Co-Ni-Mn complex (hydrated)	Asbolane		a har the state of the state	
Fe oxide	Limonite		The second s	
Fe-Ni sulphide	and and the sector	Bravoite	Contract Contraction of Contract of Contra	And a second second second
Ni-As sulphide	n and then origin	Gersdorffite	all about the second	REALTH EXCHANCEMENT
K-Fe sulphate (hydrated)	A CHARTEN STATE (CO.)	Jarosite	ienenne onnesp	CHILDOOLUS (DEPERT)
Fe-Cu sulphate (hydrated)	o me localiticos	Melanterite var.	pisanite	edq. objuojaejita
Fe sulphides	g dirita gatin bajahna	Pyrite	index signed by the second second	Marcasite
Pb-Cu sulphate (hydrated)	th Shide pullips a	idil , ghideagan	Linarite	charkoterra (lutke)
Pb-Cu vanadate + As (hydrated)	a instant devotion	bie meda nid	Mottramite	involutile an invited
Ni-Co arsenide	subbirb benefits	ten basilture	Pararammelsbergite	weileliter interview
Co-Fe sulphide + Zn, Ag	OR Beer Besteld	ass deliverity	Tetrahedrite	Follow the december of the work
Zn-Cu carbonate (hydrated)	a Buston Bundand	and an and an	CONDISIONER FOR	Aurichalcite
Co arsenate (hydrated)	and the second second		and a second and	Erythrite
Pb-Cu-Al sulphate (hydrated)	forman a	tents the second	and the second second	Osarizawaite
K-Fe arsenate (hydrated)		1	and the second	Pharmacosiderite
Ag			Action and assess	Silver

 Table 4.1 Confirmed occurrences and relative abundances of ore minerals from the Alderley Edge mining district (from Braithwaite, 1994).

iron oxyhydroxide (Milodowski *et al.*, 1999, fig. 93); gold (Milodowski *et al.*, 1999, p. 145, fig. 94). Holmes *et al.* (1983) detected < 3 ppm of uranium in Alderley ore; cadmium (Ixer and Vaughan, 1982; Holmes *et al.*, 1983), chromium

and zirconium (Mohr, 1964a, table 2), selenium and strontium (Milodowski *et al.*, 1999, pp. 141, 148), and cerium and lanthanum (Timberlake and Mills, 2003, table 1) have also been reported. Ixer and Stanley (1998) referred to Alderley Edge District

the occurrence of the copper-iron-arsenic sulphide tennantite in chalcopyrite, but the source cited (Ixer and Budd, 1998) does not contain that record.

With the exception of barite, which is widespread in the Wilmslow Sandstone and Helsby Sandstone formations, primary minerals only occur in proximity to faults. Secondary species, which include the bulk of the copper ores, are more widely dispersed and occur as disseminations occupying pore spaces in the host-rock sandstones, particularly in the Wood Mine Conglomerate and the West Mine Sandstone members. The host rocks are typically red-brown in colour but sites of polymetallic mineralization are bleached, colourless to yellow, with a fairly distinct boundary (Warrington, 1965, fig. 1B) that is often a convex front that indicates the direction of fluid migration.

The Alderley deposits were worked mainly for copper ore, but lead ore, some of which yielded silver, was also produced, and cobalt ore was worked early in the 19th century.

Early mining on Alderley Edge may be indicated by a radiocarbon date of 3550 ± 70 years from charcoal associated with stone artefacts found in an excavation by the Engine Vein openworks (Timberlake and King, 2005, pp. 42-44). Roman coins were found in the 'Pot Shaft', also at Engine Vein (Nevell et al., 2005; Timberlake and Kidd, 2005). The earliest known record of 'Myne holes' on Alderley Edge, from 1598 (Kidd and Taylor, 2005, p. 178), does not indicate whether there was contemporary mining or whether the excavations, around Stormy Point, were from an earlier period. Mining activity beginning in 1693 was implied in 1696, in the oldest known contemporary record of such activity. Mining was documented at various times in the 18th and 19th centuries and in the early 20th century, and finally ceased in 1919 (Carlon, 1979; Warrington, 1981). The most productive phases were in the mid-18th century and between 1857 and 1877. Prior to 1857 copper was recovered by smelting, with varying success due to the nature and low grade of much of the ore. From 1857 extraction by an acid-leaching process (Carlon, 1979; Warrington, 1981) proved very effective and enabled the profitable treatment of large tonnages of the low-grade disseminated ores that formed the bulk of the deposits in the Alderley district. Warrington (1981) suggested, from recorded and estimated output figures (Warrington, 1981, fig. 4), that copper-ore production between 1857 and 1877 may have been about 250 000 tons, from which about 3100 tons of copper were recovered. No output records exist for earlier periods, and output in the early 20th century, when acid-leaching was also used, was very small (Warrington, 1981, fig. 6). Small quantities of lead ore were produced between 1859 and 1861, and in 1918; until 1864, concentrates containing cobalt and nickel were produced.

