Mineralization of England and Wales

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Chapter 3

The Northern Pennines

B. Young

INTRODUCTION

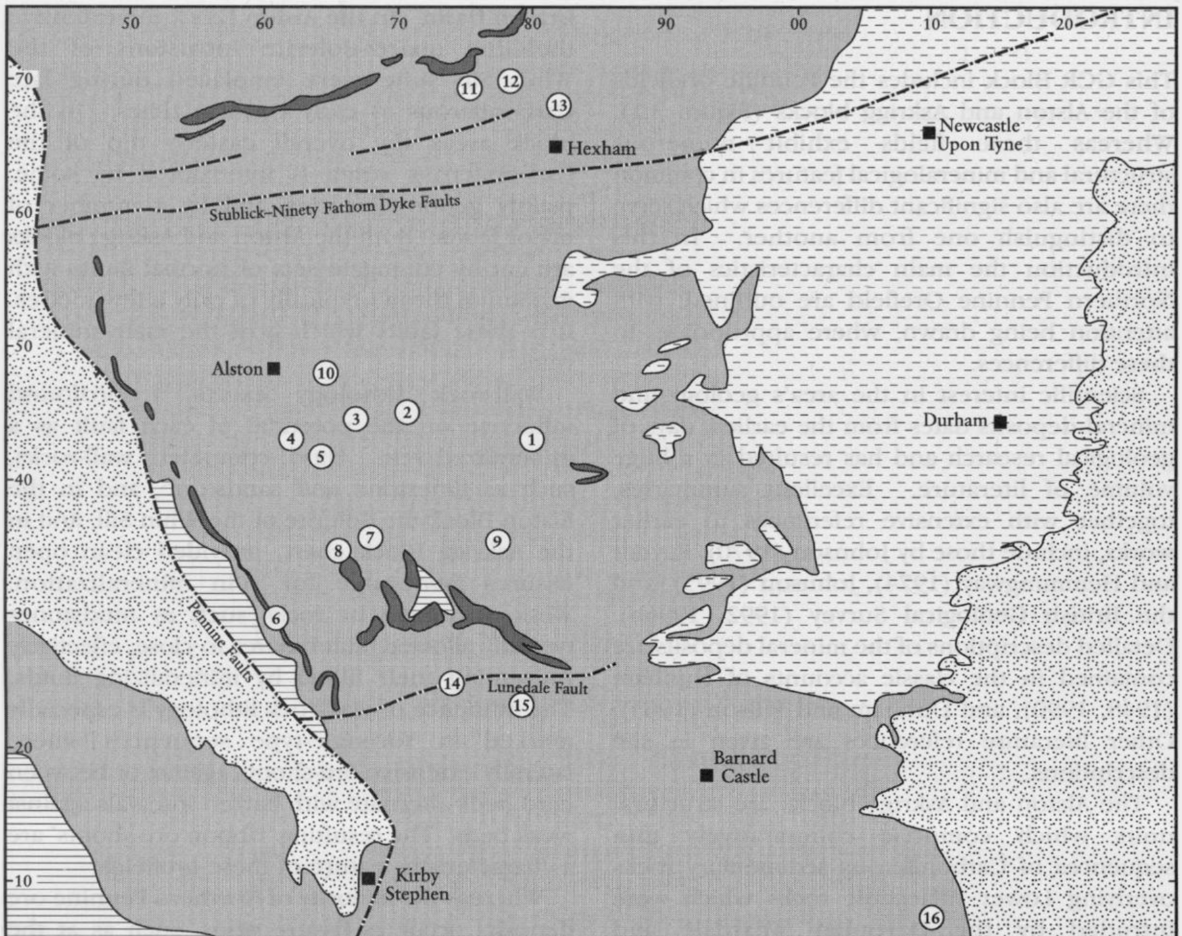
This GCR Block includes the Pennine orefields of the Alston and Askrigg blocks (Figure 3.1). Whereas these fields exhibit numerous structural and mineralogical features in common there are also significant differences which serve to distinguish one from another. In this introduction the main characteristics of the Northern Pennine Orefield are outlined, with attention being drawn, where appropriate, to these differences.

Scientific interest in the area's geology and mineral deposits dates from the earliest days of geological research and has resulted in a huge volume of literature. Excellent summaries, together with extensive references to earlier works, include those by Johnson (1970), Rayner and Hemmingway (1974), Johnson (1995), and the British Geological Survey (1992, 1996b). Detailed descriptions of the mineral deposits are contained in the classic accounts of Dunham (1948, 1990), and Dunham and Wilson (1985). Other literature references are given in site descriptions.

The Alston and Askrigg blocks are structural units which comprise comparatively thin sequences of Carboniferous sedimentary rocks overlying Lower Palaeozoic rocks which were intruded by the Devonian Weardale and Wensleydale granites. Substantial parts of the Lower Carboniferous succession in these areas consist of marine limestones, especially in the southern, Askrigg Block. Cyclic 'Yoredale-type' sequences, composed of regularly repeated units of limestone, mudstone, sandstone and locally thin coals, pass upwards into cyclic sequences in which limestones become subordinate, culminating in the almost wholly non-marine mudstone–sandstone–coal-dominated sequences of the Coal Measures. The block areas are bounded by major fault belts, many of which controlled Carboniferous sedimentation, allowing substantially greater thicknesses of sediment to accumulate in the intervening 'troughs' than on the 'blocks'. To the north of the Alston Block, and separated from it by the Stublick–Ninety Fathom Fault System, lies the Northumberland–Solway Trough. The Stainmore Trough, bounded on the north by the Lunedale Fault System, separates the Alston and Askrigg blocks. The Craven Fault System bounds the Askrigg Block on the south, separating it from the Craven Basin. In the Alston Block the extensive tholeiitic quartz-dolerite intrusions of the Whin Sill suite were emplaced during late Carboniferous to early Permian times. In the block areas the overall easterly dip of the Carboniferous strata is interrupted by some, mainly gentle, flexuring and by a number of major faults. Both the Alston and Askrigg blocks are cut by conjugate sets of normal faults with maximum throws typically of only a few metres. It is these faults which host the main mineral veins.

Wall-rock lithology exerts a profound influence on the potential of each fault as a mineralized vein. Hard, competent wall-rocks, such as limestone and sandstone, and in the Alston Block the dolerite of the Whin Sill, and in the Askrigg Block chert, provided clean open fissures favourable for vein mineralization. Weak, incompetent rocks such as mudstones typically allowed fault fissures to close, effectively preventing their filling by mineralizing fluids. The influence of wall-rock lithology is especially marked in Yoredale-type sequences where laterally extensive ore-shoots against or between hard beds alternate with barren intervals against weak beds. The resulting 'ribbon ore-shoots' are a characteristic feature of these orefields.

Whereas the majority of Northern Pennine ore deposits occur as fissure veins, such as at the **Killhope Head** GCR site, in the Alston Block and the **Gunnerside Gill** (potential) GCR site in the Askrigg GCR Block, the area is noted for the widespread occurrence of metasomatic replacement orebodies, mainly of limestone wall-rock, by introduced minerals. Adjacent to many veins, especially in the Alston Block, limestone has undergone extensive metasomatism with the original lithology replaced wholly or partly by ankerite, dolomite, siderite, quartz, fluorite, galena, sphalerite and smaller amounts of other minerals (see **Smallcleugh Mine** GCR site report, this chapter). This replacement is commonly restricted to certain beds within the limestones, and may extend for many metres laterally from the parent vein, such as at the **Tynebottom Mine** GCR site. From their characteristic horizontal form these deposits are known as 'flats' in the Alston Block or occasionally as 'flots' in the Askrigg Block. Orebodies of this sort have provided several of the area's richest and most productive deposits of galena and sphalerite and a few important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Alston
Durham
Pennine Faults
Lunedale Fault
Barnard Castle
Kirby Stephen
Richmond
Dent Fault
Askrigg
Settle
North Craven Fault
Permo-Triassic rocks
Coal Measures rocks
Lower Carboniferous rocks and 'Millstone Grit'
Whin Sill and related intrusions
Lower Palaeozoic rocks
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◂**Figure 3.1** Geological sketch map with locations of GCR sites. 1 – **West Rigg Opencut**; 2 – **Killhope Head**; 3 – **Smallcleugh Mine**; 4 – **Tynebottom Mine**; 5 – **Sir John's Mine**; 6 – **Scordale Mines**; 7 – **Lady's Rake Mine**; 8 – **Willyhole Mine**; 9 – **Pike Law Mines**; 10 – **Blagill Mine**; 11 – **Settlingstones Mine**; 12 – **Stonecroft Mine**; 13 – **Fallowfield Mine**; 14 – **Closehouse Mine**; 15 – **Foster's Hush**; 16 – **Black Scar**; 17 – **Cumpston Hill North and South Veins**; 18 – **Greenhow (Duck Street) Quarry**; 19 – **Pikedaw Calamine and Copper Mines**; 20 – **Gunnerside Gill**.

deposits of barite, as at the **Scordale Mines** GCR site. Within the Alston Block, large 'flat' deposits of iron ores, both fresh carbonate ores, seen at the **Killhope Head** GCR site, and oxidized 'limonitic' ores, as at the **West Rigg Opencut** and **Killhope Head** GCR sites, have been worked in places.

The Pennine orefields may be considered as part of the worldwide Mississippi Valley-type, although Dunham (1983) suggested grouping them with the deposits of the Illinois–Kentucky fields of the USA within a fluoritic subgroup.

Throughout the Pennines the main sulphide ore minerals are galena and sphalerite. Most of the galena in the Alston Block is argentiferous, typically with silver contents ranging from 111–251 ppm, although with exceptional values of up to 2511 ppm at a very few locations (Dunham, 1990). Silver was a valuable by-product of lead smelting in this part of the ore-field. Historical claims of silver production in the 11th and 12th centuries could not have been sustained from ores with the silver contents normally encountered during 18th and 19th century smelting, leading Dunham *et al.* (2001) to speculate on the possibility that ores with a much higher silver content, perhaps resulting from a supergene enrichment in silver, may then have been available. Silver was also recovered from a number of mines in the Askrigg Block from galena with silver contents of between 50 ppm and 166 ppm. However, the galena throughout much of this area typically exhibits silver contents of less than 100 ppm, although with very rare occurrences of values as high as 2052 ppm. Sphalerite is abundant in parts of the Alston Block. It is generally less common in the Askrigg Block, although the local abundance here of substantial amounts of supergene hemimorphite and smithsonite suggests it may formerly have been more abundant. A unique deposit of supergene smithsonite, known locally as 'calamine', was worked at the **Pikedaw Calamine and Copper Mines** (potential) GCR site. Copper minerals are widespread in trace amounts throughout the Pennine deposits. Small economic concentrations were found locally, for example in the Alston area, and on the western, eastern and southern extremities of the Askrigg Block, for example at the **Cumpston Hill North and South Veins** GCR site, near Kirkby Stephen, at the **Black Scar** GCR site, near Richmond, and immediately north of the Craven Fault System at the **Greenhow Quarry** GCR site, respectively.

The iron carbonate minerals siderite and ankerite are widespread within the Alston Block deposits where they have been of considerable economic importance. They are generally rare or absent from most of the Askrigg Block. Dunham (1948, 1990) has suggested that the abundance of iron in the Alston Pennine deposits, compared to its general scarcity in the Askrigg area, may indicate derivation of the iron from the Whin Sill in the former area. Gangue minerals throughout the Northern Pennine Orefield include barite, locally with abundant witherite, and fluorite. Calcite is common, particularly in the Askrigg Block, while quartz is abundant in the Alston Block.

Both orefields, but especially that of the Alston Block, are characterized by a strong zonal distribution of the constituent minerals, particularly the gangue minerals. Central, fluorite-rich zones, as seen at the **Killhope Head** and **Pike Law Mines** GCR sites in the Alston Block, are surrounded by outer zones in which barium and calcium carbonate minerals are dominant, as at the **Blagill Mine**, **Foster's Hush** and **Settlingstones Mine** GCR sites. The genetic significance of this pattern was first recognized by Dunham (1934), who drew comparisons with the zonation of minerals around the granites of South-west England. By analogy with that area, a concealed Hercynian granite beneath the Northern Pennines was postulated to account for the mineralization. Geophysical evidence in both the Alston and Askrigg blocks lent strong support to this hypothesis (Bott and Masson-Smith, 1957; Bott, 1967). Drilling at Rookhope in the Alston Block and at Raydale in the Askrigg Block proved the presence of pre-Carboniferous granite at each site. Clearly the mineralization could not be the direct result of the intrusion of these granites.

The discovery of pre-Carboniferous granites beneath the Northern Pennine Orefield provided a fresh impetus for research on the origin of these deposits, and much has since been published on the topic. Notable contributions include those of Sawkins (1966a, 1976), Mitchell and Krouse (1971), Solomon *et al.* (1971), Russell and Smith (1979), Brown *et al.* (1987), Dunham and Wilson (1985), Plant and Jones (1989), Dunham (1990), Halliday *et al.* (1990), Ixer and Vaughan (1993), Crowley *et al.* (1997), Cann and Banks (2001), and Bouch *et al.* (2006). Most recent work suggests that the ore-forming fluids were 'oilfield'-type brines derived by the dewatering of adjoining pene-contemporaneous Carboniferous basins. The abundance of fluorite within the Pennine deposits may indicate a contribution of fluorine to the mineralizing fluids from the granites, although a source within the sedimentary basins is also possible. By virtue of being 'high-heat-production' granites the Pennine granites also offer an explanation for the relatively high mineralization temperatures and for the complex ore mineralogy, including elements characteristic of granite associations. An interaction between the basinal brines and the granites is thus envisaged, including the role of the granites, especially in the Alston Block, in creating convective circulation of fluids and the formation of well-developed mineral zonation. The mineralization must have been introduced soon after the emplacement of the late Carboniferous to early Permian Whin Sill. The **Lady's Rake Mine** GCR site (Young *et al.*, 1985b) represents a sulphide-bearing skarn deposit and provides an important insight into the genesis of the Northern Pennine sulphide-bearing veins and their relationship to the Whin Sill.

Mining in the Pennine orefields may be traced back over several centuries. Originally worked for iron, lead and locally minor associated silver, the working of zinc became important last century, for example at the **Smallcleugh Mine** and **Stonecroft Mine** GCR sites. In the late 19th and early 20th centuries, witherite (at the **Settlingstones Mine** and the **Fallowfield Mine** GCR sites), barite (at the **Closehouse Mine** GCR site), and fluorite became the main mineral products, although apart from some commercial mining for high-grade fluorite specimens at Rogerley Mine in Weardale, all mining of vein minerals has now ended.

The Northern Pennines have long been famous as a source of beautiful specimens of a number of minerals which are to be seen in major mineralogical collections throughout the world. Pre-eminent amongst these are spectacular examples of purple, green and yellow fluorite, and beautiful examples of barite and witherite (e.g. Greg and Lettsom, 1858; Hacker, 2003; Symes and Young, 2008). The Northern Pennine Orefield is unique for the abundance of barium carbonate minerals and provides the type locations for witherite together with the much rarer double calcium, barium carbonate minerals alstonite (from the **Fallowfield Mine** GCR site) and barytocalcite (from the **Blagill Mine** GCR site) (Young, 1985c).

The Northern Pennine deposits have also yielded some fine examples of supergene species (Young *et al.*, 1989, 1992a, 2005; Dunham, 1990; Bridges and Young, 1998), and include the type locality for the supergene zinc carbonate sulphate hydrate mineral brianyoungite (Livingstone and Champness, 1993). The **Willyhole Mine** GCR site is renowned for the extensive development of supergene greenockite after primary sphalerite.

Reports of a number of very rare supergene species from a group of veins on Grassington Moor, in the southern part of the Askrigg Block, are based on specimens collected by the late A.W.G. Kingsbury. Species recorded from here include cinnabar, metacinnabarite and native mercury (Kingsbury, 1968), parahopeite and spencerite (Embrey, 1977), and plumbojarosite and argentojarosite (Dunham and Wilson, 1985). Ryback *et al.* (2001) have shown that Kingsbury falsified the localities of numerous rare mineral species in his collection. It seems that from about 1951 he began to pass off classic foreign material from old collections as having been collected by him from British localities. Ryback *et al.* (2001) demonstrated that his specimens of mercury minerals, alleged to have been collected on Grassington Moor, are quite atypical of Pennine material and probably originated from the Berehove–Dubrinihi area in Hungary. Although Kingsbury's specimens of other rare species from Grassington have not been examined in detail, serious doubt must be attached to his claims, as, despite the best efforts of numerous subsequent collectors, none of his supposed finds have been repeated.

WEST RIGG OPENCUT, DURHAM (NY 911 392)

Introduction

West Rigg Opencut is a large abandoned quarry, which, during the 19th century, worked a metasomatic replacement deposit of 'limonitic' ironstone associated with the Slitt Vein within the Namurian Great Limestone. It is one of a number of similar deposits, formerly worked in the Northern Pennines, in which primary iron carbonate minerals have undergone supergene alteration to 'limonitic', or 'brown hematite' ores. These deposits have been compared to those of 'Bilbao-Type' (Percival, 1955; Gross, 1970). At West Rigg today, remnants of the worked orebody may be studied *in situ* in their structural, statigraphical and metallogenic context. The site provides the finest surviving exposure of such a deposit within Britain. In addition the site offers excellent opportunities to examine one of the orefield's major mineralized veins. The site has been described previously by Dunham (1948, 1990), and Young (1995).

Dunham (1990) recorded that these workings were amongst the Weardale Iron Company's main producers of iron ore during the second half of the 19th century. Iron contents varied from 34.3% to 43.4%. The ore was transported from the quarries by means of a specially constructed standard-gauge railway. Total production figures from these formerly important workings are not available.

Description

At West Rigg the Great Limestone, the basal unit of the local Namurian succession, is approximately 18 m thick. Slitt Vein, the longest single vein within the Northern Pennine Orefield, cuts the limestone at West Rigg. This vein here strikes roughly east–west and comprises one of a small number of veins with this general trend known as the 'Quarter Point' veins (Dunham, 1990). Like other Quarter Point veins, Slitt Vein is commonly a wide mineralized structure carrying large amounts of fluorite and quartz, but with comparatively low concentrations of galena and other sulphide ores. The vein has been worked for lead in the past, but its main economic importance lay in the large metasomatic replacement deposits of ironstone present in several places where the vein cuts the Great Limestone, and in the local abundance of fluorite, for which it was worked recently in nearby mines.

The Slitt Vein at West Rigg is up to 5 m wide, and is mineralized mainly with quartz with some impersistent bands and lenses of fluorite. Small amounts of galena have been extracted from near the centre of the vein in old stopes now exposed in the workings. Adjacent to the vein, almost the full thickness of the Great Limestone has been replaced by limonitic ironstone, derived from the supergene alteration of primary carbonates, almost certainly siderite and ankerite. A few metres away from the vein margins this replacement was most extensive within the upper part of the limestone. Here iron mineralization locally extended for up to 61 m on either side of the vein. The extent of the West Rigg Opencut gives a very clear impression of the size and form of these replacement orebodies. Although almost totally extracted, small exposures of ore remain locally in the walls of the workings. Slitt Vein itself has been left as an unworked rib which forms a striking wall-like feature across the centre of the quarry (Figure 3.2). Exactly similar replacement deposits, also associated with Slitt Vein, were worked immediately to the west of West Rigg, at Slitt Pasture and to the east at Rigg, although little is exposed *in situ* at these workings today.

Interpretation

A characteristic feature of veins within the Northern Pennine Orefield is their tendency to be almost vertical, or very steeply inclined, well-mineralized structures within competent wall-rocks, such as limestone and sandstone. In less-competent rocks, such as shales, they are commonly barren or only weakly mineralized. Wall-rock alteration, commonly with the introduction of iron carbonate minerals, is typical of many veins, particularly within limestone. Locally, much more extensive metasomatic replacement of limestone wall-rock has taken place adjacent to some veins, with the development of sometimes very large replacement deposits, known to the local miners as 'flats'. Many 'flats', including those at West Rigg, contain high concentrations of iron carbonate minerals such as ankerite or siderite. Others are

Figure 3.2 West Rigg Opencut. Large metasomatic replacement flats of iron ore in the Great Limestone have been removed leaving the vein, here composed mainly of quartz and a little fluorite, as a conspicuous rib across the centre of the quarry. Old lead workings in the centre of the vein may be seen to the left of the figure. (Photo: B. Young.)

distinguished by concentrations of sulphides such as galena and/or sphalerite significantly higher than in the adjacent veins. Original sedimentary features such as bedding, stylolites and some fossils, are commonly clearly preserved in the altered rock. Such 'flats' are especially common within the Great Limestone. Although such replacement may be found at almost any level within this limestone, three principal 'flat' horizons, known respectively as the 'High', 'Middle' and 'Low' flats have been widely recognized across the orefield (Dunham, 1948). The most extensive replacement at West Rigg occurs at the 'High Flat' horizon.

As noted above, Slitt Vein is the longest single vein within the orefield and is one of the Quarter Point group of veins. These are distinguished from the majority of Northern Pennine veins in being fissures which resulted from original transcurrent rather than vertical movement (Greenwood and Smith, 1977; Dunham, 1990). Where their strike direction most nearly approaches east–west these veins typically contain considerable widths of introduced mineral. This is well demonstrated at West Rigg where most of the vein is composed of quartz. West Rigg Opencut demonstrates, in spectacular fashion, the development of metasomatic alteration of Great Limestone wall-rock by iron carbonate minerals, introduced during an early stage in the main mineralizing process. The 'flats' produced at West Rigg are distinguished by their high iron and low sulphide content. Supergene alteration of the original iron carbonates has produced a large workable deposit of limonitic ore. The West Rigg and similar nearby orebodies may thus be considered as good examples of the 'Bilbao-Type' of iron ore deposit (Percival, 1955; Gross, 1970). Much of this ore, examples of which may be seen locally in some of the remaining faces, is typically a rather structureless, massive or earthy limonitic ore composed dominantly of goethite, although pseudomorphs after curved rhombic crystals of either siderite or ankerite may be found locally.

A characteristic feature of the deposits of the northern, Alston Block, portion of the Northern Pennine Orefield is the great abundance of iron minerals. Indeed, Dunham (1990) observed that ankerite is more abundant than any other mineral in the unoxidized portions of the metasomatic replacement deposits. Iron minerals are, by contrast, remarkably scarce in the otherwise generally similar deposits of the Yorkshire Pennines. Wager (1929) suggested that the abundant iron was derived by the reaction of mineralizing fluids with the Whin Sill which underlies much of the Alston Block. Dunham (1990) has advocated a similar origin for at least part of the silica which is also so abundant here.

Post-mineralization movement along most of the orefield's veins is apparent in the form of locally brecciated vein minerals or slickensided fractures parallel to the vein walls. Clear evidence of renewed lateral movement along Slitt Vein is to be seen in the well-marked, almost horizontal slickensided surfaces of quartz exposed along parts of the south side of the vein at West Rigg.