Mining took place at Mottram St Andrew in the 19th century, and possibly earlier, but ceased in 1865. From 1860 the acid-leaching process adopted at the Alderley Edge mines was used; records are fragmentary but output was on a much smaller scale. Unlike the Alderley Edge mines, that at Mottram St Andrew suffered from water ingress and proved unprofitable. It has, however, a place in the annals of chemistry and mineralogy as being the source of mine residues on which research that established the valency of vanadium was carried out (Roscoe, 1868), and as the site for which mottramite, a lead-coppervanadate, was named (Roscoe, 1876). There is, however, debate as to whether specimens Roscoe based this mineral upon originated from the eponymous site, or from one in north Shropshire (Braithwaite, 1994). Manning (1991) incorrectly cited Mottram St Andrew as the type locality for roscoelite, a second vanadium mineral named by Roscoe (1876).

Interpretation

The sediments that host mineralization in the Alderley district are of continental, part-aeolian and part-fluvial, origin. They were deposited in the Cheshire Basin during a phase of active rifting that commenced in Permian times and continued through the Triassic and into the Jurassic, allowing the basin to accommodate considerable thicknesses of deposits of those ages (Chadwick *et al.*, 1999; Warrington *et al.*, 1999).

The orebody at Engine Vein may be interpreted as the result of ponding of mineralizing fluids in the footwall of a fault that formed a barrier to lateral, up-dip migration below mudstones in the Engine Vein Conglomerate Member that acted as aquicludes and prevented vertical migration (Plant *et al.*, 1999a, p. 212, fig. 136a).

The nature of the Wood Mine workings reflects the discontinuous nature of the orebodies in the Wood Mine Conglomerate Member. This is attributable to the presence of laterally persistent mudstone aquicludes that prevented vertical migration of mineralizing fluids, and of beds that contain quantities of mudstone debris and were partial barriers to such migration. Some orebodies are confined to one cycle whereas others extend through several cycles (Warrington, 1965, map 3). Convex fronts to the orebodies (e.g. Warrington, 1965, fig. 1B) are consistent with fluid flow away from faults. Orebodies in the northern and central parts of the mine may, like those in the footwall at Engine Vein, reflect ponding of fluids against faults, in contrast to those at the south which reflect fluid movement up-dip, away from the fault, in its hangingwall (Plant et al., 1999a, p. 212, fig. 136b).

The form of the West Mine workings reflects the comparatively homogeneous nature of the aeolian sandstone host-rock which, in marked contrast to that in Wood Mine, is almost devoid of mudstone aquicludes. Though faults influence their overall disposition, many of the orebodies in West Mine extend up-dip in the hangingwalls of the major faults (Milodowski *et al.*, 1999, fig. 93; Plant *et al.*, 1999a, fig. 136c–e), and mineral fabrics are consistent with migration of fluids away from the faults (Plant *et al.*, 1999a, p. 212).

The mineralization in the Alderley district was considered to be syngenetic (i.e. deposited contemporaneously with the host sediments) (Dewey and Eastwood, 1925, and earlier authors) or epigenetic (i.e. introduced subsequently; e.g. Taylor et al., 1963; Warrington, 1965; Carlon, 1979). A process involving epigenesis followed by syngenesis was invoked by Mohr (1964a). Warrington (1965) originally advocated a magmatic source for mineralizing fluids but, by 1977 (in Warrington, 1980b), had envisaged one involving chloride-rich intrastratal brines, a view reached independently by Carlon (1979, citing unpublished work, 1975). Warrington (1980b, fig. 1) demonstrated that the Alderley Horst formed a structural trap for fluids migrating through the Sherwood Sandstone Group formations beneath an impermeable cover of Mercia Mudstone Group mudstones. Warrington (1980b) proposed that the brines became enriched in metallic ions by leaching sediments through which they migrated, with an additional or alternative source of minerals being fluids of more deep-seated origin permeating the sandstones and mixing with intrastratal brines, possibly during rift-related tectonic activity that Mohr (1964a) considered potentially relevant to the Alderley mineralization and which affected Britain in the early Mesozoic, with faulting in the Cheshire Basin, and the creation of structures such as the Alderley Horst, occurring then. Enhanced geothermal activity associated with rifting may have induced or stimulated migration of mineral-bearing fluids into the horst, where minerals were deposited in a reducing environment, possibly created by hydrocarbons migrating into the classical hydrocarbon trap formed by that structure (Warrington, 1980b). This basic scenario has been adopted and developed by succeeding workers (Holmes et al., 1983; Naylor et al., 1989; Rowe et al., 1993; Rowe and Burley, 1997; Milodowski et al., 1999; Plant et al., 1999a).