Conclusions

West Rigg Opencut provides one of the finest surface exposures of a Northern Pennine vein and its associated metasomatic replacement by iron minerals within the Great Limestone. The site is of prime importance in displaying this type of deposit in its structural, stratigraphical and metallogenic context.

KILLHOPE HEAD, DURHAM (NY 820 433)

Introduction

The Great Limestone (Namurian) exposed in the bed and banks of Killhope Burn is cut by Old Moss Vein, one of at least 11 roughly NE–SW-trending veins formerly worked at Killhope Head both at surface and underground from Park Level at Killhope Mines. Old Moss Vein here carries abundant galena, siderite and fluorite, together with a little sphalerite. The adjacent limestone is extensively replaced by siderite and ankerite, forming a small metasomatic flat deposit which may be seen to extend for a few metres on the east side of the vein. Well-crystallized fluorite, quartz and some galena occur in cavities in the flats. The vein and its associated flats form a low waterfall in the stream. The Killhope Head veins, including Old Moss Vein, have been described by Dunham (1948, 1990).

Description

Where exposed in the small waterfall in Killhope Burn, Old Moss Vein strikes approximately north-east–south-west and exhibits a small downthrow to the south-east. The vein is almost 1 m wide and contains abundant fresh galena as large crystalline masses up to 10 cm across, and a little dark-brown sphalerite in an abundant matrix of partially oxidized siderite and ankerite. The limestone adjacent to the vein, particularly on its east side, is extensively replaced by siderite and ankerite forming a small 'flat'. Partial oxidation of these carbonates has produced an abundance of dark-brown 'limonite', and the vein, together with its associated flat, contrasts strikingly with the unaltered grey limestone. Cavities within this 'flat' contain abundant, well-crystallized pale-purple fluorite, quartz and some galena.

A few metres downstream of the vein outcrop, the bed of Killhope Burn provides a fine exposure of the 'Frosterley Band', a distinctive bed within the Great Limestone characterized by the abundance within it of solitary corals, most notably *Dibunophyllum bipartitum* (McCoy) (Johnson, 1958). This bed occurs widely across the Northern Pennines and was formerly much worked as an ornamental stone under the name of 'Frosterley Marble'. Examples of its use in architecture may be seen in several local churches, but its most extensive use in the area is in Durham Cathedral. The 'Frosterley Band' occurs near the base of the 'High Flat' horizon of the Great Limestone. This, together with the terms 'Low Flat' and 'Middle Flat', were names applied by the former lead miners to horizons within the Great Limestone at which metasomatic replacement was most intense. The small flat exposed adjacent to Old Moss Vein occurs at the 'High Flat' horizon.

About 20 m upstream from the outcrop of Old Moss Vein, another vein, probably the Tweed Vein, crosses Killhope Burn, although the exposures of this are not as good as those of Old Moss Vein.

Interpretation

Old Moss Vein occurs within the central, fluorite-rich, zone of the Northern Pennine Orefield. The outcrop of Old Moss Vein appears to be representative of the veins formerly worked in this part of the field where extensive iron mineralization is commonly present, especially replacing limestone wall-rocks. The relative abundance of sphalerite, accompanying galena, is characteristic of deposits in parts of the orefield, including the head of Weardale and the Nenthead area. The outcrop of Old Moss Vein provides a fine illustration of the development of a metasomatic flat deposit within one of the main 'flat' horizons of the Great Limestone.

It is noteworthy that the galena and sphalerite show little evidence of supergene alteration, and the siderite and ankerite exhibit only comparatively minor oxidation. This is consistent with Dunham's (1990) observation that in valley bottoms, unoxidized minerals should theoretically be found at the surface. The mineralized outcrops in Killhope Burn clearly confirm that this is the case. A similar situation may be observed in the lead- and zinc-rich flat deposit associated with Carr's Cross Vein exposed at the waterfall near **Smallcleugh Mine** (see GCR site report, this chapter).

Conclusions

The outcrop of Old Moss Vein is typical of fissure veins within the central fluorite zone of the Northern Pennine Orefield. The stream also provides very fine exposures of an associated iron-rich metasomatic replacement flat deposit within the Great Limestone at one of the principal horizons for this type of mineralization. The site provides a readily accessible means of demonstrating and studying these important aspects of mineralization.

SMALLCLEUGH MINE, CUMBRIA (NY 787 431–NY 789 428)

Introduction

The underground workings of Smallcleugh Mine provide some of the most extensive and clearest available exposures of lead- and zinc-rich metasomatic replacement flat deposits in limestone within the Northern Pennines. Outcrops of exactly similar deposits, in the banks of the River Nent about 100 m north-west of Smallcleugh Mine entrance, are the finest surface exposures of such deposits in the Northern Pennines.

Smallcleugh Mine is one of a large number of closely spaced and interconnected workings within the upper part of the Nent valley. Driving of Smallcleugh Horse Level, the principal access for the mine, seems to have begun in about 1770, although the main development of the mine seems to date from the London Lead Company's commencement of operations here in about 1787. The first of the flat deposits are understood to have been discovered in 1796 (Wallace, 1861), and it was these extensive and rich deposits which were to be the mainstay of the mine for many years. Production figures for Smallcleugh Mine during the London Lead Company's long tenure are incomplete. Dunham (1990) recorded a figure of 4999 tons of lead concentrates for the period 1848–1882, but commented that this figure probably represents only a fraction of the yield from these extensive deposits. During subsequent years the mine was worked by the Nenthead and Tynedale Zinc Company and their successors the Belgian Vieille Montagne Zinc Company, under whose tenure significant quantities of zinc, in addition to lead, concentrates were raised, although figures for Smallcleugh Mine alone are not available. Underground mining at Smallcleugh ended in the early years of the 20th century, although considerable amounts of zinc concentrates were recovered by reprocessing parts of the Smallcleugh and other dumps during World War II. Historical accounts of mining at Smallcleugh and nearby mines include those by Almond (1977), Critchley (1984, 1998), and Fairbairn (1993).

Smallcleugh Mine, like so many of the Nenthead mines, is connected at various levels with neighbouring mines, in the complex group of vein and related deposits for which this area was once extensively worked. The principal interest of this site lies in the extensive group of large replacement flat deposits, known as the 'Smallcleugh Flats' or 'Handsome Mea Flats', which are associated with a number of major veins and faults within the Great Limestone (Namurian) (Figure 3.3). Within the underground workings in the central and northernmost portions of the mine, the stratigraphical and structural relationships of the orebodies and their mineralogical composition and textures are clearly visible in extensive exposures of very fresh mineralized rock. In the southernmost parts of the mine, several orebodies were worked from a number of generally NE–SW-trending veins. Whereas some mineralization is still exposed here, these workings present few

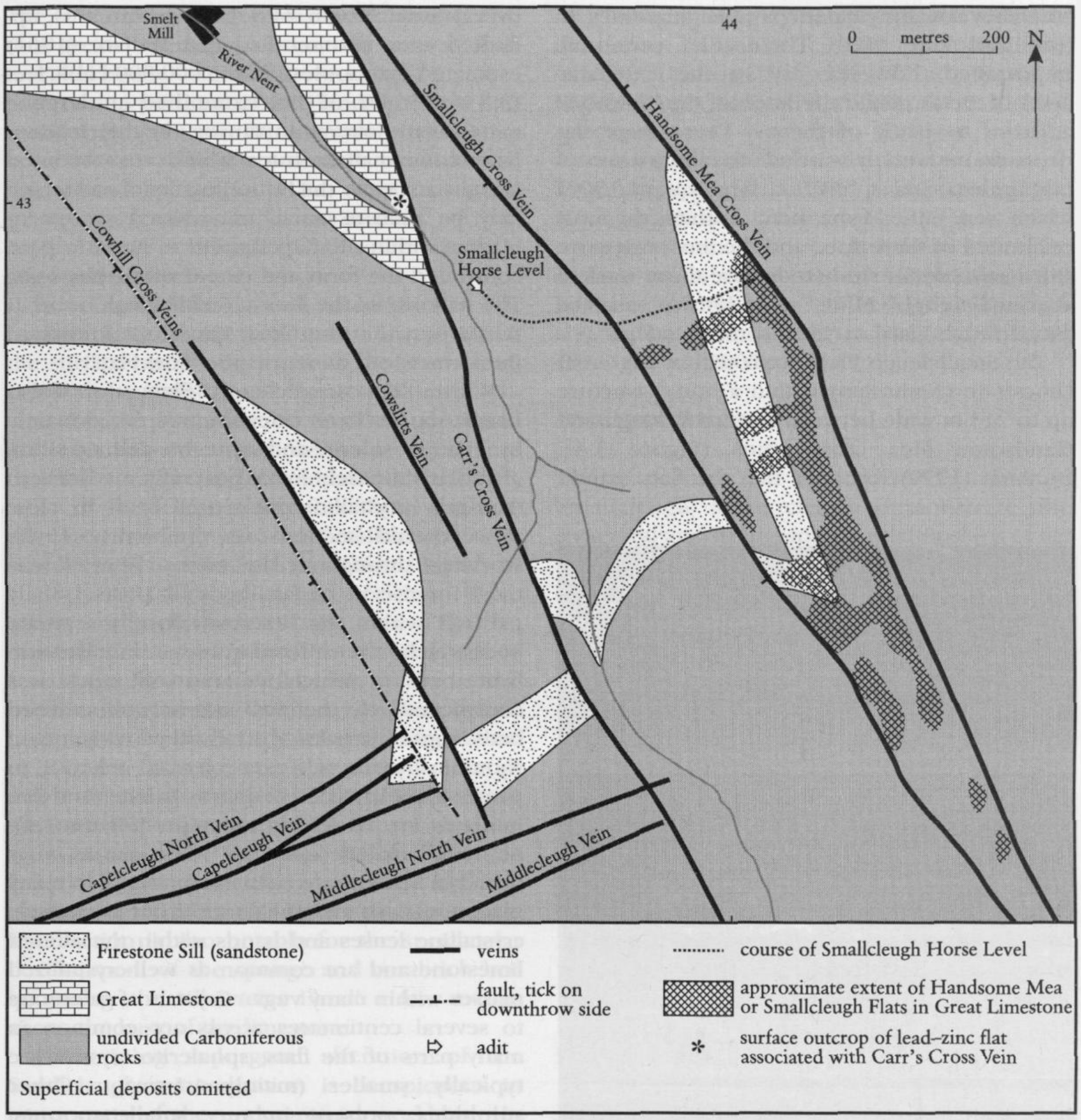

Figure 3.3 Sketch map showing main veins and approximate extent of main flat deposits at Smallcleugh Mine.

features of particular note, except locally where some rare supergene minerals have been reported. Post-mining alteration processes have led to the formation of a variety of supergene minerals throughout many parts of the Smallcleugh workings.

The structure and primary mineralization of the Smallcleugh Flats deposits have been described by Wallace (1861), and more recently by Dunham (1948, 1990). The supergene mineralization within the mine has been discussed by Dunham (1948, 1990), Bridges (1983, 1987), Livingstone (1991), and Bridges and Young (1998).

Description

In the upper part of the Nent valley, around Nenthead, the Carboniferous rocks are cut by a series of roughly parallel NNW–SSE-trending faults, known to the local lead miners as 'cross veins'. Whereas elsewhere in the orefield faults with this trend are characteristically barren or only poorly mineralized, within the Nenthead area they locally yielded payable quantities of lead and zinc ore. Their chief economic importance, however, lay in the extensive areas of metasomatic alteration of the limestone adjacent to many of them. These large flat deposits commonly carried an abundance of both galena and sphalerite, large quantities of which were mined from them. Perhaps the most celebrated of these flats, and the most extensive still accessible for study today, are those worked at Smallcleugh Mine and known as the 'Smallcleugh Flats' or 'Handsome Mea Flats'.

The Smallcleugh Flats occur within the Great Limestone (Namurian) within a horst structure up to 213 m wide between the Smallcleugh and Handsome Mea cross veins (Figure 3.4). Dunham (1990) recorded that the flats extend over a total length of 1.1 km within this up-faulted area, and recalled that Wallace (1861) estimated that not less than 5 000 000 cubic feet (3.5×10^6 m^3) of limestone had undergone metasomatic alteration during their formation. Numerous small fractures, which cross the horst at right-angles to the bounding faults and which may be seen as small mineralized strings or leaders within the flats, appear to have, in part, controlled the form and extent of the deposits. The majority of the flats at Smallcleugh occur at the level within the Great Limestone known to the former lead miners as the 'Low Flat'.

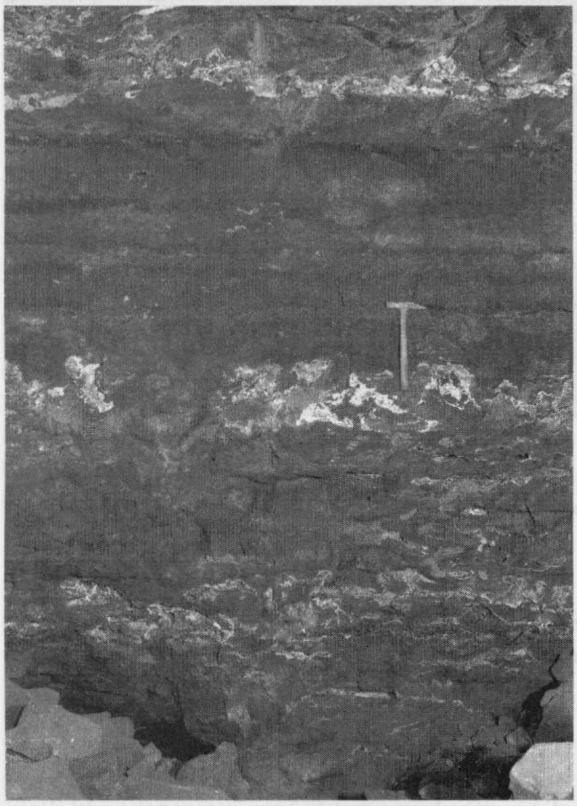

Figure 3.4 Metasomatized Great Limestone in the Smallcleugh (or Handsome Mea) Flats at Smallcleugh Mine. The limestone has been replaced mainly by ankerite and some silica. The most intensely altered limestone contains roughly horizontal bands of vugs lined with crystals of ankerite, galena and sphalerite. Above the hammer a limestone bed with numerous shaly partings has escaped intense alteration. (Photo: T.F. Bridges, BGS No. MNS 5565, reproduced by permission of the British Geological Survey, © NERC. All rights reserved. IPR/105-15CX.)

Within the Smallcleugh Flats the Great Limestone has been extensively replaced mainly by ankerite, siderite and some fine-grained silica, giving an intensely hard, generally medium- to dark-grey crystalline rock, well seen in clear unweathered sections in the walls of the workings throughout the mine. Alteration is most intense in certain beds or posts. Shaly partings within the limestone locally separate beds which have suffered intense mineralization from beds in which alteration is much less conspicuous. In the most intensely mineralized beds, vugs or cavities, typically lined with curved rhombic crystals of cream-coloured ankerite, in places accompanied by quartz, calcite, and ore minerals are extremely common (Figure 3.4). Altlhough mainly less than 30 cm across, vugs over 1 m across have been encountered in many places. Galena and sphalerite occur as coarsely crystalline lenses and bands within the altered limestone and are common as well-crystallized masses within many vugs. Crystals of galena up to several centimetres across are common in many parts of the flats; sphalerite crystals are typically smaller (mainly < 1 cm). Other sulphides, present in very small amounts, include pyrite and in places chalcopyrite. Dunham (1990) noted a silver recovery from galena equivalent to 7 oz of silver per ton of lead, although commented that this may represent an average figure for the London Lead Company's Nenthead mines, as Cameron Swan (in discussion of Nall, 1904) reported that the galena from the Smallcleugh Flats was non-argentiferous.

Extraction of the Smallcleugh Flats has created an extensive series of wide open workings, the extent of which gives a clear indication of the limits of payable mineralization. Throughout large areas of the mine, flat mineralization remains exposed in the walls of the workings.

The true extent of the metasomatic alteration is thus greater, perhaps substantially greater, than revealed by the extent of the workings.

Surviving portions of the Handsome Mea and Smallcleugh cross veins mainly comprise brecciated wall-rock cemented by ankerite, galena and sphalerite. The numerous small stringers or leaders which cross the flats, at right-angles to their bounding faults, are typically filled with ankerite.

Part of a small flat deposit, also at the Low Flat horizon of the Great Limestone, is exposed at the surface on the east bank of the River Nent, below the waterfall, approximately 100 m north-west of the entrance to Smallcleugh Mine. Although this outcrop shows some discolouration due to slight surface oxidation of ankerite, most of the features described from the flats displayed underground in Smallcleugh Mine may be seen here in fresh condition. Lenses of coarsely crystalline galena greater than 10 cm across are particularly conspicuous. The flat exposed here is not part of the Smallcleugh or Handsome Mea suite of flats. It occurs on the western side of the Carr's Cross Vein, which mapping and plans of adjoining workings show to lie a few metres east of the present outcrop. A few metres downstream from this exposure the lowest several metres of the Great Limestone are well exposed. The presence here of some ankerite replacement along joints and bedding planes is betrayed by pale-brown discolouration. The section is also notable for the spectacular development of the sponge and coral-rich bed known as the '*Chaetetes* Band' a few metres above the base of the limestone.

Post-mining supergene alteration of the Smallcleugh mineralization is conspicuous in many parts of the underground workings. In common with most of the zinc-rich deposits of the Northern Pennines, parts of the Smallcleugh workings carry abundant stalactitic and stalagmitic crusts of white hydrozincite, which is clearly being deposited today in many parts of the mine. Efflorescent crusts of colourless acicular gypsum crystals are common. These are easily confused with crusts of epsomite which in places coat large portions of the workings. Both of these minerals are also clearly forming today. The abundance of epsomite within parts of the mine appears to be controlled to a large extent by humidity levels within the mine atmosphere. Crystalline masses of melanterite are commonly associated with oxidizing pyrite in the flats cut by Hetherington's Crosscut and elsewhere in the mine (Dunham, 1990). Post-mining encrustations on the walls of old stopes in Middlecleugh Second Sun Vein have yielded specimens of serpierite (Bridges, 1987), namuwite and schulenbergite (Livingstone *et al.*, 1990), ktenasite (Rust, 1991), and brianyoungite (Livingstone and Champness, 1993). Other supergene minerals recorded from the mine include an as yet un-named zinc analogue of ktenasite (Livingstone, 1991), devilline (Bridges and Young, 1998), and beudantite and erythrite (Young *et al.*, 2005).

Interpretation

The exposures of mineralized ground in Smallcleugh Mine clearly demonstrate the structural and stratigraphical relationships of flat mineralization which occurs here mainly within the 'Low Flat Horizon' of the Great Limestone. The Smallcleugh (or Handsome Mea) Flats which represent the most extensive development of flat mineralization within the Nenthead area occur within the horst of Great Limestone which lies between the Smallcleugh and Handsome Mea cross veins. The smaller development of flat mineralization, exposed near the waterfall, is closely associated with the Carr's Cross Vein.

Throughout much of the Northern Pennine Orefield, NNW-trending faults or cross-veins carry little or no workable mineralization. In the Nenthead area these veins have proved to be workable locally, including within Smallcleugh Mine. However, these veins have been of prime importance as major channels, along which flowed the mineralizing fluids responsible for the widespread metasomatism within the Great Limestone. Within the Smallcleugh horst it seems very likely that numerous minor cross-fractures, or leaders, which cut the limestone at right-angles to the bounding faults, also acted as important mineralizing channels. Parts of the flats, as revealed by their worked-out extent on mine plans, clearly show an elongation along these leaders.

The Great Limestone has proved to be one of the most important host-rocks within the orefield for mineralization. Not only have many of the field's veins been at their most productive in this wall-rock, but the limestone has been one of the principal beds in which metasomatic flats have been developed. It has long been appreciated by the local miners that three main levels within the limestone have been preferentially mineralized in this way. These were known locally as the 'High', 'Middle' and 'Lower' flat horizons (Dunham, 1948). The predominance of flat mineralization at any one of these levels varies from place to place across the field. At Smallcleugh, and the nearby Carr's Cross Vein, flat mineralization occurs mainly at the 'Low Flat' horizon.

The reasons for the preferential development of flat mineralization at one or more of these three distinct levels are not fully understood. It is, however, worth recalling that individual beds or 'posts' within the Great Limestone exhibit a remarkable persistence across much of the Alston Block (Fairbairn, 1978). Factors such as original composition or texture within certain limestone beds may have exercised a profound influence on their susceptibility to metasomatism. The role of interbedded shale partings within the Great Limestone in presenting barriers to the upward or downward passage of mineralizing fluids is clearly apparent in many sections exposed within the Smallcleugh workings (Figure 3.4). In these sections the intensity of metasomatism varies considerably between beds, even within the overall thickness of the flat deposit. It has also been observed that flat mineralization is only widely present within the Great Limestone where the limestone is overlain by shaly beds: where sandstones directly overlie the limestone, flats are normally absent (Dunham, 1990). Shales overlie the Great Limestone at Nenthead.

Exposures of the Smallcleugh deposits provide abundant evidence of the nature and origins of flat mineralization. Dunham (1990) has provided a detailed summary of the mineralogical processes involved in the development of flats within the orefield. The earliest event generally appears to have been the introduction, along mineralizing channels, of fluids which converted much of the limestone wall-rock into ankerite rock in which some siderite and silica is also common. More recently, Bouch *et al.* (2006) have highlighted the importance of increased porosity, resulting from dolomitization and ankeritization, in the development of these and similar flats throughout the orefield. It is likely that this alteration may have created an environment unfavourable to replacement by later fluids which carried lead and fluorine. In places, however, these later fluids were able to break through areas of earlier, ankerite-rich, alteration to affect replacement of limestone beyond with galena and fluorite. The sections remaining at Smallcleugh, and at the waterfall, clearly show that both galena and sphalerite generally post-date ankeritization and may also be the product of a later influx of lead- and zinc-rich mineralizing fluids, although without fluorite or barium minerals. The Smallcleugh deposits lie within an intermediate zone of Northern Pennine mineralization in which neither fluorite nor barium minerals occur within the gangue assemblage. Dunham (1990) also demonstrated that the replacement of limestone by the denser minerals of the metasomatic deposits should lead to a volume reduction within the affected rock mass. He suggested that within deposits of this sort the volume reduction may be accommodated either by the formation of cavities within the altered limestone or by the development of collapse breccias within the altered rock. At Smallcleugh replacement of the limestone has been complete, with bedding planes, joints and stylolites and even some fossils faithfully replaced, and the formation within the deposit of numerous cavities. Collapse breccias have not been observed within the Smallcleugh Flats.

The cavities within the Smallcleugh Flats have, like those of many other deposits within the orefield, yielded striking specimens of well-crystallized minerals, most notably galena, sphalerite and ankerite. Good examples of the latter mineral in many collections are incorrectly labelled as 'dolomite'. Dolomite appears to be absent or extremely rare within these deposits.