Ixer and Vaughan (1982), in the first paragenesis for the Alderley mineralization, proposed a four-stage, polyphase origin. Authigenic anatase and quartz overgrowths with bravoite, pyrite and chalcopyrite developed in the earliest stages of sandstone host-rock diagenesis. In the third stage, primary sulphides formed vein-fillings and intragranular cements in and adjacent to faults. A paragenetic sequence of: bravoite and nickel-cobalt-iron sulpharsenides pyrite - chalcopyrite - sphalerite - galena was reported from Stormy Point, Engine Vein and Wood Mine. In the final stage these sulphides were largely replaced by secondary species, or by carbonates and sulphates that enclose vestiges of the primary minerals. The relationship of mineralization to diagenesis recognized in this work has been emphasized by Holmes et al. (1983) and subsequent workers.

The first fluid-inclusion data from Cheshire Basin ore deposits (Naylor et al., 1989) indicated that the mineralizing fluid was a basinal brine (cf. Carlon, 1979; Warrington, 1980b) with a salinity of 9-22 wt% NaCl equivalent and a temperature of 60°-70°C. Sulphur isotope data from barite (Naylor et al., 1989) indicated that the sulphate came from Mercia Mudstone Group evaporites, and comparable isotope values from sulphide minerals suggested that they resulted from the reduction of sulphate-bearing fluids from the same source; this reduction was considered to result from bacteriogenic action or interaction with hydrocarbons (cf. Warrington, Metcalfe et al. (1993) presented a 1980b). hydrogeochemical model involving mixing of a Alderley Edge District

reducing fluid from a deep-seated, probably Carboniferous, source, with red-bed formation water. This reproduced the main features of the Alderley ore deposits, with a requirement of only 3–4% of the total fluid being from the deep source. Rowe and Burley (1997) invoked a comparable fluid mixing process but suggested that the sulphate-rich brine originated from either the Mercia Mudstone Group or from Permian evaporites in the Manchester Marls Formation, underlying the Sherwood Sandstone Group.

The earliest attempt at dating the Alderley mineralization isotopically, using galena (Moorbath, 1962), gave an age of 210 ± 60 Ma (mid-Permian to late Jurassic). The structuraltrap scenario of Warrington (1980b) implied a maximum Mid-Triassic (Anisian) age, after the lower Mercia Mudstone Group formations were deposited, forming a seal above the Sherwood Sandstone Group. Rowe and Burley (1997) concluded, from studies at Engine Vein and Wood Mine, that mineralization post-dated faulting, and suggested that primary mineralization occurred during late Mesozoic burial or Tertiary uplift. Alteration to secondary species by supergene oxidizing groundwaters, and the migration of mobile products away from faultrelated primary mineralization sites, therefore occurred later in the Tertiary.

The latest study of the Alderley mineralization was in a multidisciplinary investigation of the Cheshire Basin (Plant et al., 1999b) in which a four-stage metallogenic model, commencing with remobilization of metals by breakdown of parent minerals during eodiagenesis of the Triassic succession, was proposed. During a complex mesodiagenesis (Milodowski et al., 1999), successive phases of density-driven fluid expulsion from the Mercia Mudstone Group into the Sherwood Sandstone Group occurred. Early fluids were sulphate-rich and resulted in sandstones in the latter group being tightly cemented with anhydrite. Later fluids were metalliferous brines that flowed through that group towards basin-bounding faults where mixing with small amounts of reducing fluids, probably sourced by Carboniferous rocks, caused precipitation of the polymetallic assemblage; contrary to Rowe and Burley's (1997) conclusion, this was regarded as occurring in latest Triassic to Early Jurassic times, between c. 205 Ma and 175 Ma. The primary mineralization was complex and episodic and, contrary to Rowe and Burley's (1997) view, was associated with faulting and fracturing; a paragenesis reported from West Mine (Milodowski *et al.*, 1999) differs from those of Ixer and Vaughan (1982) and Naylor *et al.* (1989) from other Alderley sites. The primary assemblage was extensively altered after 65 Ma, during telodiagenesis following post-Cretaceous basin inversion.