Although the flats exposed within Smallcleugh Mine mostly lie well below the present level of oxidation, and thus do not exhibit extensive natural supergene alteration, they locally exhibit assemblages of supergene minerals where oxygen-rich air has attacked the deposits since their opening by mining. Within the workings, oxidation of pyrite and other sulphides has provided sulphate-rich waters which, upon reaction with calcite and dolomite, have locally resulted in the formation of concentrations of gypsum and epsomite where air humidity and temperature have allowed them to crystallize. Efflorescent crusts of delicate, acicular epsomite crystals are common in several places, although the quantity present appears to fluctuate, apparently in response to variations in the temperature and humidity of the mine atmosphere. Reaction of sulphate-rich waters with further pyrite has produced local concentrations of melanterite. Precipitation of zinc from solution in mine waters has produced widespread stalactitic and stalagmitic coatings of hydrozincite widely throughout the mine. Soft, brown coatings of hydrated iron oxides are widespread. Supergene alteration of zinc, copper, and locally traces of nickel, within the flats, has given rise to local occurrences of the range of supergene minerals listed above.

The outcrop of the flat mineralization at the waterfall contains fresh galena and sphalerite and only very limited oxidization of the ankerite is apparent. This, like the outcrop of Old Moss Vein at the **Killhope Head** GCR site (see GCR site report, this chapter), is consistent with Dunham's (1990) observation that unoxidized primary minerals are found at outcrop in valley bottoms.

Conclusions

The underground workings of Smallcleugh Mine, together with the nearby exposures of similar mineralization at the waterfall in the River Nent, provide extremely important exposures of lead- and zinc-rich metasomatic replacement flat mineralization within the Great Limestone. These extensive sections demonstrate clearly the stratigraphical and structural relationships of the deposits. They also display the main constituent minerals and offer fine opportunities to study post-mine supergene alteration.

TYNEBOTTOM MINE, CUMBRIA (NY 739 418)

Introduction

Tynebottom Mine is a comparatively small mine which is known to have been worked for lead between 1771 and 1873. The recorded total production of lead concentrates amounts to 11 529 tons (Dunham, 1990).

The mine was developed at the intersection of the ENE–WSW-trending Dryburn Washpool–Browngill Vein, one of the main feeder channels of mineralization in Alston Moor, with a roughly NW–SE-trending vein known as 'Windshaw Bridge Vein'. At Tynebottom these lead ore-shoots were present in both of these veins and in metasomatic replacement flats associated with them in the Tynebottom Limestone (Dinantian).

The mineralogy of the Tynebottom deposits has attracted much research interest. Erythrite has long been known to be common at Tynebottom (Dunham, 1931), although the source of the necessary cobalt and arsenic within the primary assemblage has more recently been explained by the work of Ixer *et al.* (1979). Further works by Vaughan and Ixer (1980), and Ixer (1986) have added much to the understanding of the ore mineralogy of the deposit. It is almost certain that the unique assemblage of silver minerals, described by Ixer and Stanley (1987) on the basis of specimens in the A.W.G. Kingsbury collection now held by the Natural History Musuem, London, did not originate at Tynebottom Mine, an error quite unknown to these authors at the time of their investigation.

The mine is a notable locality for a variety of unusual supergene minerals (Braithwaite, 1982; Bridges, 1987; Bridges and Young, 1998). Well-developed calcite crystals, in a variety of crystal habits, obtained from Tynebottom Mine may be seen in numerous major mineralogical collections.

Description

Extensive sections of the veins and associated flat deposits are accessible via two adits driven into the deposits from the south bank of the River Tyne (Figure 3.5). In addition, good representative specimens of mineralized material are present in abundance on the adjacent spoil-heaps.

Tynebottom Mine was developed near the intersection of the Dryburn Washpool–Browngill and Windshaw Bridge veins where they cut the Tynebottom Limestone (Dinantian). Associated with both veins were extensive metasomatic replacement flats within the limestone. Dunham (1990) recorded that the flats extended for a distance of at least 244 m along the Dryburn Washpool–Browngill Vein, and for a similar distance along the Windshaw Bridge Vein, west of its intersection with the latter vein. The flats are said to have averaged about 6 m in width but to have increased to as much as 15 m wide near the intersection of the two veins. The accessible underground workings at Tynebottom provide extensive sections through unworked portions of the flats, and in places the veins. The extent of these workings gives a very clear impression of the form and extent of the payable mineralization. Wallace (1861) suggested that

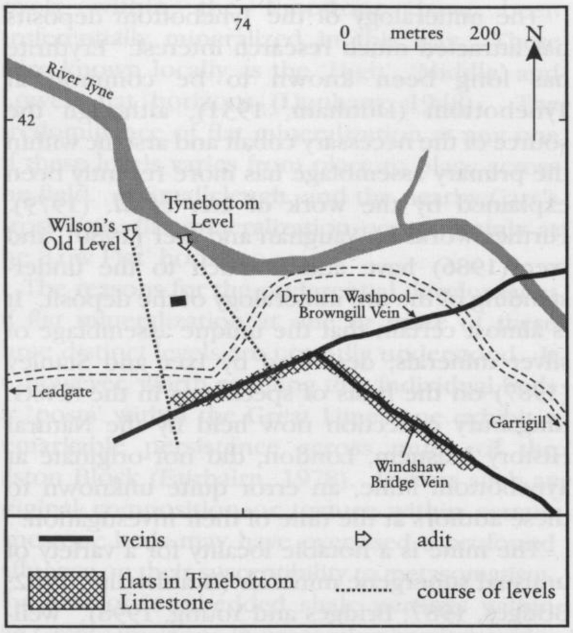

Figure 3.5 Sketch map showing main veins and associated flats at the Tynebottom Mine GCR site.

workings were restricted to portions of the flats in which economically recoverable lead ore concentrations were found. The full extent of the metasomatic alteration, and hence the true extent of the flats, may be considerably greater. Trials of the veins in the Whin Sill, which lies at a shallow depth beneath the Tynebottom Limestone, found only carbonates (Dunham, 1990).

Within the Tynebottom flats the limestone has typically been replaced by fine-grained quartz and chalcedony, producing a very hard, dark-grey, siliceous rock in which occur disseminated crystals of galena, marcasite and pyrite. Numerous vugs within the flats are lined with quartz, calcite, and ankerite and in places purple fluorite (Dunham, 1990). Ixer *et al.* (1979) reported small amounts of glaucodot associated with arsenical marcasite. Vaughan and Ixer (1980) identified the ore minerals as pyrite, marcasite, galena and sphalerite, with minor amounts of glaucodot, gersdorffite, chalcopyrite, pyrrhotite and ullmanite. A re-investigation of specimens described by Ixer *et al.* (1979) has revealed the presence within the quartz of traces of the rare earth mineral synchysite (Ixer and Stanley, 1987).

Ixer and Stanley (1987) described a remarkable assemblage of silver minerals including argentopyrite, sternbergite, pyrargyrite, stephanite and acanthite associated with chloanthite, rammelsbergite, safflorite, löllingite, skutterudite, niccolite, gersdorffite and cobaltite in specimens claimed to have originated at Tynebottom Mine in the A.W.G. Kingsbury collection, now held by the Natural History Musuem, London. Recent investigations of this collection have shown that many of the claimed localities are demonstrably false, and very serious doubt has been cast on the veracity of many others (Ryback *et al.*, 2001). In the light of this, and in view of the general dissimilarity between the associated minerals in these specimens with those in the known assemblages at Tynebottom Mine, it is almost certain that these specimens are incorrectly provenanced in the collection. Similar doubt may also be cast on the Kingsbury specimens which contain skutterudite and cobaltite, described by Ixer (1986). The false provenance of these specimens was unknown to these authors at the time of their research.

The Dryburn Washpool–Browngill Vein is well exposed in the Tynebottom Limestone in the bed of the River Tyne, approximately 168 m east of Tynebottom Mine. The vein here carries abundant galena and marcasite; the limestone is replaced by fine-grained silica with disseminated sulphides (Dunham, 1990).

Supergene, possibly mainly post-mining, alteration of the ores at Tynebottom has produced a variety of unusual supergene minerals within the workings. Perhaps best known and most conspicuous are the crusts of erythrite which locally coat sulphide-rich portions of the workings. Erythrite is also common as inclusions, giving a distinct rose-pink colour to calcite stalactites and flowstone (Dunham, 1948). It is worth noting that fine specimens of this material in numerous mineral collections are incorrectly labelled as 'cobaltocalcite'. Small amounts of copper sulphides within the ore contribute to the formation of crusts of deep-green brochantite and blue-green devilline and wroewolfeite, which are locally common in the workings (Braithwaite, 1982; Bridges, 1987; Bridges and Young, 1998). The presence of a little zinc is revealed by snow-white crusts of hydrozincite and, very locally, small amounts of serpierite (Bridges, 1987). Bridges and Young (1998) have also recorded beudantite from this mine. Most recently, Green *et al.* (2003) have described the presence of symplesite and parasymplesite (both iron arsenates) from Tynebottom Mine.

Interpretation

Dunham (1990) has suggested that the Dryburn Washpool–Browngill Vein is one of the principal channels of mineralization in the Alston Moor area. At its intersection with the Windshaw Bridge Vein, mineralization has taken the form of extensive metasomatic replacement of the Tynebottom Limestone. Replacement here has been dominated by the introduction of abundant silica. In this respect the mineralization at Tynebottom closely resembles that in the flats, formerly worked and now inaccessible, at the nearby Rotherhope Fell Mine (Dunham, 1990). The highly siliceous nature of the flats at these localities is rather unusual in the Northern Pennines, where replacement of limestone by carbonate minerals, most commonly ankerite and/or siderite, is more normal.

The deposits of the upper Tyne Valley, of which those at Tynebottom Mine form part, exhibit features characteristic of the central parts of the fluorite zone of the Northern Pennine Orefield, including the abundance of quartz and higher than normal concentrations of chalcopyrite (Dunham, 1990). This mineralogical composition is consistent with the presence beneath this area of the Tynehead cupola on the concealed Weardale Granite (Brown *et al.*, 1987). Ixer and Stanley (1987) regarded synchysite, found in quartz at Tynebottom and elsewhere in the Alston Block, as part of the earliest high-temperature mineralization of the area. The work of Vaughan and Ixer (1980), which suggests formation temperatures of around 235°C for the sulphide assemblages at Tynebottom, also lends support to an area of higher-temperature mineralization in this area. The influence on the mineralization of the Whin Sill, which underlies the deposits exposed in Tynebottom Mine at shallow depth, has been considered by Ixer and Stanley (1987), although these authors concluded that from the available mineralogical evidence its role remains enigmatic.

Conclusions

Tynebottom Mine provides excellent opportunities to study the relationships of metasomatic replacement deposits to the parent veins. Sulphide mineral assemblages have been the subject of important work on the genesis of the orefield and much scope remains for further research. The site is important for the suite of unusual supergene species, which also offers significant research potential. Whereas the major features of the Tynebottom deposits and their constituent minerals are well exposed in the abandoned underground workings, representative specimens showing many important mineralogical and textural features may also be found on the spoil heaps.

SIR JOHN'S MINE, CUMBRIA (NY 762 378)

Introduction

Sir John's Mine is a long-abandoned small lead mine situated on the right (east) bank of the River South Tyne at Tynehead, approximately 4 km south-east of the village of Garrigill, Cumbria. Originally developed, from three adit-levels, to attempt to work lead ore from the Sir John's Vein, the working progressed south-eastwards, eventually cutting the Great Sulphur Vein, one of the major mineralized structures of Alston Moor.

Few details of the mine's history are known, although Dunham (1990) recorded a modest output of lead concentrates for the period 1850–1859. The mine was re-opened in 1941, during World War II, in an unsuccessful attempt to locate workable deposits of pyrite in the Great Sulphur Vein. Since then the mine has lain idle. The underground workings are no longer accessible, although the modest dumps contain significant amounts of veinstone characteristic of the Great Sulphur Vein.

Description

At Sir John's Mine, the cyclothemic sequence of limestones, sandstones and shales belonging to the Lower Carboniferous Alston Group is cut by the Sir John's Vein. This forms part of a prominent NW–SE-trending fracture that extends for many kilometres south-eastwards from the area north-west of Alston, through the South Tyne Valley and into Teesdale. Within the rectilinear pattern of fractures of the Alston Block, faults with this trend are generally referred to as 'cross veins'. Whereas in much of the Northern Pennines these important fractures are characteristically unmineralized or only weakly so, in parts of Alston Moor, including the South Tyne Valley, some of these fractures carry workable lead, zinc and local copper mineralization.

At Sir John's Mine three adit-levels were driven to explore the Sir John's Vein. Little is known in detail of the vein contents here, although Dunham's (1990) record of an output of 158 tons of lead concentrates for the period 1850–1859 confirms the presence of galena. There are no surface exposures of Sir John's Vein here today, and all underground workings at the mine are inaccessible. However, from material remaining on the spoil heaps, and by comparison with other nearby workings, it may be supposed that galena was accompanied by quartz and ankerite, with some fluorite and perhaps a little chalcopyrite.

As underground workings followed the Sir John's Vein south-eastwards they intersected the Great Sulphur Vein, approximately 400 m south-east of the entrance of the lowest level. The Great Sulphur Vein is one of the major mineralized structures of the Alston Block, known to 19th century lead miners as 'The Backbone of the Earth' (Thompson, 1933; Dunham, 1990). In detail it is a complex structure comprising a N-facing monoclinal flexure with, for a significant part of its 9 miles (14 km) strike length, a strong shear belt on its northern side. At present levels of exposure in the South Tyne Valley it is seen to decrease in width downwards. It attains its greatest width, of over 365 m, on Noonstones Hill (NY 749 381), a little over 1 km to the west of Sir John's Mine. Over much of its course the main vein mineral is quartz, commonly present as a replacement of limestone, shale and sandstone clasts, although pure bands of white quartz are locally conspicuous. At lower structural levels, at the horizon of the Tynebottom Limestone at Sir John's Mine, there appears to be a more-or-less continuous zone of sulphides comprising mainly pyrrhotite, pyrite, marcasite and minor amounts of chalcopyrite. Galena and sphalerite are conspicuously scarce or absent from most parts of the vein and, although tried at numerous localities, including Sir John's Mine, the vein has yielded little or nothing of economic value. World War II attempts to locate workable pyrite reserves at Sir John's Mine for sulphur manufacture proved fruitless. Dunham (1990) also recorded a wholly abortive attempt to recover gold from the vein at Sir John's Mine.

The structural relationships of the Great Sulphur Vein to other veins within the orefield are unclear. Despite being able to examine the intersection of the Great Sulphur Vein with Sir John's Vein during the 1941 re-opening of Sir John's Mine, Dunham (1990) concluded that whereas the Great Sulphur Vein appears to displace Sir John's Vein, other detailed evidence exposed in the workings suggest that the north wall of the Great Sulphur Vein is in fact displaced by Sir John's Vein. Dunham (1990) provided details of the mineralization within the vein exposed in 1941 in the underground workings at Sir John's Mine. A northern part consisted of a sheared breccia of highly silicified shale fragments. He interpreted a southern part as a replacement of the Tynebottom Limestone, here 20 m thick and dipping north at 40°, composed of quartz and iron sulphides. The Whin Sill, lying immediately beneath the Tynebottom Limestone was seen to be altered to 'white whin' with pyrite in the uppermost 1.8 m.

As already noted, none of the underground workings at this site remain accessible today. However, substantial amounts of quartz veinstone containing an abundance of pyrrhotite, pyrite and marcasite, derived from the Great Sulphur Vein, dominate the material remaining on the dumps at Sir John's Mine. These give useful opportunities to examine and interpret the sulphide-rich facies of the Great Sulphur Vein. In addition to exhibiting complex interrelationships between the iron sulphides, this veinstone is also noteworthy for the presence of small amounts of chalcopyrite, together with a local abundance of tiny acicular crystals of bismuthinite disseminated through quartz (Ixer *et al.*, 1996). Small amounts of native copper identified in this veinstone were assumed by Bridges and Young (1998) to be of supergene origin. However, in view of the apparent absence of evidence of supergene alteration in this rather fresh-looking veinstone, a primary origin for the native copper cannot be ruled out.

Interpretation

From its structural nature, great width and mineralization dominated by quartz and iron sulphides, the Great Sulphur Vein was long regarded as unique amongst the veins of the

Northern Pennines. However, in underground workings at Cambokeels fluorspar mine in Weardale (NY 935 383), mineralization in the Slitt Vein, one of the main Quarter Point veins of the orefield, was found to pass downwards into a zone dominated by quartz and iron sulphides almost identical to that found in lower parts of the Great Sulphur Vein. It is noteworthy that the Great Sulphur Vein shares the same WNW–ESE trend as the main Quarter Point veins of the orefield. Exactly similar pyrrhotite-bearing quartz veins were encountered within the Weardale Granite in the Rookhope Borehole. It seems probable that the major fluorite-bearing veins of the orefield may pass downwards into a facies of mineralization similar to that of the Great Sulphur Vein (Dunham, 1990). This vein may therefore be a manifestation of the 'root' zone of a major Quarter Point vein, the uppermost zones of which have been removed by erosion.

The presence of abundant pyrrhotite, accompanied by comparatively common chalcopyrite and concentrations of bismuthinite, might reasonably be interpreted as evidence for these mineral assemblages having crystallized at higher temperatures than those known for most of the fluorite-bearing veins of the orefield. Similar mineral assemblages in the Rookhope area of Weardale have been suggested as supporting evidence for an emanative centre of mineralization above the roof zone of the Weardale Granite (Dunham, 1990). Those in the Great Sulphur Vein at Sir John's Mine and elsewhere in the South Tyne Valley appear to occupy an analogous position above the roof of the supposed Tynehead Pluton of the North Pennine Batholith. If so, the mineral assemblages seen at Sir John's Mine may be evidence of an emanative centre of mineralization above this portion of the batholith.

Conclusions

The spoil heaps at Sir John's Mine provide a unique opportunity to examine sulphide-rich veinstone from the deeper levels of the Great Sulphur Vein. These may give important insights into the nature of mineralization at depths not normally seen within the Northern Pennine orefield, and may therefore offer important opportunities for further investigation into the origins of this orefield.

SCORDALE MINES, CUMBRIA (NY 762 226)

Introduction

The Scordale Mines GCR site comprises a number of abandoned surface and underground workings at the head of Scordale, the deep valley of the Hilton Beck, which cuts the Pennine escarpment north of Appleby. The deposits comprise vein and associated flats hosted by Lower Carboniferous limestones which are cut here by the Whin Sill. The mines on the west side of the valley are known as the 'Murton Mines'; the Hilton Mines lie on the east side (Figure 3.6). The GCR site includes only the workings of the Hilton Mines. Both groups of mines were originally producers of lead ore, and in more-recent times barite and some witherite. The mines have long been celebrated for magnificent specimens of yellow fluorite, to be seen in most major mineralogical collections (Symes and Young, 2008). Striking specimens of barite have been obtained, and in recent years fine examples of several nickel minerals have also been collected. Good exposures of the deposits remain *in situ* underground where it is possible to study the detailed mineralogy in its structural and stratigraphical context. Representative specimens are also abundant on the surface spoil-heaps.

The mines were worked by the London Lead Company between 1824 and 1876, during which time over 10 000 tons of lead concentrates were produced. The mines were re-opened in 1896, and under the Scordale Mining Company, and their successors the Brough Barytes Company, produced at least 7200 tons of barite and 70 tons of witherite until their closure in 1919. Subsequent exploration of the workings yielded little if any additional output. The mines today lie within the Ministry of Defence Warcop Training Area and access, both to the surface and underground, is restricted.

Dunham (1948, 1990) provided detailed descriptions of the geology and mineralization of the Scordale deposits, while Young (1998) presented a summary of the geology and mining history. More recently, in a review of replacement mineralization in the Northern Pennines, Bouch *et al.* (2006) have commented on these deposits. Bridges (1982) described a suite of nickel minerals, and the occurrence of supergene minerals at this site has been outlined by Bridges

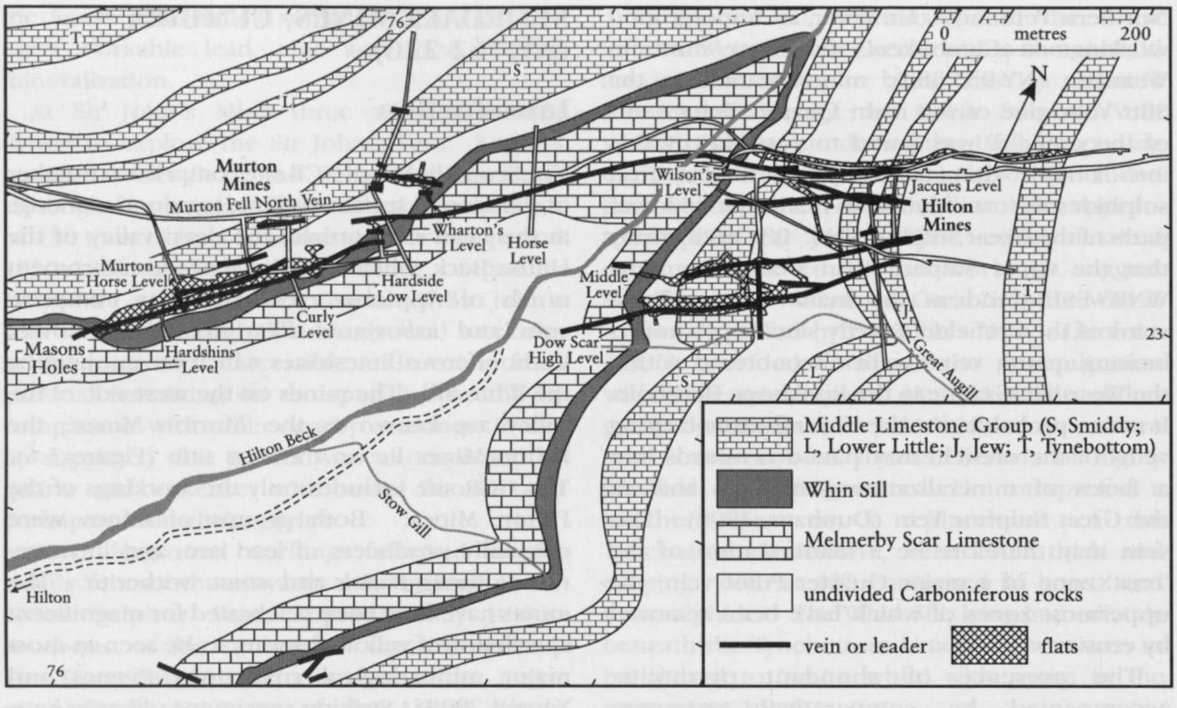

Figure 3.6 Sketch map showing the main veins and flats at the Scordale Mines GCR site. After Dunham (1990).

and Young (1998), and Bridges and Green (2005). Raistrick and Roberts (1990) published contemporary photographs of the mines.