Conclusions

The Alderley Edge mining district contains an extensive and uniquely accessible example of a copper-dominated polymetallic mineralization hosted by red-bed sedimentary rocks of late Early to early Mid-Triassic age. Host rocks are predominantly aeolian and fluvial arenaceous deposits, mainly members of the Helsby Sandstone Formation. It is the largest and most extensively studied and documented of such occurrences in Britain. Weathered outcrops of parts of the ore-bearing succession are complemented by extensive sections in more than 15 km of mine workings in which the influence of structure and the character of different hostrocks on the form and size of the orebodies may be appreciated in a three-dimensional sense in an unweathered condition.

The mineralization was originally regarded as syngenetic but is now considered to be epigenetic. An origin from intrastratal brines, rather than fluids of magmatic origin, was proposed in the late 1970s, and has been substantiated by morerecent research involving fluid-inclusion, isotope and other studies; a paragenesis has been established. Mineralization occurs in a structural trap, the Alderley Horst, capped by the impermeable Mercia Mudstone Group. Metals were sourced by dissolution of detrital grains during migration of low-temperature brines through Triassic formations, and additionally, or alternatively, from Carboniferous shales, and were precipitated in an organic-rich reducing environment. Primary mineralization includes geographically and stratigraphically widespread barite and metallic sulphides localized around faults, and may be of latest Triassic to Early Jurassic age. The bulk of the mineral assemblage comprises secondary species produced by oxidizing groundwaters acting on primary minerals and migrating away from faults to produce sandstone-hosted disseminations in Tertiary times. The full mineral assemblage is exceptionally diverse and comprises over 60 species.

The site is a geological Site of Special Scientific Interest (SSSI) and is of national and international importance for educational and scientific purposes. Examples of this type of mineralization elsewhere in Britain are on a smaller scale; most have limited or no access, as is the case with similar deposits hosted by Triassic sediments elsewhere in Europe (e.g. those of Maubach-Mechernich in Germany). The district is important for indications of early mining and was a source of cobalt ore in the early 18th century and a major producer of copper ore in the mid-18th and 19th centuries. Work that established the valency of vanadium was carried out on mine residues from Mottram St Andrew Mine, and the mineral mottramite is named for that locality.

SNAILBEACH MINE, SHROPSHIRE (SJ 374 023)

Introduction

Snailbeach Mine was the largest and most significant single mine within the West Shropshire Orefield, which occurs within an inlier of folded Cambrian and Ordovician rocks that are faulted against or unconformably overlain by Silurian and Carboniferous rocks to the north, west and south, and by Neoproterozoic Longmyndian Supergroup rocks to the east (Figure 4.32). Lead-zinc-barium mineralization occurs in E-Wand ENE-WSW-trending faults that cut resistant horizons within the Lower Ordovician (Arenig) Mytton Flags Formation (Dines, 1958; Dunham et al., 1978; Gradstein et al., 2004). Dines (1958) describes the geology in detail; the Mytton Flags Formation are about 1000 m thick, dipping at 50° WNW, overlying the Stiperstones Quartzite Formation and underlying the Hope Shale Formation (Figure 4.32). At the present time (2008), the visible traces of mining are dominated by spoil heaps (Figure 4.33).

The West Shropshire Orefield is zoned, with the zinc ore mineral sphalerite at greatest depth, then sphalerite and galena at shallower depths, and barite and calcite closest to the surface. According to Dunham *et al.* (1978), between 1845 and 1913 the orefield overall produced 250 000 tons of lead ore, no more than 25 000 tons of zinc ore, and 500 000 tons of barite (mainly from **Huglith Mine**, see GCR site report, this chapter). Silver production from Snailbeach was not significant because of the low silver content of the galena ('1/2 ounce of silver per ton of lead'; Dines, 1958). Wall-rock alteration in the orefield associated with the mineralization has been dated at 355 Ma (Ineson and Mitchell, 1975), corresponding to an early Carboniferous age.

Description

Snailbeach Mine is the most recent of the Shropshire mines to close (in 1919), and dates back probably to the 12th and 13th centuries (Smith, 1922). There is evidence of Roman mineworkings at or near this location, as a Roman pig of lead was found in Snailbeach Mine (Dines, 1958). The mine won most ore from a lead vein ('Main Vein' or 'Snailbeach Vein') that reached thicknesses of over 7 m, most usually 3 m, with 'ore-shoots' of galena extending for up to 50 m along the length of the vein. As the mineralization occurs within the more competent sedimentary units, ore-shoots follow these down-dip (Dines, 1958). The vein itself dips at 60° S at depth, and is near-vertical close to the surface (Carruthers et al., 1916). Workings extended for approximately 1 km along the length of the eastwest vein, and to depths of 500 m below the surface (Smith, 1922). Parallel veins to the south ('South Vein') and north ('Black Tom Vein') were also mined (Dines, 1958). In addition to galena, sphalerite and barite, the barium carbonate mineral witherite is reported by Smith (1922), together with pyrite and minium (lead oxide - a weathering product). Calcite (Figure 4.34) and quartz are the gangue minerals. The ore raised at Snailbeach was crushed with some sorting and handpicking (of galena and witherite) on site, leading to extensive surface operations and spoilheaps (Carruthers et al., 1916). After picking, the ore was transported by rail to Minsterley.

Interpretation

The origin of the Snailbeach mineral deposits is constrained by geochemical as well as geological information which demonstrates a strong lithological control on the mineralization. The West Shropshire Orefield has yielded bitumens associated with the mineral deposits, in some respects similar to those reported for **Windy Knoll** (see GCR report, this chapter). Carruthers *et al.* (1916) reported the presence of mineral oil that 'oozes from cavities' in barite in the



Figure 4.32 Sketch map of the West Shropshire Orefield in the vicinity of Snailbeach Mine. After Dines (1958).

upper levels of Snailbeach Mine, and this observation is repeated in later descriptions of the mine (e.g. Dines, 1958).

Parnell (1983) discussed the origin of the Snailbeach hydrocarbons in the context of the occurrences of these materials within the Shropshire region, concluding that the bitumen was formed from hydrocarbons that entered the fractured mineral vein system from Carboniferous source rocks to the north, and that what has been observed in the mine workings is a relic of a Carboniferous petroleum reservoir system. Using organic geochemical techniques, Robinson *et al.* (1986) confirmed a South Pennine Orefield: Cheshire, Leicestershire and Shropshire



Figure 4.33 Spoil heaps at Snailbeach Mine. (Photo: J. Aumônier.)



Figure 4.34 Calcite on spoil heaps at Snailbeach Mine. (Photo: J. Aumônier.)

'conventional' biogenic source for the bitumens, and Parnell *et al.* (1991) used biomarker evidence to demonstrate that the Snailbeach bitumens are associated with the English Midlands Carboniferous-sourced petroleum province, whereas other bitumens in south Shropshire and farther south are associated with Ordovician source rocks.

Other geochemical information that bears on the origin of the Snailbeach mineral deposits includes sulphur isotope data for mineral deposits of this age from across the British Isles (Pattrick and Russell, 1989). Although the precise locations of samples reported in this study are not given, data for 'west Shropshire' almost certainly include samples from Snailbeach. In any case, Pattrick and Russell (1989) commented that the δ¹³S values for the West Shropshire Orefield are very similar, with galena having an average value of 6.1‰, sphalerite 9.65‰ and barite 17.81‰ (all relative to Canyon Diablo Troilite). These values are very similar to those of the mineral deposits of the Tyndrum Main Mine GCR site (Scotland), suggesting a similar origin. Sulphide was derived from underlying rocks whilst sulphate was derived from groundwater or surface water, precipitating barite in the upper levels of the mineralizing system.

Conclusions

Snailbeach Mine is an example of mineralization within Lower Palaeozoic rocks that has a complex subsequent history overprinted by the impact of a Carboniferous petroleum system. The distribution of the metal ore minerals is clearly controlled by wall-rock lithology, with sulphur derived from underlying formations. Barite mineralization is related to the charateristics and geochemistry of younger rocks, and may genetically be associated with petroleum reservoir processes.