Description

Lower Carboniferous (Dinantian) limestones, from the Melmerby Scar up to the Tynebottom Limestone, crop out at the head of Scordale. The Whin Sill, here intruded immediately above the Melmerby Scar Limestone, forms conspicuous dark-grey crags which contrast with the pale-grey limestone scars. Cutting these rocks are several roughly E–W-trending veins, the strongest of which is the Murton Fell North Vein. Several other sub-parallel veins, notably the Middle Vein and the Dow Scar Vein, occur to the south of this and form striking landscape features (Figure 3.7). Most of the veins show evidence of open-cast workings, and several levels have been driven into them. Substantial spoil-heaps are associated with most of these workings.

The Scordale veins carry galena in a gangue dominated by barite, fluorite and some quartz. Associated with several of the veins are extensive replacement flat deposits within the Melmerby Scar Limestone. In these the limestone has typically been replaced by the same minerals which fill the veins. The flats, which were the source of most of the economic mineralization worked here, occur at the top of the Melmerby Scar Limestone. The shale, which lies between the limestone and the Whin Sill and which has been baked by this intrusion, forms a sharply defined roof to the flats in many parts of the mines. Dunham (1948, 1990) recorded that the flats were generally up to 1.8 m thick at the top of the Melmerby Scar Limestone. They are locally up to 37 m wide, although average widths are usually around 18 m. A feature of these flats is the abundance within them of cavities lined with well-formed cubic crystals of yellow fluorite, together with tabular white barite which clearly encloses euhedral fluorite. Colourless, pyramidal crystals of quartz also occur but in generally smaller amounts. Galena is also common. Dunham (1990) commented that the mineralization in both the Murton and Hilton mines was generally similar, although with rather more barite and less quartz in the Hilton deposits. Witherite was found in the Murton Mines and some was worked from a flat known as the 'Carbonate Shake'. A little witherite may be seen today *in situ* in a small area of flat mineralization remaining in the opencast known as 'Mason's Holes', west of

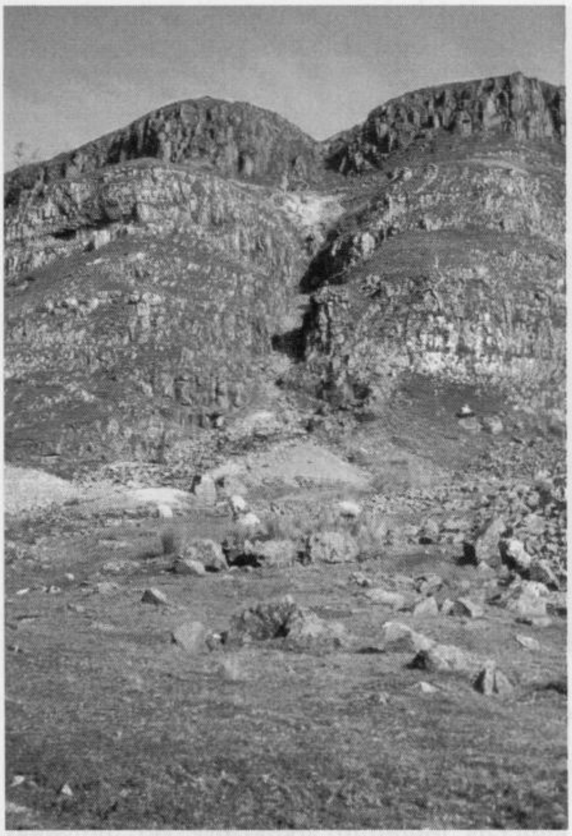

Figure 3.7 Scordale Mines. The Dow Scar Vein here forms a prominent gully crossing the outcrop of the Melmerby Scar Limestone. The dark, upper, crags are composed of Whin Sill dolerite. Dow Scar High Level lies adjacent to the small area of pale-coloured spoil immediately beneath the Whin Sill crags. (Photo: B. Young.)

Murton Mines, and fragments of this mineral occur sparingly on spoil heaps on the hillside below Masons Holes. Witherite has not been observed in the Hilton deposits. Bridges (1982) described a pocket of niccolite, associated with gersdorffite and millerite in the eastern wall of Dow Scar High Level. Supergene minerals are scarce in the Scordale Mines, although fine specimens of crystallized annabergite were found within the nickel-rich pocket in Dow Scar High Level (Bridges, 1982; Bridges and Young, 1998), and a little aurichalcite and malachite have been observed elsewhere in the mine (Young *et al.*, 1985a).

More recently, Bridges and Green (2005) have reported the occurrence also of adamite, mimetite, smithsonite, anglesite, calcite, hydrozincite, limonite and rosasite from Hilton Mines. For the arsenates adamite and mimetite, this represents the first occurrence of these minerals in the Alston Block of the Northern Pennine Orefield.

Interpretation

The stratigraphical and structural relationships of the veins and associated flats are clearly displayed in the remaining accessible underground workings of Scordale Mines. Whereas some lead ore was worked from stopes in the veins, the main source of economic mineralization lay in the extensive flats. These are widely developed adjacent to most of the Scordale veins. All occur within the top beds of the Melmerby Scar Limestone, immediately beneath the thermally metamorphosed shale which intervenes between the limestone and the Whin Sill. The concentration of abundant flat mineralization at this horizon almost certainly results from the ponding effect of this impervious bed to the upward passage of mineralizing fluids. Dunham (1990) commented on the similar relationship of flat mineralization to the presence of shale or sandstone immediately above the Great Limestone elsewhere in the orefield. Flats may occur where shale immediately overlies the limestone; where sandstone overlies the limestone, flats are typically absent. The available plans and sections of Scordale Mines suggest that mineralization, whether in veins or flats, was mainly concentrated beneath the Whin Sill. The sill, together with its envelope of thermally altered shale, thus appears to have been a very effective barrier to mineralizing fluids.

The Scordale flats, unlike other flats within the orefield, are characterized by the replacement of limestone principally by fluorite and barite, with minor galena and quartz. Elsewhere in the Northern Pennine Orefield ankerite and/or siderite, locally with abundant silica, are the usual replacement minerals. Ankerite and siderite are rare or absent at Scordale.

The abundance of fluorite and barite within the same deposit is a feature of interest at Scordale. Within the zonal pattern of mineralization in the Alston Block portion of the Northern Pennine Orefield, occurrences of fluorite and barium minerals are usually mutually exclusive. In the few instances where fluorite and barite do co-exist, such as Scordale, fluorite invariably pre-dates barite. At Scordale, fluorite and barite occur together in roughly equal proportions within a restricted area towards the distal margin of the outer, barium, zone of the field. The zonation of the orefield, including the major central fluorite zone, has been related to the role of major cupolas on the upper surface of the Weardale Granite at Rookhope and Tynehead acting as channels for mineralizing fluids (Dunham, 1990). The small centre of fluorite-rich mineralization at Scordale may correlate with the presence of an emanative centre of mineralization above a minor concealed granite cupola (Bott and Masson-Smith, 1957; Bott, 1967; Dunham, 1990).

Dunham (1937, 1952b, 1990) drew attention to the distribution of colour within Northern Pennine fluorite, noting that yellow is particularly common in the outer parts of the fluorite zone, further observing that the yellow varieties typically exhibit appreciably lower rare-earth-element contents than the purple and green forms abundantly present within the inner parts of the zone. If the rare earth elements within Northern Pennine fluorite were derived from the Weardale Granite it may be that they were deposited abundantly within the inner parts of the fluorite zone with much lower contents in the outer portion of the zone, including Scordale.

The genetic significance of the co-existence of fluorite and barite at Scordale and the rare-earth-element content of the fluorite, in the overall context of the Northern Pennine Orefield, remain to be fully explored.

The presence of a small concentration of nickel minerals, including niccolite, gersdorffite and millerite, in Dow Scar High Level led Bridges (1982) to speculate on the Whin Sill as a possible source rock. Whereas this cannot be confirmed, it is noteworthy that other concentrations of nickel mineralization within the orefield are also closely associated with this intrusion, such as at the **Settlingstones Mine** and the **Lady's Rake Mine** GCR sites (see GCR site reports, this chapter).

Conclusions

The Scordale Mines GCR site provides excellent clear sections of vein and extensive flat mineralization within the Melmerby Scar Limestone, where the influence of the Whin Sill and its envelope of thermally altered shales in confining mineralizing fluids to the upper beds of the limestone can readily be demonstrated. The abundance of fluorite and barite within the same deposit is an unusual feature within the Northern Pennine Orefield, perhaps related to a cupola on the concealed Weardale Granite. Considerable research scope remains to investigate both the significance of this paragenesis and the presence within the deposit of a small concentration of nickel mineralization.

LADY'S RAKE MINE, DURHAM (NY 806 341)

Introduction

Lady's Rake Mine is an abandoned mine which worked lead ore-shoots in the NE–SW-trending Lady's Rake Vein, mainly in the Tynebottom and Jew limestones. The total recorded output of lead concentrates amounts to 7486 tons between 1882 and 1908 (Dunham, 1990). Historical descriptions of the mine, including some contemporary photographs, have been presented by Beadle (1971, 1980).

The principal mineralogical interest of the mine lies in a highly unusual assemblage of ore minerals found in abundance on the spoil heaps. This includes galena, sphalerite, niccolite and ullmanite in association with abundant magnetite and some calc-silicate minerals. Investigations by Young *et al.* (1985b) have identified this as a sulphide-bearing skarn assemblage, unique in the Pennines, and genetically associated with the Whin Sill which is here emplaced within, or close to, the Teesdale Fault. The assemblage gives important insights into the genesis and timing of Pennine sulphide-bearing veins and their relationship to the Whin Sill.

No mineralization is exposed at the surface and all underground workings are flooded and totally inaccessible. The unique mineral assemblages for which this mine is so important are known only from abundant material remaining on the spoil heaps.

Description

Lady's Rake Vein, the principal structure worked at this mine, is known to have carried galena in association with some sphalerite in a matrix of barite, ankerite and siderite (Dunham, 1948, 1990). The spoil heaps adjacent to the Lady's Rake Shaft (NY 8063 3414) and adit (Figure 3.8)

Figure 3.8 General view of Lady's Rake Mine in 1982. The spoil heaps which contain the unusual skarn assemblage are immediately to the right of the buildings. The site of the main shaft is marked by the large rising main in the bottom right of the picture. (Photo: B. Young.)

contain representative examples of this assemblage. Parts of the dumps are, however, notable for the presence of an abundance of large blocks of magnetite-rich rock. In hand specimen this rock typically exhibits magnetite forming almost pure, fine-grained, dull-grey masses up to 10 cm across. Fine- to medium-grained calcite is common and in numerous specimens magnetite veinlets may be seen cutting the calcite. A calcareous alga, replaced by magnetite, was found in one thin-section of this rock (Young *et al.*, 1985b). Many specimens show streaks and pockets, up to 1 cm across, of greenish-white phyllosilicates which include talc, chlorite and smectite. Streaks and pockets of galena and sphalerite are locally common and in places niccolite is conspicuous as spots and patches up to 1 cm across (Figure 3.9). Thin pale-green coatings of annabergite commonly betray the presence of niccolite within weathered blocks. Minor constituents, not visible in hand specimen, include ullmannite, gersdorffite and pyrrhotite.

Magnetite-rich ore with abundant galena, although without obvious nickel mineralization, is also common on the spoil heaps from a trial shaft (NY 8028 3446) approximately 427 m north-west of Lady's Rake Shaft (Figure 3.10). Small amounts of magnetite-bearing rock with ugrandite garnets, although without sulphides, are present on the spoil heaps of the Cadger Well Level (NY 7978 3480) at the head of the Harwood Valley, approximately 1 km north-west of Lady's Rake Shaft.

Interpretation

The magnetite- and niccolite-bearing rock at Lady's Rake Mine and the nearby workings is unlike any previously described from the Northern Pennines. The common factor is that the workings at each locality cut the Teesdale Fault or related fractures.

Contemporary records and mine plans show that at Lady's Rake Mine the Jew Limestone Level cut the Teesdale Fault near its junction with the Teesdale–Winterhush Vein. Dunham (1948) noted that the plans recorded the fault as a 12 m-wide 'whin dyke', although was unable to confirm the presence of dolerite. Young *et al.* (1985b) were unable to find dolerite on the dumps at either Lady's Rake or the nearby trial-shaft, but suggested that the hard, grey magnetite-rich rock, abundantly present at both localities, might have been taken by the miners as 'whin' or dolerite. Dunham (1948) recorded

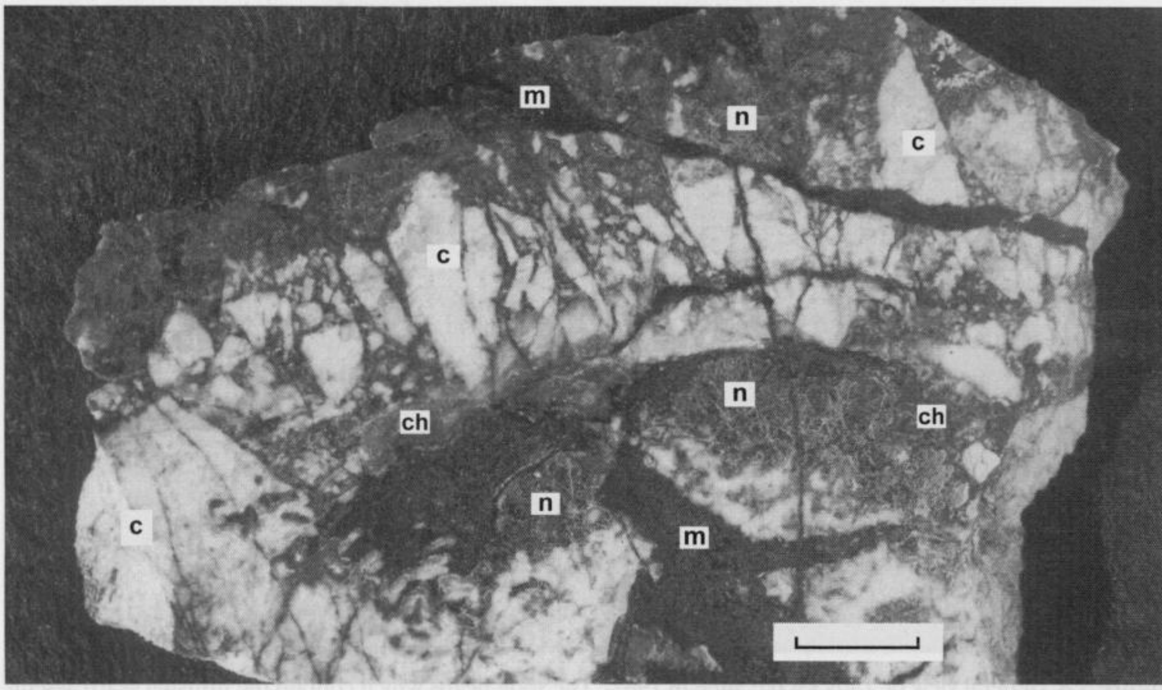

Figure 3.9 Cut and polished slab of magnetite-calcite-niccolite ore from Lady's Rake Mine. White calcite (c) is brecciated and veined by magnetite (m), accompanied by some chlorite (ch). Niccolite (n) forms irregular streaks and rounded masses. The scale bar is 10 mm. (Photo: B. Young.)

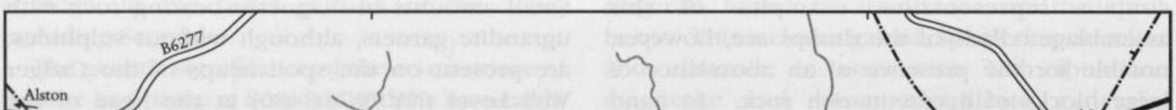

Figure 3.10 Sketch map of Lady's Rake Mine showing main veins and mine workings referred to in the text. After Young *et al.* (1985b).

that the Cadger Well Level at the head of the Harwood Valley was reported to have been driven through the Teesdale Fault into dolerite, and Young *et al*. (1985b) noted the presence here of dolerite fragments on the same part of the dump as samples of magnetite-rich rock.

Elsewhere in Teesdale, metamorphism of limestones within the contact aureole of the Whin Sill has produced garnet-bearing calc-silicate assemblages (Dunham, 1948; Robinson, 1970). The mineralogy of the ore specimens from Lady's Rake Mine and the nearby workings, with abundant magnetite, calcite, locally ugrandite garnet, and in one instance a remnant calcareous alga replaced by magnetite, suggests a skarn environment within the contact zone of the Whin Sill. Young *et al*. (1985b) produced evidence that the top of the Whin Sill may lie only a few metres beneath the deepest workings at Lady's Rake Mine, and suggested that the Whin Sill may have been intruded into the Teesdale Fault where reaction with limestone wall-rocks produced the magnetite-rich skarn assemblages.

In their brief review of other nickel mineral occurrences within the Northern Pennine Orefield, Young *et al*. (1985b) noted the apparently close association between these and the Whin Sill. Drawing comparisons with the Nippissing Sill of the Cobalt–Gowganda region of Ontario (Jambor, 1971; Petruck, 1971) they canvassed the view that the nickel may have been derived from the Whin Sill. The limited evidence available from the nickel-bearing minerals at Lady's Rake Mine suggests formation temperatures of 550°C or higher. This is appreciably higher than the highest temperatures previously proposed for the main Northern Pennine mineralization (e.g. Smith and Phillips, 1974; Vaughan and Ixer, 1980). Young *et al*. (1985b) suggested that the mineralogy of the Lady's Rake ores may therefore be the product of skarn alteration in the contact zone of the Whin Sill accompanied, or followed by, the introduction of nickel-rich fluids from the cooling sill. The abundance of galena and sphalerite, sulphides typical of the main Northern Pennine mineralization, in the magnetite-rich ores at Lady's Rake Mine and the trial shaft, are suggested to be the result of the circulation, within the Teesdale Fault System, of at least some of the main Northern Pennine mineralizing fluids whilst the Whin Sill was still hot.

Conclusions

Whereas no mineralization is to be seen *in situ* at Lady's Rake Mine or at the nearby localities, the abundance of ore specimens on the dumps provides excellent opportunities for studying this assemblage which is unique within the Northern Pennine Orefield, and which gives important insights into the timing of mineralization and its relationship to the Whin Sill.

WILLYHOLE MINE, DURHAM (NY 805 336)

Introduction

Two relatively short, roughly ENE–WSW-trending, veins known as 'Reddycomb Vein' and 'Willyhole Vein', cut Lower Carboniferous limestones, sandstones and mudstones on the east side of Herdship Fell, Upper Teesdale. The spoil heaps are noted for the abundance of supergene greenockite in association with both smithsonite and oxidized sphalerite (Young *et al*., 1987). Originally worked for lead ore between 1852 and 1889, when 758 tons of lead concentrates were raised, the workings were re-opened in 1896 to produce zinc ore, some 712 tons of which were produced between then and 1912 when mining ceased. The remains of the small dressing plant erected at this time can still be seen at the site (Beadle, 1980). The bottom level of the mines was re-opened for investigation during the 1914–1918 war, although no mining appears to have followed (Carruthers and Strahan, 1923). Although described here as 'Willyhole Mine' it is commonly referred to locally by the alternative name of 'Reddycomb Mine'.

Dunham (1990) recorded that the Reddycomb Vein averaged 0.6–0.9 m in width, although locally this increased to as much as 3 m. No figures are given for the Willyhole Vein however. Both veins contained galena and sphalerite together with a little barite. Carruthers and Strahan (1923) noted that a mass of sphalerite 0.6 m across was encountered during the 1914–1918 re-opening. Supergene smithsonite is abundant.

The veins lie close to the inner margin of the barium zone of the Northern Pennine Orefield within one of the local concentrations of zinc mineralization outlined by Dunham (1948).

Description

Although no mineralization is exposed *in situ* in either of the veins today and the underground workings are inaccessible, the remaining spoil-heaps contain an abundance of zinc ore. Both smithsonite and highly oxidized sphalerite are plentiful. Much of the smithsonite is present as the brown cellular 'dry bone' variety, although pale-buff to pale-grey small mammillated crusts are not uncommon and a few smithsonite pseudomorphs after 'nail head' calcite have been found.

Newly fractured surfaces of sphalerite commonly display rich, vivid-yellow crusts of greenockite up to 40 mm across. These crusts resemble specimens of greenockite reported from numerous worldwide localities in a similar paragenesis (Palache *et al.*, 1944).

Interpretation

Supergene cadmium mineralization is more abundant at this site than so far described at any other site in the orefield. Young *et al.* (1987) described similar, but much less-abundant, mineralization from several localities within the Northern Pennines. These authors confirmed the presence of greenockite at Willyhole Mine and **Blagill Mine**, but draw attention to the difficulty of obtaining undoubted X-ray patterns for either greenockite or its cubic dimorph hawleyite from many of these sites, despite the confirmation of the yellow encrustations as cadmium sulphide by microchemical and energy dispersive X-ray analysis. They concluded that in fact many of the vivid-yellow cadmium sulphide crusts found on oxidizing sphalerite in the area are amorphous.

The distribution of supergene cadmium mineralization within the Northern Pennines seems to be principally concentrated in areas of most intense zinc mineralization. Analyses of Northern Pennine Orefield sphalerites reveal a range of cadmium contents, held in solid solution, of between 343 ppm and 3000 ppm (El Shazly *et al.*, 1957; Young *et al.*, 1987). Within the Northern Pennine Orefield there appears to be no clear correlation between the cadmium content of sphalerite and the occurrence of free cadmium sulphide encrustations. There is limited evidence that there is a similar lack of correlation between these features in other areas of Britain where supergene cadmium mineralization has been recorded (El Shazly *et al.*, 1957; Smith, 1982; Mostaghel, 1985a). Young *et al.* (1987) concluded that the presence of supergene cadmium mineralization in the Northern Pennines is related more to the state of oxidation of the sphalerite than to its cadmium content. They also suggested that the amorphous nature of much of the area's cadmium sulphide encrustations may be explained by its development as a residual phase, remaining as zinc was removed in solution during supergene alteration.

Conclusions

Willyhole Mine presents the finest opportunity in the Northern Pennine Orefield to examine and study the occurrence of, and processes which lead to the formation of, supergene cadmium mineralization of this sort.

PIKE LAW MINES, DURHAM (NY 902 314)

Introduction

The Pike Law Mines GCR site comprises a closely spaced group of workings on a complex of veins which crop out over approximately 2 km^2 on the ridge known as 'Pike Law' on the north side of Teesdale. The site includes one of the densest concentrations of mineralization within the Northern Pennine Orefield, and is one of the finest surface localities in the orefield at which vein and associated replacement mineralization, together with supergene alteration features, may be studied. Details of the geology have been given by Dunham (1990), and more recently Bridges and Young (2007) have reviewed the mineralization in some detail.