HUGLITH MINE, SHROPSHIRE (SJ 405 016)

Introduction

Huglith Mine (SJ 403 015–SJ 407 016) lies within the West Shropshire Orefield in the Shelve– Habberley district (Dines, 1959), approximately 2 km south of Habberley (see Figure 4.35 for location and geological map). The mineral deposits in this region are hosted by two geologically diverse districts either side of the Pontesford Fault (Pattrick and Bowell, 1991), also known as the 'Habberley Fault', which defines the eastern margin of, and strikes parallel (NNE-SSW) with, the W-dipping Stiperstones Quartzite Formation (Arenig) ridge (Dines, 1959). The fault separates the Precambrian Ba-Cu region of the orefield from the Ordovician Pb-Zn-Ba region in the Shelve area to the west, although the western margin of the fault is actually composed of Shineton Shales Formation of Tremadoc (Cambrian) age. Huglith Mine lies to the east of the Pontesford Fault and is one of a number of mines that worked barite and copper ores from the Neoproterozoic Wentnor Group strata (Pattrick and Bowell, 1991) (see Figure 4.35). Barite and lead and zinc ores were mined from flags and shales of the Mytton Flags Formation (Arenig) of the Shelve Inlier to the west of the fault (Pattrick and Bowell, 1991).

Economically important barite and copper deposits were mined at Huglith episodically from the early 19th century until 1945, when the mine closed. Initially copper ores were worked at the site, but from the early 20th century barite was the principal ore; by 1936 the mine was producing over 20 000 tons of barite per year and was the largest mine of its kind in the county. The ore was 95% pure, the main impurity being silica. Records indicate that in total 295 108 tons of barite were produced from Huglith Mine before its closure in 1945.

There were originally two mines at Huglith, No. 1 and No. 2, but only No. 2 was developed significantly. The mine worked three major barite-rich veins that were up to 120 m in length and 2–6 m in width (Carruthers *et al.*, 1916). The veins were principally worked via stopes with associated shafts, the latter of which were sunk to depths of over 70 m in some cases.

Description

The geology of the Habberley area is summarized in Figure 4.35. Two sets of faults are shown to trend east–west and ESE–WNW; both these fault sets are mineralized and have a predominantly horizontal movement. The veins occupying the faults are wide but show no evidence of brecciation, although more than one phase of barite deposition is indicated.

The exposed Bayston–Oakswood Formation strata that host the Huglith deposits dip easterly



Figure 4.35 Sketch map of the Habberley area showing the relationship of mineralization to geology. After Dines (1958).

(Pocock *et al.*, 1938; Dines, 1959) and are buffand grey-coloured coarse sandstones grading into sandy shales and mudstones. These units are interpreted to be of fluvial origin and are red or purple in colour, but in places are stained green or blue when in close proximity to the mineralized veins. This is due to the oxidation of secondary copper minerals within the vein. Some brown staining from hydrocarbon seeps is also evident.

The vein deposits typically comprise thickly banded pink, red and sometimes white barite which swells up to 6 m in thickness in places. The pink colouration of the barite is attributed to absorption of iron from the ferruginous Neoproterozoic strata (Dines, 1959). Traces of secondary copper minerals (in the form of chalcocite stringers and encrustations of azurite and malachite) and quartz with occasional calcite (Dines, 1959) are also evident in the vein infill. Pattrick and Bowell (1991) suggested that the banding observed in the Huglith barite deposits, and in the mineral deposits to the west of the Pontesford Fault, indicates that the mineralizing fluids were likely to have entered the region in a series of contemporaneous pulses, and that these controlled the development of the vein system in the West Shropshire Orefield. To this end, the same authors suggested that this could only have been achieved in a well-connected, open fault-fracture system.

The three principal veins worked at Huglith were the Main Vein (also known as 'No. 2 Vein'), the Riddleswood Vein and the Mud Vein, which occupy steep, S-dipping (70°) oblique-slip faults and generally trend ENE–WSW along bearings varying between 068° and 073°. The Main Vein occupies a fault that shows dextral (right-lateral) movement with a lateral displacement of some 300 m. To the west, mineralization in the Main Vein is truncated sub-surface by the Pontesford Fault, and to the east, the vein is observed to taper and eventually terminate along strike after approximately 800 m.

Much of the mined area is now forested, which makes navigation difficult; however, surface exposure of the workings around the Main Vein is still generally good, and parts of the Riddleswood Vein workings are also accessible. The line of the Main Vein can clearly be traced

Huglith Mine

up Westcott Hill (SJ 406 014) along an ENE-WSW bearing, and there are many sections where the vein has been worked to the surface. Large stopes dominate the Main Vein workings up the hillside, and it is possible to observe the vertical extent of these down-dip of the fault planes. In places remnant patches of pink-white barite are evident on either side of the fault planes, as are stringers of unworked, heavily brecciated vein that appear to branch off at low angles to the Main Vein. Where the vein has been worked to great depths, 'arches' of barite have been left in place at higher levels; these structures can be seen bridging gaps between fault planes where the vein infill has been worked out. These were presumably left intact for stability reasons.