The courses of several of the veins can be clearly traced through a series of deep opencast workings, commonly referred to as 'hushes', on either side of the Newbiggin to Westgate Hill road. Numerous nearby circular spoil mounds mark old underground workings on parts of the vein complex.

The date of the earliest working here is not known, although Dunham (1990) has suggested that the deposits may have been discovered and worked in ancient times. The oldest documentary records of working relate to mining between 1852 and 1891, by which time, according to

Dunham (1990), the deposits were almost certainly nearing exhaustion. No further mining is known after 1891.

Description

Pike Law, the ridge that lies between Wester Beck and Flushiemere Beck, is composed of a cyclothemic sequence which comprises mainly limestones, sandstones and mudstones, belonging to the Alston and Stainmore groups of the local Carboniferous succession. Strata from the Four Fathom Limestone up to beds above the Firestone Sill sandstone crop out here. Particularly prominent is the wide outcrop of the Great Limestone, a grey bioclastic limestone approximately 19 m thick of Namurian age, which comprises the uppermost unit of the Alston Group. These Carboniferous rocks are cut by a remarkable concentration of mineralized veins which occupy normal faults which trend between east–west and north-east–south-west (Figure 3.11). Whereas Dunham (1990) noted a vertical displacement of up to 15 m on the Pike Law Old Vein, the amount of displacement on most of the other veins cannot be reliably determined, although, in common with similar veins elsewhere in the orefield, displacements are unlikely to exceed 5 m. Minor folding, both parallel and oblique to the trend of the veins, with dips locally reaching 30°, has been described by Dunham (1990).

The mineralized veins of the Alston Block occupy a remarkable pattern of conjugate fractures in which three principal trends may be discerned. The majority of the formerly most productive lead-bearing veins trend between north-east–south-west and ENE–WSW. Cutting these veins locally are several NW–SE-trending 'cross-veins'. These are also normal faults, although they typically exhibit larger throws, commonly over 10 m. Over much of the orefield, these 'cross veins' are usually barren or only weakly mineralized. A third group of veins, with a predominantly east–west to WNW–ESE orientation, the so called 'Quarter Point' veins, intersects both of these trends. The Quarter Point veins typically occupy faults with a sinistral transcurrent displacement, and, although they are often strongly mineralized, usually carry low sulphide concentrations. Many of the largest and most valuable fluorite orebodies of the orefield occur within Quarter Point structures.

The Pike Law vein complex includes fissures belonging to the first two vein orientations with a few roughly E–W-orientated veins perhaps

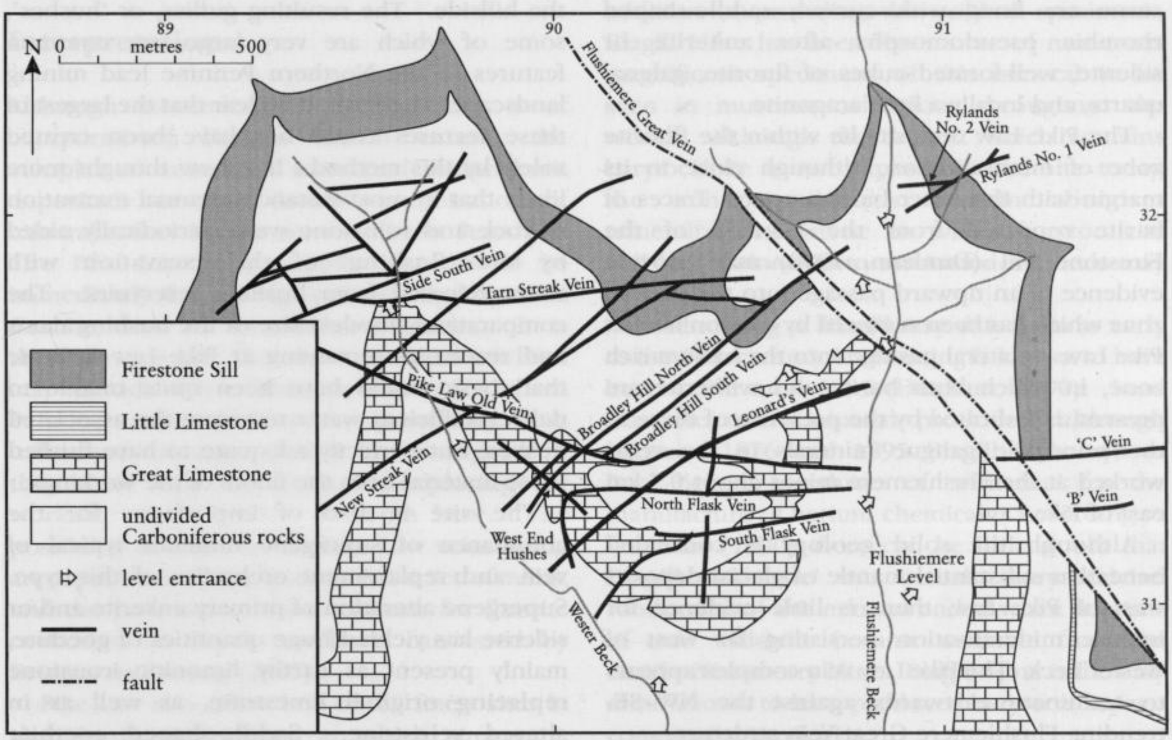

Figure 3.11 Geological map of Pike Law Mines. Courtesy of British Geological Survey.

representing an expression of the Quarter Point orientation.

So far as can be established from the remaining remnants of vein outcrops, the Pike Law veins, which rarely exceed 1 m in width, typically carry galena in a matrix of fluorite with smaller amounts of quartz. Limonitic pseudomorphs of supergene origin attest to the former abundance in the veins of an original iron carbonate mineral, either siderite or ankerite, or both. Neither fresh ankerite nor siderite has been seen at Pike Law. A common feature of the mineralization of the Alston Block is the widespread occurrence of extensive metasomatic replacement of limestone wall-rocks by introduced minerals adjacent to many veins. Such alteration, forming so-called 'flat' deposits, is particularly conspicuous here at Pike Law where the Great Limestone has been intensely mineralized for several metres adjacent to most veins. Ankerite and/or siderite were clearly the most abundant introduced minerals in this wall-rock, although as in the veins, supergene alteration has left only limonitic pseudomorphs after the primary carbonate minerals. Much of the original limestone is seen today as massive, brown-weathering limonitic ironstone in which remnants of ankerite or siderite rhombs are commonly recognizable. Numerous cavities in the ironstone are lined with curved, saddle-shaped rhombic pseudomorphs after ankerite or siderite, well-formed cubes of fluorite, galena, quartz, and locally a little aragonite.

The Pike Law deposits lie within the fluorite zone of mineralization, although close to its margin with the outer barium zone. Traces of barite reported from the horizon of the Firestone Sill (Dunham, 1990) may provide evidence of an upward passage into the barium zone which has been removed by erosion here at Pike Law. A lateral passage into the barium-rich zone, in which both barite and witherite are present, is indicated by the presence of these as the principale gangue minerals in the veins worked at the Flushiemere mines about 0.5 km east of Pike Law.

Although the solid geology is concealed beneath a substantial mantle of glacial deposits west of Pike Law, there is little evidence for intense mineralization persisting far west of Wester Beck. The Pike Law vein complex appears to terminate eastwards against the NW–SE-trending Flushiemere Great Vein structure.

The veins and associated 'flat' deposits at Pike Law have been worked on a spectacular scale from the complex of opencast excavations and 'hushes', including West End Hushes, Leonard's Hush, Pike Law Hush and Flask Hushes, that scar the bench-like outcrop of the Great Limestone on either side of the Newbiggin to Westgate Hill road. Parts of these old workings provide fine sections through both the veins and the highly mineralized limestone wall-rock. In addition, numerous heaps of mine spoil contain an abundance of richly mineralized rock and veinstone. Good examples of all the constituent primary, or hypogene, minerals are easily seen. Fluorite is locally abundant, commonly in well-formed interpenetrant twinned crystals. Like much of this mineral in the Northern Pennines, purple is the commonest colour at Pike Law, although yellow crystals are also present, a feature consistent with Dunham's (1990) observation that this colour tends to be prominent in the outermost parts of the fluorite zone. Coarsely crystalline galena is common, in places exhibiting euhedral crystal faces in cavities.

'Hushing' is a term applied to an early form of hydraulic mining or prospecting in which rock and veinstone are claimed to have been excavated by the repeated release of huge torrents of water from specially constructed reservoirs higher up the hillside. The resulting gullies, or 'hushes', some of which are very large, are common features in the Northern Pennine lead mining landscape. However, it is clear that the largest of these features could not have been created solely by this method. It is now thought more likely that in most instances manual excavation of rock and veinstone were periodically aided by the 'flushing' of the excavation with water released from hushing reservoirs. The comparatively modest size of the hushing dams and reservoirs remaining at Pike Law indicate that these would have been quite unable to deliver sufficient water to create the associated hushes, but perfectly adequate to have flushed loose material from the floors of the workings.

The site is also of importance for the abundance of supergene minerals typical of vein and replacement orebodies of this type. Supergene alteration of primary ankerite and/or siderite has yielded huge quantities of goethite, mainly present as earthy limonitic ironstone replacing original limestone, as well as in altered veinstone. Saddle-shaped goethite pseudomorphs are abundant in cavities in both the veins and the ironstone, and small crusts of mammillated crystalline goethite are seen locally. Although fresh galena is common, cerussite and anglesite are common in the highly oxidized limonitized limestone. The former occurs both as compact crystalline masses and also as acicular white 'jack straw' crystals. A feature of the site is the presence of well-crystallized anglesite as white crystals up to 20 mm long (Bridges and Young, 2007). Supergene oxidation of galena has also produced small yellowish-grey powdery masses of bindheimite, indicating the presence of small quantities of antimony in the primary galena (Bridges and Young, 1998). The presence of zinc within the deposits is revealed by the local occurrence of hemimorphite as crusts of tiny colourless radiating crystals, and of smaller amounts of smithsonite as tiny globular crystalline masses and cellular 'dry bone' aggregates (Bridges and Young, 2007). The apparent absence of sphalerite suggests that supergene alteration of zinc has been complete at the levels of exposure seen at this locality. Further evidence for the intensity of supergene alteration is provided by the presence of fluorite cubes showing deeply etched faces, a feature noted elsewhere in the orefield by Dunham (1990).

Interpretation

Although mineralization at Pike Law is of comparatively limited lateral extent, the complex of veins and associated replacement deposits is one of the densest concentrations of mineralization known in the Alston Pennines. The Pike Law vein complex appears to lie immediately above a high point on the Weardale Granite close to its southern margin. It is therefore possible that the mineralization here may coincide with an emantive centre of Northern Pennine mineralization, a possibility that influenced Dunham (1990) in his suggestion that there may be merit in exploring for workable mineralization at depth here. The possibility of some of the Pike Law veins being an expression of the Quarter Point set of veins, and the potential of these as hosts for fluorite orebodies at depth has been canvassed by Bridges and Young (2007).

Pike Law also offers one of the finest sites in the Northern Pennines at which supergene alteration of vein and associated replacement mineralization may be examined, both *in situ*, and in adundant mine spoil. Bridges and Young (2007) have proposed a multi-stage development of supergene mineralization here. An early stage of oxidation of ankerite and/or siderite by meteoric water produced porous 'limonite', perhaps accompanied by the formation of some cerussite, which was then followed by oxidation of galena to anglesite.

Conclusions

Pike Law is an important site at which a dense concentration of mineralized veins and associated replacement deposits, showing also the effects of supergene alteration of these, may be examined both *in situ* and in abundant mine spoil.

BLAGILL MINE, CUMBRIA (NY 741 473)

Introduction

Blagill Mine is the type locality for the very rare barium calcium carbonate mineral barytocalcite ($BaCa(CO_3)_2$) (Brooke, 1824). In addition to providing the original specimens, Blagill Mine has been the source of numerous magnificent specimens of this mineral to be seen in museum collections throughout the world. Although the deposit which contains barytocalcite is not exposed at the site today, the mine spoil-heaps contain abundant mineralized veinstone in which barytocalcite and its relationship to associated minerals may be studied.

Lead mining at Blagill may date from as early as the 14th century, and mining is known to have been active until 1895 (Dunham, 1990). Lead was the main mineral produced, although between 1876 and 1895 Blagill is known to have been a producer of 'witherite' for the manufacture of barium chemicals. According to Dunham (1990) there can be little doubt that Blagill 'witherite' was actually barytocalcite. Production of this mineral ended when deposits of true witherite became available from the nearby Nentsberry Mine. Blagill Mine is the only mine known to have produced barytocalcite as a commercial product.

Description

The strong NE–SW-trending vein known as 'Fistas Rake' has been worked for lead from underground workings on the east side of Blagill Burn at Blagill Mine. Vein ore-shoots were present in the Great Limestone, the underlying Quarry Hazle Sandstone and the Four Fathom Limestone. In addition, metasomatic replacement flats are understood to have been associated with the vein in the limestones. The vein is reported to have been up to 3 m wide and to have been composed mainly of barytocalcite with smaller amounts of witherite, calcite, galena and sphalerite (Dunham, 1948, 1990). The vein is not exposed at the surface today and none of the underground workings is safely accessible. However, the remaining spoil-heaps contain an abundance of mineralized veinstone in which examples of the primary minerals and their paragenetic relationships may be studied (Young, 1985c, 1993). In addition the dumps contain small quantities of supergene minerals including smithsonite, hydrozincite, barite and rare traces of greenockite (Young *et al.*, 1987).

Barytocalcite was first described as a new mineral species by Brooke (1824), and, although no precise locality details were given for the original specimens, Young (1985c) has concluded that Blagill Mine was the source. Despite the mineral's great abundance at Blagill it was for many years known, in very small amounts, from only a very few other Northern Pennine localities. Fine specimens of barytocalcite from a number of Northern Pennine locations are in the Russell Collection at the Natural History Museum, London. In a review of the occurrence of barytocalcite, and the chemically identical species alstonite, Young (1985c) showed that barytocalcite is relatively widespread, and locally abundant, in the outer, barium, zone of the Northern Pennine Orefield. Outside of the Northern Pennines the mineral appears to remain a great rarity and has been reported from only a handful of other localities including the Aberfeldy barite deposit, Perthshire (Moles, 1985), the Mendips and South Wales (Alabaster, 1990; see **Mwyndy Mine** GCR site report, Chapter 5), Dolyhir, Wales (see **Dolyhir Quarry** GCR site report, Chapter 5), Langbån, Sweden and Himmelsfürst Mine, Freiburg, Germany (Roberts *et al.*, 1990) and Rorrington, Shropshire (Starkey *et al.*, 1994). Blagill Mine remains the world's most accessible and most prolific source of specimens of this rare species.

Barytocalcite is the monoclinic trimorph of barium calcium carbonate ($BaCa(CO_3)_2$). The orthorhombic trimorph, alstonite, which also has its type locality within the Northern Pennines, occurs much more sparingly within the orefield (see **Fallowfield Mine** GCR site report, this chapter). Paralstonite, the trigonal trimorph, has recently been reported from the **Dolyhir Quarry** GCR site (Chapter 5).

Much of the barytocalcite at Blagill occurs as coarsely crystalline masses commonly in excess of 10 cm across. Cavities lined with white to colourless, slender monoclinic prisms, sharply terminated by prominent (121) faces and occasionally forming fan-shaped aggregates, are common. Individual barytocalcite crystals are typically up to 5 mm in length, but crystals up to 15 mm long are not uncommon (Symes and Young, 2008). Numerous blocks of recrystallized limestone, in part replaced with barytocalcite, and containing many crystal-lined cavities, are almost certainly derived from replacement flats adjacent to the vein. More rarely, barytocalcite is found as relatively fine-grained compact crystalline masses. A few specimens have been collected in which barytocalcite appears to pseudomorph original tabular barite crystals (Young, 1993).

In many blocks of veinstone the barytocalcite exhibits an outer crust of compact, rather chalky, barite, almost certainly produced by supergene alteration. Specimens may be found in which this alteration has produced compact, chalky barite pseudomorphs after well-formed barytocalcite crystals.

Interpretation

Blagill Mine lies within the outer zone of the Northern Pennine Orefield in which barium minerals comprise the characteristic gangue. Throughout this zone barite is the most widespread and abundant mineral. However, the Northern Pennine Orefield is unique in the world for the abundance within it of barium carbonate minerals. Most abundant and widespread of these is witherite, many thousands of tons of which have been mined from the area. Barytocalcite is also an important member of this barium carbonate assemblage and has been shown to be both widespread and locally abundant in the orefield (Young, 1985c). The reasons for the remarkable abundance of barium carbonates, particularly the rare barium calcium carbonates barytocalcite and alstonite, within the Northern Pennines have yet to be satisfactorily explained.

In a study of the distribution and relationships of barium carbonate minerals within the orefield, Young (1985c) showed that barytocalcite, together with alstonite, usually occurs in deposits in which witherite is also present. In most instances the double carbonates comprise relatively minor proportions of the assemblage, although in some deposits barytocalcite is present in equal or, more rarely, greater amounts than witherite. Blagill is one of the deposits in which barytocalcite greatly predominates over witherite. In his review, Young (1985c) demonstrated that barytocalcite and alstonite almost invariably occur in deposits within limestone wall-rock and that the crystallization of these minerals usually post-dated that of witherite.

Hancox (1934) presented evidence that much of the witherite within the Northern Pennine Orefield was produced by hydrothermal alteration of previously deposited barite by reaction with fluids carrying an abundance of carbonate ions. The close association of barytocalcite and alstonite with witherite suggests that these minerals may be a product of this event and that these late carbonating fluids may have become locally enriched in calcium. Indeed Hancox (1934) observed that at the **Settlingstones Mine** GCR site (see GCR site report, this chapter), near Hexham, barytocalcite occurred as the final encrustation on witherite and suggested that the development of barytocalcite and alstonite resulted from an influx of calcium carbonate in the final stages of the carbonating episode. That the lithology of the wall-rocks in general exercised little influence on the formation and deposition of witherite is clear from the range of wall-rocks which host the main witherite orebodies. However, the strong correlation between the presence of barytocalcite and alstonite and limestone wall-rocks is persuasive evidence for a reaction between the carbonating fluids and the adjacent wall-rocks. Leaching of the wall-rock during the final stages of mineralization may thus have provided the calcium ions necessary for the formation of these minerals (Young, 1985c). The great abundance of barytocalcite as a replacement of limestone, as appears to be the case in parts of the Blagill deposit, suggests that conditions locally favoured the formation of barytocalcite rather than witherite.

Young (1993) described and figured a specimen from the Blagill dumps in which barytocalcite clearly forms large tabular pseudomorphs, presumably after primary barite, in recrystallized and ankeritized limestone. There is thus evidence that some barite may have originally been deposited as a component of the replacement flats at Blagill. The hydrothermal event which converted large volumes of barite to witherite throughout the orefield may, at least locally, have effected the conversion of some of this barite to barytocalcite.

Supergene alteration at Blagill has produced an abundance of barite which locally pseudomorphs barytocalcite.

Conclusions

Blagill Mine, the type locality for the rare mineral barytocalcite, has provided numerous fine crystallized specimens of this mineral. The site remains the world's most accessible and most prolific source of specimens of this unusual mineral. Although no mineralization is exposed *in situ* today, the mine spoil-heaps contain abundant mineralized veinstone in which barytocalcite and its relationship to associated minerals may be studied in the context of barium carbonate mineralization in the outer zones of the Northern Pennine Orefield.

SETTLINGSTONES MINE, NORTHUMBERLAND (NY 849 688)

Introduction

Settlingstones Mine (Figure 3.12) is the largest and most important of a small cluster of mines which worked several veins on the north side of the Tyne Valley around the small town of Haydon Bridge. The **Fallowfield Mine** and **Stonecroft Mine** GCR sites (see GCR site reports, this chapter) also lie within the Haydon Bridge portion of the orefield. Although these deposits are hosted by Carboniferous rocks which structurally form part of the Northumberland Trough (see Figure 3.1), they are generally regarded as comprising the northernmost worked deposits of the Northern Pennine Orefield. The Settlingstones Vein,

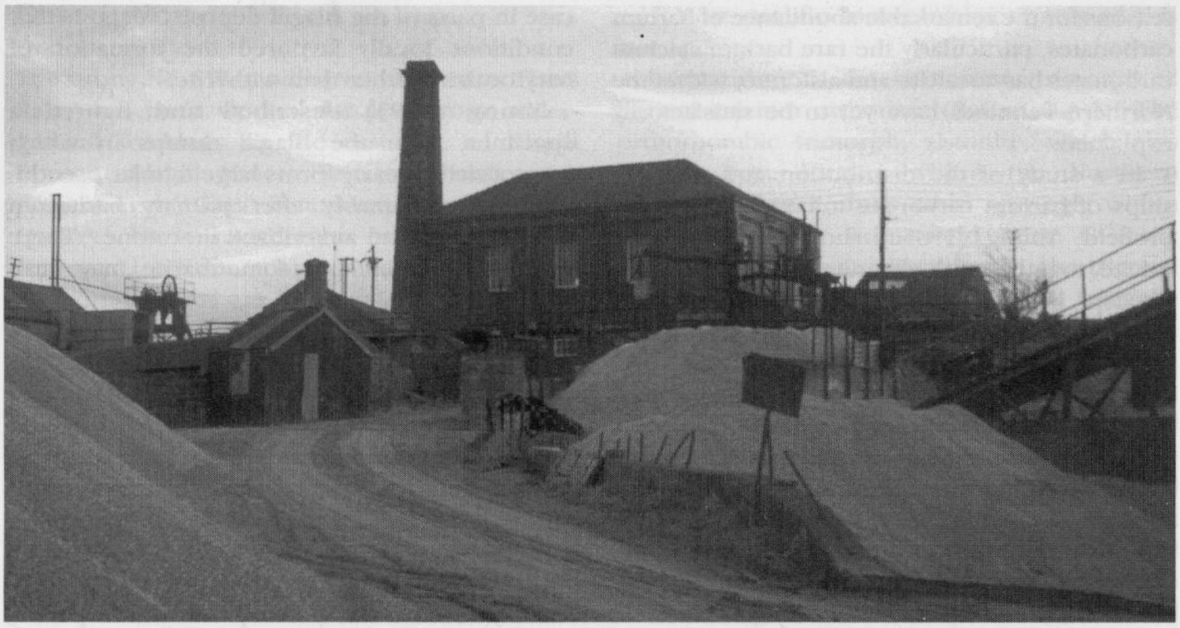

Figure 3.12 The treatment plant and stockpiles of witherite product in 1967 at Settlingstones Mine. The head frame of the Ellen pumping shaft may be seen behind the buildings to the left of the picture. (Photo: B. Young.)

which strikes approximately north-east–south-west, cuts Lower Carboniferous limestones, sandstones and mudstones into which the Whin Sill is intruded. The sill formed one of the most important wall-rocks for the ore-shoots worked in this mine.