Dines (1958) also reported good exposures of the vein at the portals of the Adit Level and the Badger Level. The vein can be seen to split into several parts at an opencast area in front of the Adit Level; around this area, brecciated country rock between the branched vein is cross-cut by stringers of barite.

A cross-cut was driven northwards from the Main Vein to intersect the Riddleswood and Mud veins between the years 1932–1936. Between the Main Vein and Riddleswood Vein some 15 S-dipping stringers and veins of barite were intersected; these were up to 0.15 m thick in places. From Riddleswood Vein towards Mud Vein a further 14 stringers were crossed, all N-dipping.

Various underground surveys have been conducted at Huglith Mine in an attempt to investigate the remains of mining activities and sub-surface deposits. However, these surveys have been dependent on low water-levels for access to the underground workings, some of which have also suffered collapse. Striking azurite pearl strings have been observed within the adit levels and shafts associated with the Main Vein, and more spectacular remnants of the Huglith ore mineralization may be expected in the underground workings where erosion has not played such a significant part.

The remains of the Adit Level and Badger Level, together with various shafts (including the main shaft) and buildings (winding engine-house, compressor and boiler, metal chimney and smithy) associated with the mine works, can be seen at the base of Westcott Hill to the west of the exposed Main Vein. A Forestry Commission track lies just to the west of these features. North of this area a tramway entered the mine; this entrance is now a large open stope dipping at 70° south, towards the vein. Above the Adit Level the vein is stoped out to the surface, forming a gash in the wooded hillside, and above this the Badger Level can be reached farther up Westcott Hill, following the ENE trend of the vein. Above the Badger Level, large and dangerous open stopes have been used to work the vein up the hillside.

Various access points to the main underground workings via the east and south faces of Westcott Hill were also used when the mine was producing ore. To the north and north-east of the latter are the disused shafts (now commonly backfilled) and exposed stopes associated with the Riddleswood Vein, the line of which can similarly be followed up the hill along a ENE–WSW bearing. Today there is no apparent access to the Mud Vein workings, and, like many of the adit-level workings at Huglith, they are likely to be flooded. Further studies of the sub-surface mineralization at this site are consequently restricted by limited access to the underground mine-workings.

No workable or significant sulphide-bearing ores have been observed at Huglith Mine, but the mines to the west of the fault have yielded significant amounts of zinc and lead ores (principally sphalerite and galena) with patches and stringers of copper ore (chalcopyrite) at depth.

Interpretation

Various studies relating to the genesis of the West Shropshire Orefield have been undertaken over the years, the most widely accepted of which are those by Hall (1922), Dines (1959), and Pattrick and Bowell (1991). Few works discuss solely the genesis of the mineral deposits at Huglith Mine, but the latter authors provided a comprehensive review of the current models of the genesis for the entirety of the West Shropshire Orefield, which encompasses the many smaller mined districts either side of the Pontesford Fault. The work by Pattrick and Bowell (1991) incorporates evidence from fluidinclusion studies, sulphur isotopic ratios and sphalerite chemistry to support the various hypotheses proposed in the review.

The findings of sulphur isotopic ratio studies using barite samples from Huglith Mine and from the west side of the Pontesford Fault led Pattrick and Bowell (1991) to conclude that the source of mineralizing fluids is the same for the entire West Shropshire Orefield. The vein and vein breccias that comprise the orefield in the region are best developed in the more competent strata of the Ordovician rocks on the west side of the fault, and this fact has been used to identify a paragenetic sequence for the mineralization in the region. Barite and galena tend to dominate at higher levels in the orebodies on the west side of the fault, and textural evidence from microscope studies conducted by Pattrick and Bowell (1991) has allowed the order of mineral precipitation to be deduced. Several initial stages of quartz, sphalerite and calcite precipitation are followed by a penultimate phase of galena, chalcopyrite and barite, and a final phase of barite precipitation. These latter phases are significant, as by deduction the Huglith barite and copper deposits can be assigned to a late stage in the formation of the West Shropshire Orefield.

Further characterization of the mineralizing fluids has been provided by the use of fluidinclusion studies. Thermometric analysis of fluid inclusions in barite and calcite samples collected at Huglith Mine, as well as from several other localities either side of the Pontesford Fault, has indicated that the mineralizing fluids that sourced the West Shropshire Orefield were highly saline CaCl2-rich brines, and contained MgCl₂ salts in addition to NaCl (Pattrick and Bowell, 1991). Homogenization temperatures yielded from barite inclusions indicate that precipitation occurred from comparatively lowtemperature fluids, with an upper temperature limit of 120°C. Given the nature of mineralization in the region, Pattrick and Bowell (1991) inferred that precipitation of the barite deposits at Huglith Mine and on the west side of the Pontesford Fault occurred at shallow depth (< 1 km) under hydrostatic pressure.

Considering these data, an appropriate model for the precipitation of barite (and late calcite) at Huglith Mine and at other localities on the east side of the Pontesford Fault in the West Shropshire Orefield has been proposed by Pattrick and Bowell (1991) to involve the largescale mixing of two separate fluids. The sulphate source for the barite is suggested to be an oxidized, sulphate-bearing low-salinity fluid in the upper regions of the vein system, which represented an overlying reservoir; several years previously Pattrick and Russell (1989) suggested that this may have been a type of early Carboniferous seawater derived from evaporitic margins. Pattrick and Bowell (1991) proposed that a late mixing event of the latter fluid with an earlier input of a rising, high-temperature, highsalinity, Ba-rich brine in the upper regions of a well-connected fracture-system (followed by subsequent cooling of the fluids) would explain the existence of barite in the uppermost reaches of the orefield, as at Huglith Mine. The lack of sulphide minerals in the Huglith Mine workings suggests that either sulphides may be present at greater depth or that the section of the fracture system beneath Huglith Mine only opened in the later stages of mineralization, when sulphide precipitation had ceased in other parts of the orefield.

Hall (1922) suggested that the copper ores commonly associated with the barite veins may be the result of alteration at depth of a primary ore, and noted the widespread distribution of secondary copper ores that occur between the Stiperstones Ridge and Longmynd area. Murchison (1839) regarded these deposits as having emanated from 'trap rocks' (igneous rocks) in the area prior to secondary alteration. Pocock et al. (1938) also suggested that the copper minerals present at Huglith Mine are the result of secondary alteration, and not primary vein infills in situ. Their presence has led to suggestions that significant Cu-sulphides exist at depth (Dines, 1959), and this hypothesis is further supported by the inferred presence of late high-salinity Cu-rich fluids to the west of the Pontesford Fault (Pattrick and Bowell, 1991).

The age of mineralization at Huglith Mine, as for the entirety of the West Shropshire Orefield, is constrained by fault movements and intrusive rocks, which place the mineralizing event between the early Devonian and the Westphalian (Dines, 1959; Ineson and Mitchell, 1975). Radiometric dating (Ineson and Mitchell, 1975), together with other characteristics, have led to the interpretation that the orefield is one of a number of Lower Carboniferous Pb and Zn vein systems hosted by Palaeozoic or older rocks of the British Isles (Russell, 1972, 1976; Pattrick and Russell, 1989), and is contemporary with the carbonate-hosted stratiform base-metal mineralization in central Ireland, also thought to have been formed in response to Dinantian extensional tectonics (Boyce et al., 1983). These deposits are classified as being of the Mississippi Valley-type. An extensional regime would encourage fluid migration, where reactivated Caledonian faults would have provided

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conduits through which hydrothermal fluids could flow. The Pontesford Fault is interpreted either as part of the Church Stretton Fault System (Smith, 1987) or part of the Pontesford Lineament, a structure that has controlled the geological development of the region from mid-Ordovician to Triassic times (Woodcock, 1984), and would have provided an ideal network of channels for fluid flow.

Conclusions

Huglith Mine is renowned for the economically significant barite deposits that were once mined there. Studies of the associated mineralization and of the surrounding district have aided greatly in unravelling the true genesis of the deposits and in identifying their close association with the westerly region of the West Shropshire Orefield. The barite mineralization at Huglith Mine almost certainly succeeds the sulphide mineralization at Shelve to the west of the Pontesford Fault, and as at other localities within the orefield, the barite deposits at Huglith Mine are considered to be a late phase of the same mineralizing event. The latter was characterized by an initial input of saline hydrothermal fluids that rose through a well-connected fracture-system, precipitating sulphides and cooling with time and vertical extent. Mixing of this fluid with a reservoir of sulphate-rich waters in the upper sections of the vein system led to the later precipitation of barite and calcite deposits high in the orefield stratigraphy, as observed at Huglith Mine. Dinantian extensional tectonics are thought to be responsible for the initial fluid migration in the region, with Carboniferous seawater as a possible fluid source within the Lower Palaeozoic or Precambrian sequences. Thus a modified basinal brine model is favoured, but there still remains a lack of clarity over the exact derivation of the fluids responsible for the mineralization present at Huglith Mine and in the associated district.