Settlingstones was first worked as a lead mine, probably during the 17th century. Records of lead production are available only for the period 1849–1873 when a total of 16 902 tons of lead concentrates were raised. In the original lead workings the main gangue minerals were barite and ankerite. As the mine was developed south-westwards the vein was followed through a NNW–SSE-trending cross-course beyond which the vein filling changed dramatically to witherite, with only very small amounts of sulphides and other minerals. From 1873 the mine's production changed from lead ore exclusively to witherite. Settlingstones soon became established as the world's leading, and for long periods sole, commercial source of witherite. Between 1873 and its closure in 1969 Settlingstones produced around 630 000 tons of witherite product.

The Settlingstones deposit was remarkable for the great abundance of witherite, which, outside of the Northern Pennines, is of considerable rarity. The mine yielded numerous very fine specimens of crystallized witherite and barite, spectacular examples of which are to be seen in most of the world's major mineralogical collections. The Settlingstones Vein also contained local concentrations of nickel ores and strontianite, and was noted for the presence of the barium zeolite harmotome.

Descriptions of the mine, its orebodies and the minerals present include those by Russell (1927), Trestrail (1931, 1938), Dunham (1948, 1990), Ineson (1972), and Young and Bridges (1984). Research on the Settlingstones witherite orebody has contributed much to the understanding of the origins of the Northern Pennine Orefield.

Although no mineralization is exposed *in situ* at the site today, and all underground workings are totally inaccessible, the remaining dumps contain vein material which still offers opportunities for study and research on this unique deposit.

Description

The mineralogical importance of Settlingstones Mine lies in the mineralization present in Settlingstones Vein south-west of the cross-course at which the vein filling changed to witherite. According to Dunham (1990) the vein ore-shoots averaged 2.4 m in width, although locally widths of 9.1 m were recorded. The vein was noted for the presence of a number of branches or loops, at least two of which were large enough to be workable for witherite. Witherite contents in the run of mine ore were commonly above 77%. Witherite at Settlingstones typically occurred as white to pale-cream crystalline masses. In cavities, terminated crystals, commonly forming complex twinned aggregates, were abundant. Specimens of witherite exhibiting rounded, rather nodular crystalline surfaces were also common. The only other mineral present in quantity in the vein was barite, much of which occurred as sharply terminated crystals lining cavities in the witherite. Dunham (1990) noted that the distinctive morphology of these crystals, in which the dominant faces are (110) combined with (001), appears to be characteristic of barite found in association with witherite.

Minor constituents of the witherite vein included well-formed, colourless, small cruciform twinned crystals of the barium zeolite harmotome, commonly found encrusting witherite crystals in vugs (Young and Bridges, 1984; Dunham, 1990). Radiating crystalline aggregates of pale-green or pale-buff strontianite were present locally (Young *et al.*, 1985b) and some good calcite crystals were found in places. Barytocalcite is a very rare late-stage member of the mineral assemblage (Young, 1993).

Ore minerals were comparatively scarce within the witherite orebodies, although galena and sphalerite, together with a little pyrite, were widely found in small amounts. Russell (1927) described the occurrence of niccolite and ullmannite in a pipe-like deposit within the vein from which about half a ton of niccolite is said to have been raised. Young *et al.* (1987) identified gersdorffite in specimens from this occurrence.

The Whin Sill was a major wall-rock throughout the workings at Settlingstones Mine. Metasomatism by mineralizing solutions altered large volumes of the Whin Sill dolerite to the pale-grey clay-carbonate rock known to miners as 'white whin'. Hard sandstone, including a thick sandstone thermally altered by contact with the sill, was also an important wall-rock in parts of the mine.

During its long life as a witherite mine, ore was raised at Frederick Shaft (NY 8423 6825) adjacent to the Fourstones to Grindon Hill road, the Stanegate. Processing took place at the treatment plant adjacent to the Ellen pumping shaft (NY 8500 6878) on the south bank of Settlingstones Burn. Upon closure the shafts were sealed, the mine buildings demolished and much of the site was cleared. Remnants of the spoil heaps remain today near the site of the treatment works. These contain an abundance of witherite, together with blocks of the very distinctive barite. Small specimens of harmotome, commonly encrusting witherite or filling veinlets within 'white whin' may also be found on the spoil heaps.

Interpretation

The veins of the Haydon Bridge area occur within Carboniferous rocks, and locally the Whin Sill, in the southern portion of the Northumberland Trough. They thus do not form part of the structural unit known as the 'Alston Block', to which the other veins of the orefield belong. However, their form, and mineralogy have much in common with the main Northern Pennine Orefield, of which they appear to comprise the northernmost expression. These veins all lie within the outer, barium-rich, zone of the orefield.

The Northern Pennine Orefield is unique in the world for the abundance, within its outer zones, of large concentrations of barium carbonate minerals, most abundant of which is witherite. Settlingstones Vein was the largest witherite deposit known. The reasons for the considerable abundance of barium carbonate minerals in this orefield have not yet been satisfactorily explained.

Dunham (1990) noted that examination of witherite veinstone from the south-western workings of Settlingstones Mine, where an increasing amount of barite was present in the vein, shows undoubted evidence of witherite replacing original barite. Dunham (1990) described thin-sections of witherite forming interlocking platy pseudomorphs after barite. Moreover, bands of galena and sphalerite, seen as part of the crustified structure where the vein was dominantly barite, were seen to continue through cavities in the later witherite, or to hang into them. This is entirely consistent with the work of Hancox (1934) which showed that much of the area's witherite resulted from replacement of original tabular barite.

Young and Bridges (1984) suggested that reaction between these late-stage carbonating fluids and altered dolerite wall-rock produced the small but widespread encrustations of harmotome found coating witherite and other minerals in vugs both at Settlingstones Mine and the nearby **Stonecroft Mine** and Greyside Mine. In limestone wall-rocks the same paragenetic position is typically occupied by barytocalcite or alstonite (Young, 1985c). Barytocalcite has been observed as a very rare late-stage constituent of the Settlingstones witherite deposit (Young, 1993).

The nickel mineralization at Settlingstones appears to have been restricted to one pocket cut many years ago at the mine's 70-Fathom Level (Russell, 1927). Young *et al*. (1985b) presented comparative analyses of the nickel minerals from Settlingstones and other Northern Pennine localities, and suggested that the Whin Sill may have been the source of the nickel for each of these occurrences.

Although generally regarded as being distal deposits of the Northern Pennine Orefield, the view has been canvassed that the veins of the Haydon Bridge area may be related to mineralization associated with the Stublick Fault Zone, which forms the boundary between the Alston Block and the Northumberland Trough (Young *et al*., 1992b). It is significant in this context that barium and base-metal mineralization is common along a restricted belt of country astride this fault zone across much of northern England (Cooper *et al*., 1991). Some mineralization on the southern margin of the Northumberland Trough shows important similarities to deposits with similar structural settings in Ireland, such as Tynagh. It is thus possible that significant base-metal, and perhaps barium mineralization, may be present at depth along the Stublick Fault Zone. Similarities between $\delta^{34}S$ of anhydrite in Lower Carboniferous anhydrites in the Solway Basin and those of barite in the veins of the Haydon Bridge area support a source for mineralization within the trough and may thus lend some support to this hypothesis (Crowley *et al*., 1997). If so the deposits in the Settlingstones and nearby veins, which occupy antithetic faults within the hangingwall of the Stublick Fault Zone, may be high-level expressions of this mineralization.

Conclusions

Settlingstones Mine is an important site for witherite mineralization. Its position is crucial to understanding and interpreting the origin of this and the nearby veins. Although no mineralization is visible *in situ* at the site today, the increasingly overgrown spoil-heaps contain useful quantities of vein and wall-rock which allow study of the mineralization of this once important commercial deposit.

STONECROFT MINE, NORTHUMBERLAND (NY 855 689)

Introduction

Stonecroft Mine is a former lead mine, worked from shafts situated on the left (north) bank of the Settlingstones Burn, approximately 0.5 km east of the former processing plant at Settlingstones Mine, approximately 5 km NNW of Haydon Bridge in the South Tyne Valley, Northumberland. The mine worked deposits associated with a complex vein system, part of which was formerly worked at **Settlingstones Mine** (see GCR site report, this chapter).

Stonecroft Mine was worked between 1853 and 1896 in conjunction with the adjoining Greyside Mine, the shafts of which lie between 0.5 km and 1 km east of those at Stonecroft. Dunham (1990) recorded a total output of 74 264 tons of lead concentrates from these mines.

There are no exposures of the veins worked at Stonecroft Mine and none of the underground workings are accessible. However, substantial amounts of mineralized spoil, containing important mineral assemblages typical of these veins, remain adjacent to the former Stonecroft shafts, although these are becoming increasingly obscured by vegetation, including woodland plantations. Little remains to mark the site of the main Greyside Mine shafts.

Parts of the Stonecroft Mine spoil-heaps are of interest, and have SSSI status, as one of the very few sites at which the rare orchid, Young's helleborine (*Epipactis helleborine* var. *youngiana*), grows.

Description

Stonecroft Mine worked lead ore from fissure veins which cut a cyclothemic succession of Lower Carboniferous sandstones, limestones and shales into which the Whin Sill, a dolerite of Permo–Carboniferous age, is intruded. The main orebodies worked here occurred in veins within Whin Sill wall-rocks (Dunham, 1990).

Although there are no vein exposures, and all underground workings have long been inaccessible, the substantial spoil-heaps contain an abundance of veinstone representative of the deposits worked. Most of the dumps have, however, been planted with trees, and as these approach maturity, useful material for mineralogical examination is becoming obscured.

Galena is the main ore mineral, and the only one to have been extracted during the working life of the mine. The galena in this deposit, in common with that from other veins in the Haydon Bridge area, exhibits a silver content significantly lower than most of the galena raised in the Northern Pennines. Typical silver contents at Stonecroft were around 2.45 oz per ton of lead, compared with average values of between 4 and 8 oz per ton for most of the orefield. Sphalerite is abundant at Stonecroft, although it was never recovered during mining. Approximately 5000 tons of zinc concentrates were, however, recovered by processing the spoil heaps during the early 1950s (Dunham, 1990). Despite this, sphalerite remains an abundant mineral on the spoil heaps today. Unusually for the Northern Pennines, the sphalerite at Stonecroft typically occurs in a pale-brown, iron-poor form, unlike the more iron-rich dark-brown to black forms common elsewhere in the orefield. Much of the Stonecroft sphalerite exhibits striking banding in differing shades of brown, reminiscent of the 'schalenblende' variety (Symes and Young, 2008) (Figure 3.13).

The main gangue mineral is barite, usually present as compact white, buff or pale-pink crystalline masses. Pinkish-buff to pale-brown and cream ankerite is also common. A little witherite is present, together with small amounts of quartz (Dunham, 1990). Vugs or cavities in the veinstone are not abundant, although when found are commonly lined with very small cruciform twinned crystals of harmotome (Young and Bridges, 1984). Rarely, small radiating aggregates of strontianite crystals have also been found in vugs (Young, 1985d).

A large, brick-built pumping engine-house, adjacent to the Stonecroft pumping shaft, is a conspicuous local landmark. Large heaps of, mainly sand-grade, tailings near the Settlingstones Burn remain from the 1950s reprocessing of the heaps to recover sphalerite.

Figure 3.13 Cut surface of banded sphalerite from the spoil heaps at Stonecroft Mine. The pale minerals are barite and ankerite. (Photo: B. Young.)

Interpretation

The veins of the Haydon Bridge area, including those formerly worked at Stonecroft Mine, **Settlingstones Mine**, and **Fallowfield Mine** (see GCR site reports, this chapter), occur within Carboniferous rocks and locally the Whin Sill, in the southern portion of the Northumberland Trough. Although these veins do not lie within the structural unit known as the Alston Block, from their form and mineralogy they are generally regarded as comprising the northernmost expression of the Northern Pennine Orefield.

The possibility of mineralization in this part of the South Tyne Valley being genetically related to the Stublick Fault Zone has been discussed briefly under the **Settlingstones Mine** GCR site report (this chapter). The lead- and zinc-rich mineralization at Stonecroft Mine may thus offer important insights into the base-metal potential of this major structural line.

The common occurrence at Stonecroft Mine of primary barite, with only subordinate amounts of witherite, is of interest in the light of the site's close proximity to Settlingstones Mine at which early carbonitization of barite to witherite has been so extensive. Comparative studies of veinstone and wall-rock samples from the Stonecroft Mine and **Settlingstones Mine** GCR sites may therefore offer unique opportunities to investigate the nature of the widespread development of witherite within this orefield.

The comparatively common occurrence of the barium zeolite, harmotome, within vugs in the Stonecroft veinstone, is consistent with Young and Bridges (1984) suggestion that this mineral developed as a result of reaction between late-stage carbonate-rich fluids and altered Whin Sill dolerite wall-rock.

The genetic significance of the low silver content of the galena, and the low iron content of the sphalerite have yet to be understood.

Conclusions

Stonecroft Mine is an important site in the Northern Pennine Orefield at which lead- and zinc-rich mineralization, associated with barium gangue minerals, may be studied. Its position, both adjacent to **Settlingstones Mine** and within the Stublick Fault Zone, may have considerable genetic significance in understanding mineralizing processes in this part of northern England.

FALLOWFIELD MINE, NORTHUMBERLAND (NY 936 674)

Introduction

Fallowfield Mine is one of the largest of the small group of mines which worked a number of veins on the north side of the Tyne Valley. The mine lies immediately north of the village of Acomb. Like the deposits worked at **Settlingstones Mine**, near Haydon Bridge (see GCR site report, this chapter), the vein worked at Fallowfield is hosted by Carboniferous rocks which structurally form part of the Northumberland Trough (see Figure 3.1). The Fallowfield Vein, in common with the Settlingstones Vein and other veins in this area, is generally regarded as comprising one of the northernmost worked deposits of the Northern Pennine Orefield. Fallowfield Vein strikes approximately north-east–south-west, cutting Upper Carboniferous (Namurian) rocks, mainly sandstones and mudstones. The mine workings have proved the vein into the Lower Carboniferous (Dinantian) beds beneath the Four Fathom Limestone. Prior to 1846 coal was raised at Fallowfield Mine from the Little Limestone Coal (Namurian), and parts of the workings were connected with those of the nearby Acomb Colliery.

Mining at Fallowfield is known to date from as early as 1611 (Smith, 1923). Workings, accessed by a number of shafts, extended for at least 2 km along the vein. Detailed descriptions of the mine's geology and mineralization have been presented by Wray (in Wilson *et al.*, 1922), Smith (1923), and Dunham (1948, 1990). Fallowfield was originally worked as a lead mine up to 1846. In that year mining for witherite, which was an abundant gangue mineral here, began and continued until the closure of the mine in 1912. Production figures are incomplete, but Dunham (1990) recorded a total of 11 196 tons of lead concentrates for the period 1848–1907, and suggests that the mine's total output of witherite amounted to around 105 000 tons.

In addition to the abundance of witherite, a remarkable feature of the vein was the abundance of alstonite in association with witherite. Fallowfield shares with Brownley Hill Mine, near Alston, the distinction of being the type location for this rare species (Young, 1985c). Magnificent specimens of alstonite, commonly associated with beautiful crystals of witherite, from Fallowfield Mine are to be seen in major mineralogical collections throughout the world.

Although all underground workings have long been inaccessible, and despite the absence of any surface outcrop of the vein, the site remains of importance for the local abundance within several spoil-heaps of specimens of alstonite, locally in association with other vein minerals.

Description

Fallowfield Vein has been worked from a number of shafts along a strike length of over 2 km. Smith (1923) noted that the Fallowfield Vein maintained a width of 6.1 m throughout much of the mine, although in places this increased to over 12 m. The vein filling consisted mainly of witherite with smaller amounts of barite, galena, alstonite, calcite and rarely a little sphalerite.

Witherite occurred as ribs up to 1.8 m wide, containing up to 70% barium carbonate (Dunham, 1990). The mine was, after **Settlingstones Mine**, one of the region's most important commercial sources of this mineral. It also yielded, during its long working life, some of the finest specimens of crystallized witherite known. Examples of these, often highly distinctive, white pseudohexagonal pyramids are to be seen in major mineralogical collections throughout the world. Rounded, nodular masses, typically with an internal radiating crystalline structure, were also common. Examples of all of these morphologies are present on the spoil heaps but do not compare with the superb specimens collected when the mine was working.

Alstonite was an important constituent of the vein and Fallowfield is, jointly with Brownley Hill Mine, near Alston, the type locality for this rare species. Alstonite is the orthorhombic trimorph of barium calcium carbonate ($BaCa(CO_3)_2$). The monoclinic trimorph, barytocalcite, which also has its type locality in the Northern Pennines, occurs more widely within the orefield (Young, 1985c). Paralstonite, the trigonal trimorph, has been found for the first time in Great Britain at **Dolyhir Quarry**, Wales (see GCR site report, Chapter 5).

Specimens of the mineral which was to become known as 'alstonite' were first described by Johnston (1835, 1837), and Thomson (1835), from specimens collected at both Fallowfield Mine and Brownley Hill. Although regarded in these early descriptions as a form of barytocalcite, which had first been described several years previously (Brooke, 1824), the separate identity of this mineral was recognized by Thomson (1837), who proposed the name 'bromlite', apparently based on a mis-spelling of Brownley Hill. The name 'alstonite' was introduced by Breithaupt (1841) and soon became the accepted name despite the apparent priority of Thomson's name 'bromlite'.

Alstonite occurs most commonly as highly distinctive acute pseudohexagonal pyramidal or bipyramidal crystals which generally exhibit horizontal striations on the pyramid faces. A vertical medial re-entrant line is commonly seen on these. Euhedral crystals up to 5 mm long are common in vugs in crystalline alstonite, or encrusting witherite or other vein minerals. Crystalline alstonite, with a rather sugary texture, commonly forms pure, or almost pure, masses up to 10 cm across at Fallowfield. The mineral is most commonly colourless or white with a vitreous lustre. More rarely alstonite exhibits a delicate rose-pink colour. Palache *et al.* (1951) noted that this colour fades on exposure to light. Magnificent specimens of crystallized alstonite, commonly associated with distinctive pseudohexagonal pyramidal or prismatic crystals of witherite, are to be seen in many mineralogical collections (Symes and Young, 2008). Alstonite is today known from a handful of other locations within the Northern Pennines and has been reported in small quantities from South Wales (Alabaster, 1990; see **Mwyndy Mine** GCR site report, Chapter 5) and in the Welsh Borderland, at the **Dolyhir Quarry** GCR site. Elsewhere in the world it remains a great rarity.

Smith (1923), Hancox (1934), and Dunham (1948, 1990) all referred to the presence of barytocalcite at Fallowfield Mine, although Young (1985c) was unable to confirm this, and no undoubted specimens from this site are known.

Although the underground workings of Fallowfield Mine are totally inaccessible and there are no surface exposures of the vein, spoil heaps which remain adjacent to several of the shafts contain representative specimens of the vein minerals, including alstonite. Many of these heaps lie within a partially landscaped caravan park, although a few lie within adjoining agricultural land. Most of the spoil heaps are today rather overgrown.

Interpretation

Fallowfield Vein occurs within Carboniferous rocks in the southern portion of the Northumberland Trough. Although it therefore does not lie structurally within the Alston Block, from its form and mineralogy it is generally regarded, along with other veins in the Hexham–Haydon Bridge area, as comprising the northernmost expression of the Northern Pennine Orefield. Like all other veins in this northern area the Fallowfield Vein lies within the outer, barium-rich, zone of the orefield.

The possibility of mineralization in the Tyne Valley being related to the Stublick Fault Zone has been discussed briefly in the **Settlingstones Mine** GCR site report (this chapter).

The Northern Pennine Orefield is unique in the world for the abundance, within this outer zone, of barium carbonate minerals. Fallowfield Vein contained large concentrations of these otherwise rare minerals, and, as has been noted above, was one of the field's major commercial producers of witherite, as well as a celebrated source of fine mineralogical specimens of both this species and alstonite. The double carbonates of barium and calcium, barytocalcite and alstonite, are also locally abundant within this outer zone, although the reasons for their local abundance here and extreme rarity elsewhere in the world have not been satisfactorily explained (Young, 1985c).

In a study of the distribution and relationships of barium carbonate minerals within the orefield, Young (1985c) showed that both alstonite and barytocalcite usually occur in deposits in which witherite is also present. In most instances the double carbonates comprise relatively minor proportions of the assemblage, although locally barytocalcite appears to be the most abundant barium mineral. In the comparatively few localities at which alstonite has been found it is always a minor, and generally inconspicuous, member of the assemblage. In his review Young (1985c) demonstrated that alstonite and barytocalcite almost invariably occur in deposits hosted by limestone wall-rock, and that crystallization of the double carbonate mineral usually post-dated that of witherite. Examination of numerous specimens of witherite with alstonite from Fallowfield reveals that here too formation of the double carbonate, alstonite, typically post-dated crystallization of witherite.

Hancox (1934) presented evidence that much of the witherite within the Northern Pennine Orefield was produced by hydrothermal alteration of previously deposited barite by reaction with fluids carrying an abundance of carbonate ions. The close association of barytocalcite and alstonite with witherite suggests that these minerals may be a product of this event and that these late carbonating fluids may have become locally enriched in calcium. That the lithology of the wall-rocks in general exercised little influence on the formation and deposition of witherite is clear from the range of wall-rocks which host the main witherite orebodies. However, the strong correlation between the presence of barytocalcite and alstonite and limestone wall-rocks is persuasive evidence for a reaction between the carbonating fluids and the adjacent wall-rocks. Leaching of the wall-rock during the final stages of mineralization may thus have provided the calcium ions necessary for the formation of these minerals (Young, 1985c). The orebodies at Fallowfield typically occurred where limestone formed at least one wall of the vein. The reasons for the crystallization of the double barium calcium carbonate as alstonite in preference to barytocalcite has yet to be explained, although Young (1985c) has suggested that temperature may be a major factor.

Conclusions

Fallowfield Mine, the joint type locality for the very rare mineral alstonite, has provided numerous beautifully crystallized specimens of alstonite and witherite. Despite the inaccessibility of the underground workings and the absence of exposures of mineralization, the site comprises the world's most accessible and prolific source of alstonite. The remaining spoil-heaps contain veinstone in which alstonite and its relationship to other minerals may be studied in the context of barium carbonate mineralization in the outer zones of the Northern Pennine Orefield.

CLOSEHOUSE MINE, DURHAM (NY 850 227)

Introduction

Closehouse Mine is a disused barite mine at the head of the Arngill Valley, a tributary of the River Lune which in turn drains into the River Tees near Middleton-in-Teesdale. The Closehouse deposits occur within the Lunedale Fault

System, a complex, roughly E–W-trending structural zone which defines the boundary between the Alston Block to the north and the Stainmore Trough to the south (see Figure 3.1). The cyclothemic sequence of Lower Carboniferous limestones, sandstones and mudstones are strongly folded adjacent to the fault, which is here intruded by a wide dolerite dyke belonging to the Whin Sill suite of intrusions. Wide bodies of barite mineralization occur within the fault, mostly within the dolerite. The structural and stratigraphical relationships of the orebody are spectacularly displayed in the large opencast workings.

The presence of rich mineralization in this area appears to have been discovered at an early date as numerous ancient hushes mark the course of the main ore-bearing structures. The London Lead Company acquired the lease for the mine in 1770 and explored the deposits by driving a long level, the Deerfold Level, beneath the old hushes. Despite the great abundance of barite it seems that little lead ore was obtained. The London Lead Company surrendered its Lunedale leases in 1880 and the mine lay abandoned until 1939, when, attracted by the abundance of barite, Athole G. Allen (Stockton) Ltd acquired the lease. Production of barite, by underground mining, began at Closehouse Mine in 1945. At this time selective room and pillar mining was employed to extract the purest masses of barite. By the 1960s opencast extraction had started, and all underground mining ended at Closehouse in 1981. Dunham (1990) recorded that total output of dressed barite had by then reached over 300 000 tons. Opencast extraction ceased in 2000.

The geology and mineralization of the Closehouse deposits have been described in detail by Dunham (1948, 1990), and Hill and Dunham (1968). The Closehouse area was also the subject of an IGS Mineral Reconnaissance Study (Cornwell and Wadge, 1980). Vaughan and Ixer (1980) have described an early high-temperature sulphide assemblage from part of the workings, and Young (1985e) and Young *et al.* (1985a, 1994) have described the occurrence of several supergene minerals.

Description

Hill and Dunham (1968) provided a very detailed description of the stratigraphical and structural features of the Closehouse Mine deposits. Although subsequently brought up to date by Dunham (1990), most of the features outlined in the earlier account are still readily appreciated at the site, and Hill and Dunham's map and section are therefore reproduced here (Figure 3.14).

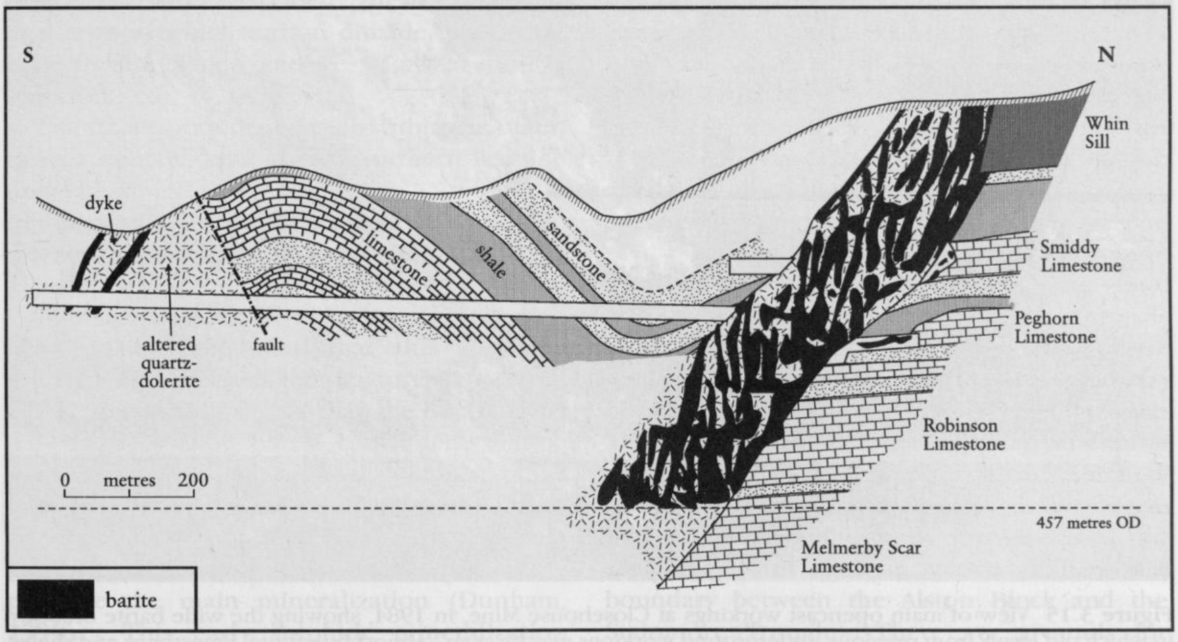

Figure 3.14 Section through the main orebody at Closehouse Mine, showing folding in associated Carboniferous beds. After Hill and Dunham (1968).

Mineralization at Closehouse occurs within several sub-parallel veins within the Lunedale Fault System. The Lower Carboniferous rocks here comprise a cyclothemic succession of limestones, sandstones and shales, locally intruded by the Whin Sill. The main deposits occur within the Closehouse North Vein on the west side of the Arngill Valley (Figure 3.15). This occupies a fault which dips at 45°–52°S with a downthrow to the south. In the immediate vicinity of the mine the Carboniferous rocks lie almost horizontally on the north side of the vein. On the south, or hangingwall side, they are folded into an asymmetric anticline and complementary syncline (Figure 3.14). The fault was intruded, prior to mineralization, by a dolerite dyke up to 30 m wide, which comprises part of the Whin Sill suite of intrusions. Much of the dolerite is altered to the distinctive clay-carbonate rock known to miners as 'white whin'. Mineralization occurs mostly within this dolerite intrusion, both as fissure-fillings and replacing the altered dolerite. Barite is the most abundant introduced mineral throughout the Closehouse deposits. Much of this is typically very coarse-grained with individual crystals commonly up to 10 cm long. Dunham (1948) described the presence of water-clear barite in a replacement flat deposit within the Smiddy Limestone on the north side of the vein. Galena occurs sparingly as coarsely crystalline lenses. A little sphalerite is found locally. Massive quartz is present in places. Large blocks of metasomatized limestone found within the opencast workings, but unlocated *in situ*, have been found to consist of ankerite with cavities containing calcite and acicular crystals of aragonite. Coatings of a bluish-green clay within barite-rich 'white whin' vein breccia have been identified as barium-muscovite (Lawson, pers. comm. in Dunham, 1990).

Vaughan and Ixer (1980) described a sulphide assemblage including pyrite, pyrrhotite and arsenopyrite from parts of the deposit for which they proposed an early, high-temperature origin.

Supergene minerals recorded from Closehouse Mine include pyromorphite (Dunham, 1948; Young, 1985e), rosasite (Young *et al.*, 1985a), anglesite (Dunham, 1990), and aurichalcite, cuprite and leadhillite (Young *et al.*, 1994).

Figure 3.15 View of main opencast workings at Closehouse Mine, in 1984, showing the wide barite orebody in which old levels from previous underground workings may be seen. Almost horizontal limestones and shales on the footwall are exposed on the right of the picture. Steeply folded sandstones and limestones on the hangingwall can be seen on the left. (Photo: B. Young.)

Interpretation

The Lunedale Fault System, into which the Closehouse deposits are emplaced, is regarded as the southern boundary of the Alston Block, separating it from the Stainmore Trough and Cotherstone Syncline to the south. This clearly acted as a growth fault, during Carboniferous times, allowing much greater thicknesses of sediment to accumulate in the Stainmore Trough than on the Alston Block. The Carboniferous rocks on the south, downthrow, side of the fault are folded into a conspicuous asymmetric anticline and associated syncline (Figure 3.14). Dunham (1990) suggested that this may result either from compression or from subsidence into the Stainmore Trough.

Folding was followed by intrusion into the fault of a wide dyke of dolerite belonging to the Whin Sill suite. Francis (1982) suggested that the Haydon Bridge and Hett dykes may have acted as feeders for the emplacement of the Whin Sill. The wide dyke at Closehouse in a very similar structural setting may also be considered as a potential feeder dyke. Further tension, perhaps accompanied by some transcurrent movement following the emplacement of the dyke, produced numerous closely spaced, near-vertical fractures in the dyke, allowing access of fluids which converted much of the intrusion to the clay-carbonate rock known as 'white whin'. Ineson (1968) described these alteration processes in which carbon dioxide, water and potash were added and Fe, Mg, Ca and Na removed.

The Closehouse deposits lie within the outer, barium mineral, zone of the Northern Pennine Orefield.

Vaughan and Ixer (1980) described a sulphide assemblage which includes pyrite, pyrrhotite, high-Fe sphalerite and arsenopyrite, which appears to pre-date the main barite mineralization. They concluded that this provided evidence of formation temperatures of around 250°C, significantly higher than the depositional temperatures of the main constituents of the barium zone of the orefield. Similar small occurrences of relatively high-temperature mineral assemblages have been described from elsewhere in the orefield, where they also clearly pre-date the main mineralization (Dunham, 1990). This early sulphide mineralization exhibits some similarities to vein mineralization in parts of the Lake District for which a Caledonian age is generally advocated. The proximity of this mineralization at Closehouse to the Lunedale Fault and to the sub-Carboniferous basement may invite speculation on a genetic relationship, perhaps involving the remobilization by the intrusion of the Whin Sill, of Caledonian mineralization in the Lunedale Fault and its emplacement in fissures in Carboniferous rocks.

The main mineralization at Closehouse is dominated by an abundance of barite, whilst other minerals, including sulphides, are typically present only in subordinate amounts. Whereas some of this mineralization clearly fills fissures, a considerable proportion of the barite ore deposits clearly replaces Whin Sill dolerite. It appears that during mineralization substantial volumes of carbonate-rich 'white whin' reacted with mineralizing fluids in a similar fashion to limestone, giving rise to large replacement deposits dominated by barite. Replacement of limestone has also occurred at Closehouse where, for instance, a barite-rich flat containing water-clear barite occurred within the Smiddy Limestone (Dunham, 1948).

The great abundance of mineralization within the Lunedale Fault System at Closehouse suggests that this may have acted as a major channel, conveying mineralizing fluids, perhaps originating in the adjacent Stainmore Trough. Dunham (1990) presented evidence that significant mineralization may be associated elsewhere with this structure, including the Durham Coalfield, where mineralization is concentrated adjacent to its easterly continuation, the Butterknowle Fault.

Supergene mineralization at Closehouse is consistent with oxidation of the deposit at present topographical levels.

Conclusions

Closehouse Mine provides excellent large-scale sections through a major barite deposit in the outer zone of the Northern Pennine Orefield. The mineralization can readily be studied in its stratigraphical and structural context. Much of the barite mineralization occurs as a replacement of Whin Sill dolerite intruded into the Lunedale Fault System, which defines the boundary between the Alston Block and the Stainmore Trough. There are grounds for supposing that this structural line may have acted both as a route for the emplacement of the

Whin Sill and as a major channel for mineralizing fluids. The presence of earlier relatively high-temperature sulphide mineralization invites speculation on possible remobilization of Caledonian mineralization at depth within the Lunedale Fault System.

FOSTER'S HUSH, DURHAM (NY 8556 2040)

Introduction

Foster's Hush is an abandoned opencast working on Hunter's Vein, one of the complex of veins formerly worked for lead ore and barite at Lunehead Mines. The partially landscaped spoil-heaps at this site are of importance for the abundance within them of fine examples of the rare barium calcium carbonate mineral barytocalcite ($BaCa(CO_3)_2$). Whereas **Blagill Mine**, near Alston, is described in this volume (see GCR site report, this chapter) as the type location for this mineral, Foster's Hush is an important source of fine specimens and, in addition, provides small exposures of the mineral *in situ* in its parent vein. Barytocalcite and witherite are also known from the **Dolyhir Quarry** GCR site (see GCR site report, Chapter 5).

Little is known of the earliest history of lead working at Lunehead prior to the London Lead Company's tenure of the mines between 1770 and 1880. The mines were re-opened for barite mining in 1884, and production of this mineral continued, intermittently, until 1937 (Dunham, 1990). Further intermittent working, including unsuccessful exploration for workable witherite, took place between 1939 and 1981, since when the mines have lain idle.

Description

South of the Brough to Middleton-in-Teesdale road (B6276), the Great Limestone and overlying Namurian beds up to the Crow Limestone, are cut by a number of sub-parallel fissure-veins which strike between WSW–ENE and south-west–north-east. All carry galena in a gangue dominated by barite, although with local concentrations of witherite and barytocalcite, together with minor amounts of aragonite (Young, 1985c; Dunham, 1990). Small replacement flats in the Great Limestone are known to have been worked adjacent to several veins. Extensive underground workings for lead ore, and later workings for barite, exist in several of the veins, although none of these are accessible today. Opencast workings and trials mark the outcrop of several veins, and a number of spoil heaps provide representative samples of the mineralization. Detailed descriptions of the geology and mining have been published by Dunham (1990).

The easternmost of the Lunehead group of veins is the SW–NE-trending Hunter's Vein, the course of which may be seen today as a conspicuous shallow gully, known as 'Foster's Hush', which extends south-westwards from the roadside at NY 8590 2045 (Figure 3.16). The vein here lies within the Great Limestone. Brown limonitized limestone wall-rock adjacent to the vein can be seen locally in the sides of the hush. In addition to opencast working,

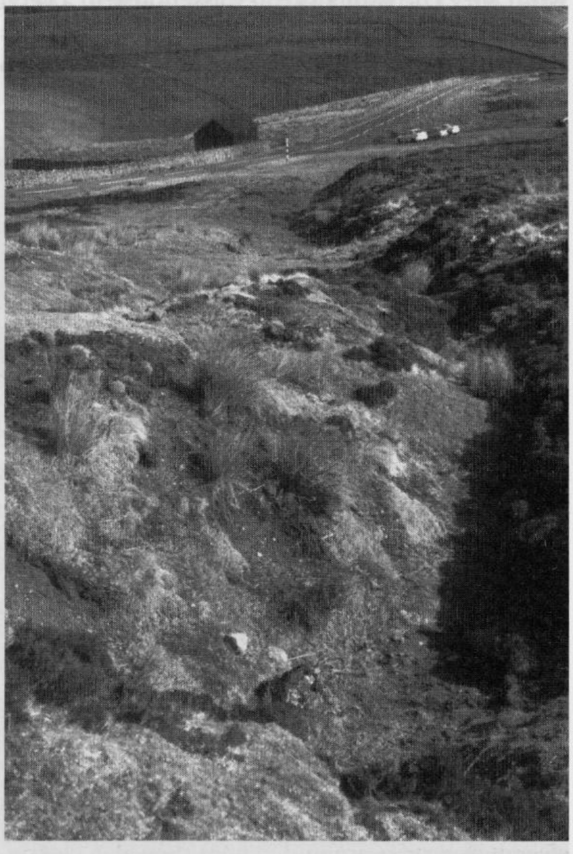

Figure 3.16 Foster's Hush, looking north-east towards the B6276 road. The cars in the distance are parked on the partially landscaped spoil-heap derived from the hush. (Photo: B. Young.)

Hunter's Vein has been worked underground from a level driven south-westwards towards it from the south bank of Lune Head Beck at Rennygill Bridge (NY 8638 2058). Dunham (1990) noted the presence of replacement flats associated with the vein. Little is known in detail of the content or productivity of Hunter's Vein in these workings, although Dunham recorded unsuccessful trials for witherite between 1959 and 1962.

Recently fenced-off areas surround portions of the floor of the hush that have collapsed into the underground workings. The sides of these collapsed areas expose partially limonitized Great Limestone with a few clear, although rather inaccessible, unworked portions of the vein, or branches of it. These reveal vein widths of up to approximately 30 cm, comprising crude bands of barite, witherite and barytocalcite with included slices of partially limonitized limestone wall-rock (Figure 3.17). A few small scattered crystals of galena are present locally. Near-surface supergene alteration has produced crusts of rather chalky barite on some of the barytocalcite and witherite. In places, the former presence of masses of barytocalcite or witherite is indicated by more extensive cellular masses of tiny barite crystals which exhibit the distinctive morphology described by Dunham (1990) as characterisitic of this mineral where it has formed by alteration of a pre-existing barium carbonate mineral.

Although the small vein exposures provide unique opportunities to examine *in situ* the inter-relationships of the barium mineral suite present within this vein, the nearby spoil-heaps offer an abundance of material for detailed study. A substantial heap of spoil, derived from surface workings in Foster's Hush, lies adjacent to the road at the north-eastern extremity of the hush. Although portions of this spoil heap were removed about 25 years ago, and the remaining material levelled and partly landscaped, the poorly vegetated remaining spoil is an important source of material representative of the mineral assemblages found in Hunter's Vein.

Especially common are blocks of barytocalcite-rich veinstone (Young, 1985c). Many of these are wholly or partially encrusted with supergene barite, either as dull chalky masses or as coral-like aggregates of tiny, commonly iron-stained, crystals with the characteristic morphology noted above and described by Dunham (1990).

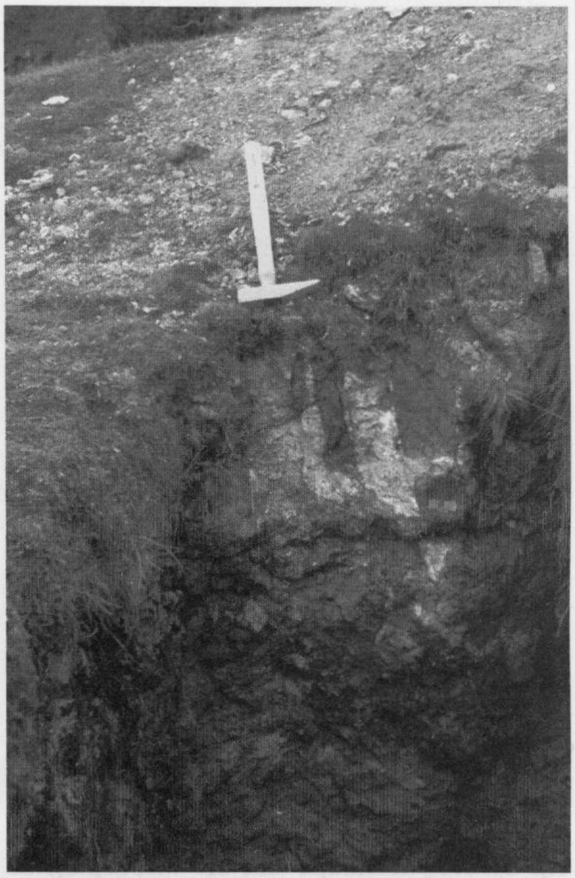

Figure 3.17 Hunter's Vein, exposed, composed of bands of barite, witherite and barytocalcite with inclusions of limonitized limestone wall-rock, exposed in the sides of collapsed workings in Foster's Hush. (Photo: B. Young.)

The site has yielded numerous notable examples of beautifully crystallized barytocalcite (Figure 3.18). These closely resemble specimens from **Blagill Mine**, the type locality for this mineral (see GCR site report, this chapter), and typically comprise white to colourless slender monoclinic prisms up to 3 mm long, sharply terminated by prominent (121) faces, lining numerous open cavities within compact crystalline barytocalcite/witherite/barite veinstone. In some specimens, the barytocalcite crystals exhibit a thin superficial coating of barite, almost certainly of supergene origin. Crude pseudomorphs of fine-grained barite after barytocalcite crystals are occasionally seen.

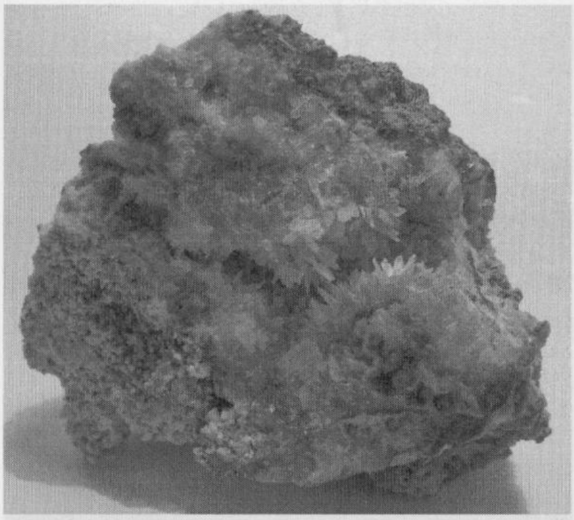

Figure 3.18 Specimen of crystallized barytocalcite from the spoil heaps adjacent to Foster's Hush. Sharply terminated monoclinic crystals project into vug in compact crystalline barytocalcite. The specimen is 80 mm across. (Photo: B. Young.)

Also present in this spoil are minor amounts of coarsely crystalline white to pale-cream witherite and small amounts of aragonite in white, or very rarely, extremely pale-blue fibrous crystalline masses. Apart from barite, supergene minerals present here include rare examples of pale turquoise-blue aurichalcite (Young *et al.*, 1985a) and tiny colourless crystals of hemimorphite (Dunham, 1990).

Smaller amounts of barytocalcite-rich veinstone are also present on the dumps adjacent to an old shaft sunk on Hunter's Vein, approximately 380 m south-west of Foster's Hush (NY 8564 2016). In this veinstone cavities up to 5 cm across are lined with terminated barytocalcite crystals up to 4 mm long.

Specimens of barytocalcite, very similar in appearance to those present at Foster's Hush, have also been found on the spoil heaps from the main adit-level of Lunehead Mine (NY 8460 2051), approximately 1 km west of Foster's Hush. It is impossible to determine whether these have been derived from underground workings in Hunter's Vein, accessed from this level, or from other veins within the Lunehead complex. It may, however, be significant that no witherite or barytocalcite has been seen elsewhere in the Lunehead area on surface spoil-heaps from any vein other than Hunter's Vein.

Interpretation

Foster's Hush lies in the outer zone of mineralization of the Northern Pennine Orefield in which barium minerals, including notable concentrations of barium carbonate minerals, comprise the typical gangue assemblage (Dunham, 1990). A remarkable feature of this orefield, noted by Dunham (1990), is the great abundance of barium carbonate minerals in this outer zone. Most common of these is witherite, though Young (1985c) has demonstrated the widespread occurrence of the barium calcium carbonate minerals alstonite and, more commonly, barytocalcite.

Aspects of the distribution of barytocalcite, its place in the paragenetic sequence of Northern Pennine deposits and the possible influence of wall-rock lithology on its occurrence are important in relation to **Blagill Mine**, the type location for barytocalcite.

Foster's Hush has many similarities to the **Blagill Mine** GCR site. It occupies a similar position within the outer margin of the orefield above the flanks of the concealed Weardale Granite. As at Blagill Mine, barytocalcite appears to have been, at least locally, the most abundant barium carbonate mineral within the vein. Unlike at Blagill Mine, no evidence has been seen at Foster's Hush of barytocalcite or witherite replacing earlier primary barite. However, there seems no reason to regard the barium carbonate mineralization at Foster's Hush as anything other than part of the widespread episode of barium carbonate emplacement that affected the entire Northern Pennine Orefield, including Blagill Mine. In the few specimens seen at Foster's Hush where witherite and barytocalcite co-exist, barytocalcite invariably encrusts witherite, a relationship that is entirely consistent with the paragentic sequence for barium carbonate minerals within the orefield proposed by Young (1985c).

Conclusions

Foster's Hush is an important site at which fine examples of the rare barium calcium carbonate mineral barytocalcite may be seen, both in abundant spoil and in a small number of exposures of the parent vein *in situ*. In this latter regard, the locality is certainly unique within the Northern Pennine Orefield and may be unique in the world.

BLACK SCAR, MIDDLETON TYAS, NORTH YORKSHIRE (NZ 231 052)

Introduction

To the east of the main concentration of mainly lead-, zinc,- barite- and fluorite-bearing veins of the Swaledale area in the Askrigg Block portion of the Northern Pennine Orefield lies a group of small deposits characterized by the abundance within them of copper minerals. Dunham and Wilson (1985) have regarded this area as an integral part of the Northern Pennine Orefield, but have pointed out that some of these deposits, around the small village of Middleton Tyas, exhibit several unique features. Apart from a few small, and generally overgrown, spoil-heaps, little remains today to mark the sites of copper mining in this area. Today Black Scar Quarry provides the only remaining accessible outcrop of copper mineralization within the Middleton Tyas area.

The Middleton Tyas copper deposits occur mainly within the Dinantian Undersett Limestone, at the east end of the small Middleton Tyas Anticline. Mining took place here between 1736 and 1779, principally within a few fields close to the centre of the village. Nothing is exposed at any of these sites today, and in the absence of any plans the exact form and shape of the deposits is rather conjectural. It is clear, however, that although the total output from these deposits was estimated at as little as 3500 tons the ore was extremely rich, averaging about 45% Cu (Dunham and Wilson, 1985). An unsuccessful attempt to revive copper working in the area took place in the 19th century, when some mining was undertaken at the nearby Merrybent and Kneeton Hall mines.

The history of this small and unique area of copper mining has been outlined by Angerstein (1755), Jars (1765), and more recently by Raistrick (1936, 1975), and Hornshaw (1975).

Notwithstanding the difficulties of obtaining representative ore specimens and the lack of good exposures of the original deposits, the mineralization has been the subject of studies by Deans (1950, 1951), Small (1977), and Wadge *et al*. (1981). Dunham and Wilson (1985) provided a useful summary of the geology, mineralization and mining history.

Description

In their summary of the Middleton Tyas copper deposits, Dunham and Wilson (1985) drew upon early descriptions of the mineralization, and suggested that a number of vein and flat deposits occur within a limited area in and around the village of Middleton Tyas. The deposits appear to have taken the form of 'pipes' or 'flats' within the Undersett Limestone. The upper flat 'resting on clay' appears to have been underlain about 3.6 m below by a second horizon, referred to as the 'underbed', which it seems was typically richer. Minerals present included covellite, chalcocite, cuprite, bornite, native copper, malachite and azurite. Sparse traces of some of these may be found on some of the small remaining spoil-heaps. Dolomitization seems to have been the characteristic wall-rock alteration in these deposits.

The exposure at Black Scar Quarry was assumed by Deans (1951) to represent a lean but representative example of the deposits. The quarry exposes the Undersett Limestone underlain by sandstone and shale in which blue and green staining by supergene copper minerals, including malachite and azurite, is conspicuous. In the southern part of the quarry a shale bed beneath the limestone, which contains numerous rounded nodules rich in chalcocite and covellite, has been excavated for up to 1 m into the face. This may be an example of the sort of 'flat' deposit worked elsewhere at Middleton Tyas during the 18th century. The quarry is today rather overgrown and presents relatively limited opportunities to establish the relationship of this mineralization to any obvious structure. In part of the quarry, blue- and green-stained shale debris covers part of the face, suggesting that copper mineralization may also be present at a higher level, although this cannot be established. It is worth noting that contemporary reports of the Middleton Tyas mines refer to the presence of copper minerals at two distinct levels (Dunham and Wilson, 1985). However, Deans (1951) observed that sand pockets within the limestone contain residual copper minerals, and that fissures filled with clay-gouge locally contained azurite and malachite. The copper-stained debris in the quarry could thus be derived from such a deposit rather than an upper, mineralized horizon.

Interpretation

In the absence of reliable plans or descriptions of the form of the Middleton Tyas deposits it is difficult to formulate a clear model for their origin. However, in their review of the available evidence, Dunham and Wilson (1985) rejected a syngenetic origin for the deposits in favour of the hypothesis of Small (1977) that the deposits originated by the mixing of low Na:K ratio metal-rich orefield brines from the Stainmore Trough with high Na:K ratio formation waters. In addition, they advocated supergene enrichment of the deposits so formed, by weathering under arid conditions during Lower Permian times. In this way they suggested that the deposits owe much of their enhanced grade to precipitation of copper both on such primary sulphides as chalcopyrite, pyrite and djurleite as well as on diagenetic pyrite nodules within calcareous shales, such as those beneath the Undersett Limestone.

Conclusions

The Black Scar GCR site provides the only opportunity accessible today to examine *in situ* the unique mineralization formerly worked in the Middleton Tyas area. The exposure, although considerably overgrown, reveals apparently secondarily enriched copper mineralization which may be studied in its stratigraphical context.

CUMPSTON HILL NORTH AND SOUTH VEINS, CUMBRIA (SD 781 976)

Introduction

Two parallel, roughly NE–SW-trending veins which cut Dinantian and Namurian limestones and sandstones at Hanging Lund Scar, on the east side of the River Eden, south of Kirkby Stephen, are distinguished by containing copper mineralization. These deposits form part of a small cluster of veins dominated by copper mineralization on the western margin of the Askrigg Block. Comparatively few metalliferous minerals may be seen in the small exposures of these veins. Much richer samples of metalliferous veinstone are available in small spoil-heaps associated with old trial workings on these veins.

The mineralogy of the veins, and their paragenetic significance within the Northern Pennine Orefield, have been the subject of studies by Small (1977, 1978, 1982), Shepherd (1979), and Dunham and Wilson (1985). Nothing is known of the history of these small workings or of any output of ore from them, although Dunham and Wilson (1985) suggested that at least some of the workings may be ancient.

Description

The Cumpston Hill South Vein is exposed in the bed of the River Eden (SD 777 969) where it cuts sandstone beneath the Undersett Limestone. It can be traced uphill into this limestone where, near Intake Farm, its outcrop is marked by a belt of silicified Undersett Limestone up to 3 m wide. Dunham and Wilson (1985) noted that a shaft sunk on the vein in the Main Limestone shows highly silicified limestone, azurite, malachite and 'a little yellow sulphide', presumably chalcopyrite. They reported similar veinstone from small trials on the higher ground to the north-east along the course of the vein which here forms a distinct low topographical feature. The North Vein also forms a wide belt of silicification up to 6 m wide where it cuts the Main Limestone. Dunham and Wilson (1985) reported a shaft on this vein at SD 7832 9768, the spoil from which is identical to that from the South Vein. Small (1977) described tetrahedrite from here. This dump cannot today be located at this grid reference, although a small spoil-heap at SD 7815 9748, above the Main Limestone outcrop, contains abundant quartz veinstone with disseminated sulphides including tetrahedrite and chalcopyrite, together with conspicuous crusts of azurite and malachite. This spoil heap has clearly been used as a source of hardcore which has been incorporated into nearby farm tracks.

Interpretation

The Cumpston Hill veins are representative of the suite of copper-bearing quartz-rich veins, designated as 'Q Zone' veins by Small (1977). These occur in the north-western part of the Askrigg Block, between the Dent Fault and the comparatively intensely mineralized area centred on Swaledale, the 'North Swaledale Mineral Belt' of Dunham and Wilson (1985). The Cumpston Hill veins are unlike others in the Askrigg Block in being dominated by quartz, often accompanied by extensive silicification of wall-rock, in which copper sulphides are commonly present. The presence of 'fahlerz' (tennantite-tetrahedrite) in the veins of this area was first recognized, at Fell End Clouds, by Clough (in Dakyns *et al.*, 1891) ,and more recently occurrences of such mineralization have been described from High Stennerskeugh Level (NY 749 010) and Stennerskeugh Clouds (NY 7440 0025) where tennantite rather than tetrahedrite accompanies galena and minor chalcopyrite (Small, 1982). The silver content of the tetrahedrite and tennantite in these deposits is, like that of the galena in the Askrigg Block, characteristically low (Small, (1982). Dunham and Wilson (1985) regarded the silicification as an early feature. They also reported that formation temperatures for this quartz, obtained by Shepherd (1979), are below the minimum temperature of around 100°C for the fluorite zone and concluded that this mineralization represents a recrudescence of relatively low-temperature, low-grade copper mineralization in the outer zones of the orefield. They further discounted any suggestion that this mineralization represents the source area for the strong mineralization of the North Swaledale Mineral Belt. The role, if any, of the nearby Dent Fault in the origins of this mineralization has not yet been fully explored.

Conclusions

The Cumpston Hill North and South Veins are strong quartz veins which locally carry small concentrations of copper sulphides, mainly as tetrahedrite. They are typical of a minor suite of veins in the north-western part of the Askrigg Block, within the outer zone of the orefield and close to the Dent Fault. Fluid-inclusion evidence suggests that they are of low-temperature origin and may be part of a small episode of copper mineralization emplaced late in the mineralization of the Askrigg Block. The veins have considerable research potential, including investigations of the role of the nearby Dent Fault in their emplacement.

GREENHOW (DUCK STREET) QUARRY, NORTH YORKSHIRE (SE 112 639)

Introduction

Greenhow Quarry, sometimes known as 'Duck Street Quarry', is an old limestone quarry in the Dinantian Greenhow Limestone in the core of the Greenhow Anticline. Within the quarry are exposed three branches of Greenhow Rake, one of the major veins of the Greenhow area.

The Greenhow Hill mining area lies in the extreme southern part of the Northern Pennine Orefield, immediately north of the Craven Fault System, the structurally complex hinge zone which separates the Askrigg Block to the north from the Craven Basin to the south. This is a classic area of British geology and is the subject of an extensive literature, an excellent summary being provided by Dunham and Wilson (1985). The Greenhow Hill area essentially comprises an E–W-trending anticline composed of thick Dinantian limestones overlain unconformably by the Namurian Grassington Grit. There is thus clear evidence here of early Namurian folding and erosion. The entire Brigantian succession is missing and the Grassington Grit rests directly on Asbian limestones. Dunham and Wilson (1985) estimated that at least 137 m of limestones are cut out by this unconformity. The limestones of Greenhow Hill are cut by numerous mineral veins, from many of which lead ore and fluorspar have been recovered. In the Greenhow area this mineralization is confined to the limestones, except locally adjacent to the North Craven Fault where mineralization occurs in the Grassington Grit. Dunham and Wilson (1985) commented that the varied stratigraphy and structure of this area provide a more varied environment for introduced mineralization than elsewhere in the region.

The area's long history of mining is the subject of a substantial literature. Important contributions include, apart from those cited below, works by Dickinson (1964a,b, 1967, 1969, 1970), and Jennings (1967). Raistrick (1973) suggested the possibility of Iron-Age or even Bronze-Age workings, and the exploitation of some of the deposits by the Romans seems likely as Roman pigs of lead have been found locally (Dunham and Wilson, 1985). The first documentary records date from the 12th century

(Raistrick, 1927, 1973; Raistrick and Jennings, 1965), but the industry reached its peak here in the 18th and 19th centuries. Little mining has been undertaken here since the depression of the 1880s, although a small amount of fluorspar has since been raised from time to time from several sites including Greenhow Quarry. The most recent working for this mineral is believed to have taken place here in the 1960s. Despite the long abandonment of the Greenhow mines the area has remained of interest for mineral exploration, and investigations were carried out as recently as the 1970s (Wadge *et al.*, 1984).

Description

Greenhow Quarry exposes a section through the Greenhow Limestone (Asbian) in the core of the Greenhow Anticline. Greenhow Rake, one of the strongest and most important NW–SE-trending veins of the area, splits into three branches at Greenhow Quarry.

The largest of these branches, regarded by Dunham and Wilson (1985) as the central branch, today forms a prominent rib through the centre of the quarry (Figure 3.19). A level has been driven into the southern wall of this vein and numerous opencuts or old stopes may be seen within it. The vein is up to 5 m wide and is composed mainly of coarse-grained columnar, white to cream-coloured calcite, and white, or more rarely very pale-purple-tinted fluorite. A few scattered crystals of galena, locally coated with cerussite, occur within the fluorite. Small pockets of pale-brown 'dry bone' smithsonite occur in places. Calcite commonly forms bands adjacent to the vein walls with inner, central, lenses or bands of fluorite. Some fluorite lenses occur in contact with limestone wall-rock. Fluorite lenses are typically up to 0.5 m wide although an extensive stope up to about 1 m wide, apparently within a fluorite-rich band, has been excavated in the northern side of the vein. Within the walls of this excavation fluorite crystals greater than 5 cm across may be seen. Much of the fluorite here is white or colourless, although traces of very faint purple colouration may be seen locally. Some of the clear, colourless fluorite contains zones of minute sulphide inclusions. Ixer (1978a) reported the presence of pyrite and bravoite inclusions in fluorite from the Greenhow area, perhaps including Greenhow

Figure 3.19 Greenhow (Duck Street) Quarry. The central branch of Greenhow Rake here forms a prominent rib through the centre of the quarry. (Photo: B. Young.)

Quarry. Vugs lined with calcite and fluorite crystals are common within the vein. These are particularly conspicuous, although rather inaccessible, above the old mine entrance on the south side of the vein. Much of the limestone wall-rock exposed in the quarry shows little obvious evidence of alteration, although locally a prominent medium-brown colouration suggests dolomitization. Sub-horizontal, post-mineralization slickensides may be seen on the southern wall of the vein and locally within it.

Smaller branches of Greenhow Rake, exposed in the northern section of the quarry, appear to unite near the main quarry face. These branches carry very similar mineralization to that seen in the main branch, with, in places, a little barite. A small isolated knoll of limestone, about 25 m north of the main branch vein, contains a vein up to 1 m wide in which fluorite clearly occurs as a central filling in a vein of coarse-grained columnar calcite.

Interpretation

The sections of Greenhow Rake exposed in Greenhow Quarry are perhaps the finest permanently exposed sections through a vein of this kind in the southern part of the Askrigg Block. Fine sections of other veins are, from time to time, exposed in the nearby workings of Coldstones Quarry, although these are usually removed or obscured as quarrying proceeds.

In common with other veins in the area the constituent minerals in Greenhow Rake are characteristically coarse-grained. The vein shows clear evidence of having been filled with rhythmic repetitions of these minerals. Whereas the veins of the Askrigg Block exhibit local evidence of lateral zonation, this is nowhere as well defined as the zonation present within deposits in the Alston Block. Indeed, Dunham and Wilson (1985) remarked that so few veins in the Askrigg Block contain fluorite without barium minerals that a zone comparable to the fluorite zone of the Alston Block cannot be established. However, concentrations of deposits with fluorite are recognizable locally, and fluorite-bearing zones have been delineated in several parts of the Askrigg Block. Unlike the deposits of the fluorite zone of the Alston Block, those of the Askrigg Block almost everywhere carry barite, and locally witherite, interbanded or intergrown with fluorite. Dunham and Wilson (1985) grouped the deposits of Greenhow Hill, together with the neighbouring deposits at Skyreholme and Appletreewick, within one of these fluorite-rich zones. Studies of fluid inclusions in fluorite from dumps in the Greenhow area gave homogenization temperatures of between 110° and 160°C and salinities of between 15 and 25 equiv. wt% NaCl. These are consistent with values obtained elsewhere in the fluorite-rich zones of the Askrigg Block.

The main branch of the vein exposed in the quarry clearly demonstrates the important role that wall-rock lithology, in this case limestone, plays in determining vein width. The term 'bearing beds' was commonly applied to such favourable stratigraphical units by the former lead miners. Dunham and Wilson (1985) noted that ore-shoots at Greenhow Hill extend over a vertical range of at least 152 m, a substantially greater range than for most parts of the Askrigg Block. This may in part result from the stratigraphical and structural control exercised by the thick sequence of Dinantian limestones within the Greenhow Anticline. These authors also noted that only in the fluorite-rich zones of the Askrigg Block do orebodies extend over substantial vertical intervals. Dunham and Wilson (1985) canvassed the suggestion that an emanative centre of mineralization may have lain beneath the Greenhow area. The presence of well-developed mineralization below the deepest levels penetrated by the Greenhow mines was established during the final years of the 19th century in driving the Bradford Corporation aqueduct tunnel as part of the Scar House Reservoir scheme.

Whereas Dunham and Wilson (1985) and others generally regarded the deposits of the Greenhow area, like those of the remainder of the Askrigg Block, as being representative of the Mississippi Valley-type, the proximity of these deposits to the major hinge line of the Craven Fault System invites speculation on the role this structure may have played in mineralization. In recent years comparisons with base-metal deposits in central Ireland has focused attention on the possibility that syn-sedimentary mineralization may be present adjacent to similar basin-margin structures such as the Craven Fault (for example Wadge *et al.*, 1984). The possibility of a similar relationship of the barium-rich mineralization at sites such as Settlingstones and Fallowfield mines, to the Stublick Fault Zone on the southern margin of the Northumberland Trough has been mentioned in the **Settlingstones Mine** and **Fallowfield Mine** GCR site reports (this chapter).

Conclusions

Greenhow Quarry provides perhaps the finest sections available of a major vein within the southern part of the Askrigg Block. The width of the vein, and the known extension of this and other nearby veins in depth, can be related to the thick development here of Dinantian limestones and to the possible presence of an emanative centre of mineralization beneath the Greenhow area. The deposits of this area thus have considerable research potential.

PIKEDAW CALAMINE AND COPPER MINES, NORTH YORKSHIRE (SD 8757 6400)

Potential GCR site

Introduction

Copper and zinc ores were worked from a number of small mines on the moorland west of Pikedaw Hill. Although comparatively small, the deposits are of considerable interest and include the unique deposit of supergene smithsonite, known locally as 'calamine', worked at the Pikedaw Calamine Mine. Copper working here is known to date back to at least the 17th century (Raistrick, 1938a,b), but no plans of the workings are known. The amount of copper ore recovered is not known, although it is likely to have been small. The smithsonite deposit was discovered during copper mining in 1788 and was worked until 1830. Here, as elsewhere in the Northern Pennines, the term 'calamine' was generally applied to the mineral now known to be smithsonite. Dunham and Wilson (1985) estimated the total production of smithsonite as 5000 tons. Raistrick (1954, 1983) gave comprehensive accounts of the deposit and the mine, and Arthurton *et al.* (1988) provided additional details, based on more-recent exploration of the workings.

Description

The Gayle, Lower Hawse and Gordale limestones (Dinantian) in the area between Grizedales (SD 872 646) and Pikedaw Hill (SD 883 638) are cut by a number of small faults which are mineralized with abundant quartz and dolomite, although in many instances without obvious ore minerals. However, rich concentrations of copper ores are also prominent locally, notably in the group of workings collectively known as 'Pikedaw Mine' (centred around SD 876 639), approximately 800 m west of Pikedaw Hill. Here a cluster of small to moderate-sized spoil-heaps marks the sites of several shafts and associated dressing floors (Figure 3.20). The workings lie on the outcrop of the Lower Hawes Limestone, and, although the pattern of old shafts suggests the presence of several mineralized veins, their precise positions are unknown and are not indicated on the most recent published British Geological Survey 1:10 000-scale map (SD86SE). Malachite and azurite are abundant on all of the spoil heaps; the former occurs mainly as cellular crystalline masses up to 20 mm across, the latter commonly as isolated rounded crystalline aggregates of a similar size. Green *et al.* (2006) have described beaverite from these, and several nearby, spoil-heaps. Although Arthurton *et al.* (1988) referred to the working of chalcopyrite from these deposits, copper sulphides are not presently to be found. The identity of the primary copper sulphide mineral or minerals cannot therefore be identified. Very small amounts of galena, commonly partially altered to cerussite and anglesite, together with a few fragments of 'dry bone' smithsonite, are also present. A little white barite and colourless quartz are the only gangue minerals observed. These deposits are unusual in the Northern Pennines in being dominated by copper rather than lead or zinc minerals.

The 'calamine' (smithsonite) deposits, which were discovered during copper mining in 1788, consist of geopetal fillings of a cavern system in the Goredale Limestone. Contemporary descriptions of the mine record that the mineral occurred mostly as a powdery sediment filling the bottom of three interconnected E–W-aligned solution caverns, referred to by the miners as the '104-yard', '44-yard' and '84-yard' caverns, according to their length (Dunham and Wilson, 1985) (Figure 3.21). The deposit was up to 1.8 m thick in places and in the 84-yard Cavern was locally covered by a layer of stalagmitic calcite (Arthurton *et al.*, 1988). Dunham and Wilson (1985) suggested that a total of 5000 tons of smithsonite may have been extracted during the

Figure 3.20 Looking west across the site of Pikedaw Calamine and Copper Mines. Spreads of tailings from hand dressing of copper ores are conspicuous. The calamine shaft lies near the centre of the view in the middle distance. (Photo: BGS No. L2755, reproduced by permission of the British Geological Survey, © NERC. All rights reserved. IPR/105-15CX.)

mine's working life, and have proposed that the total tonnage of the mineral in the deposit may amount to 15 000 tons. Although originally extracted via the copper workings, a shaft, known as the 'New Shaft', was sunk in 1806 into the junction between the 104-yard and 44-yard caverns, in order to facilitate extraction. After being lost for over a century, the position of this shaft (SD 8757 6400), was re-discovered in 1944 (Gemmel and Myers, 1952).

No material remains on the surface today to indicate the nature or composition of the 'calamine' deposits. Underground access may be arranged via the 'New Shaft', which lies adjacent to the bridleway from Settle to Malham. Remnants of the deposit are still present between boulders on the floor of the caverns and as fillings to cavities adjacent to the main caverns. Samples of the mineral collected in 1979 varied in colour from creamy-white to pale-buff, and consisted of flakes and platelets ranging in size from 0.25 mm to 4 mm in diameter. X-ray diffraction analysis proved the mineral to be smithsonite (Dunham and Wilson, 1985; Arthurton *et al.*, 1988). Chemical analysis of one sample revealed 76.7% $ZnCO_3$, 19.6% FeO and 0.8% $CaCO_3.MgCO_3$ (Dunham and Wilson, 1985). Whereas smithsonite is locally a very common mineral in the supergene zone of many Northern Pennine zinc-rich orebodies, it is typically present as the crystalline cellular form known as 'dry bone', or locally as compact crystalline stalagmitic masses. The powdery form of the mineral found at Pikedaw, and its geological setting, appear to be unique to this locality.

Interpretation

The Pikedaw copper and 'calamine' deposits lie within Dinantian limestones in the ground beneath the Mid Craven and North Craven faults. These fractures are important components of the Craven Fault System which marks the southern margin of the Askrigg Block. This complex structural line acted as a major hinge line during Carboniferous times, separating the comparatively thin succession of the Askrigg Block from the much thicker, and deeper-water, succession of the Craven Basin. The widespread occurrence of significant, although generally uneconomic, mineralization in places along the

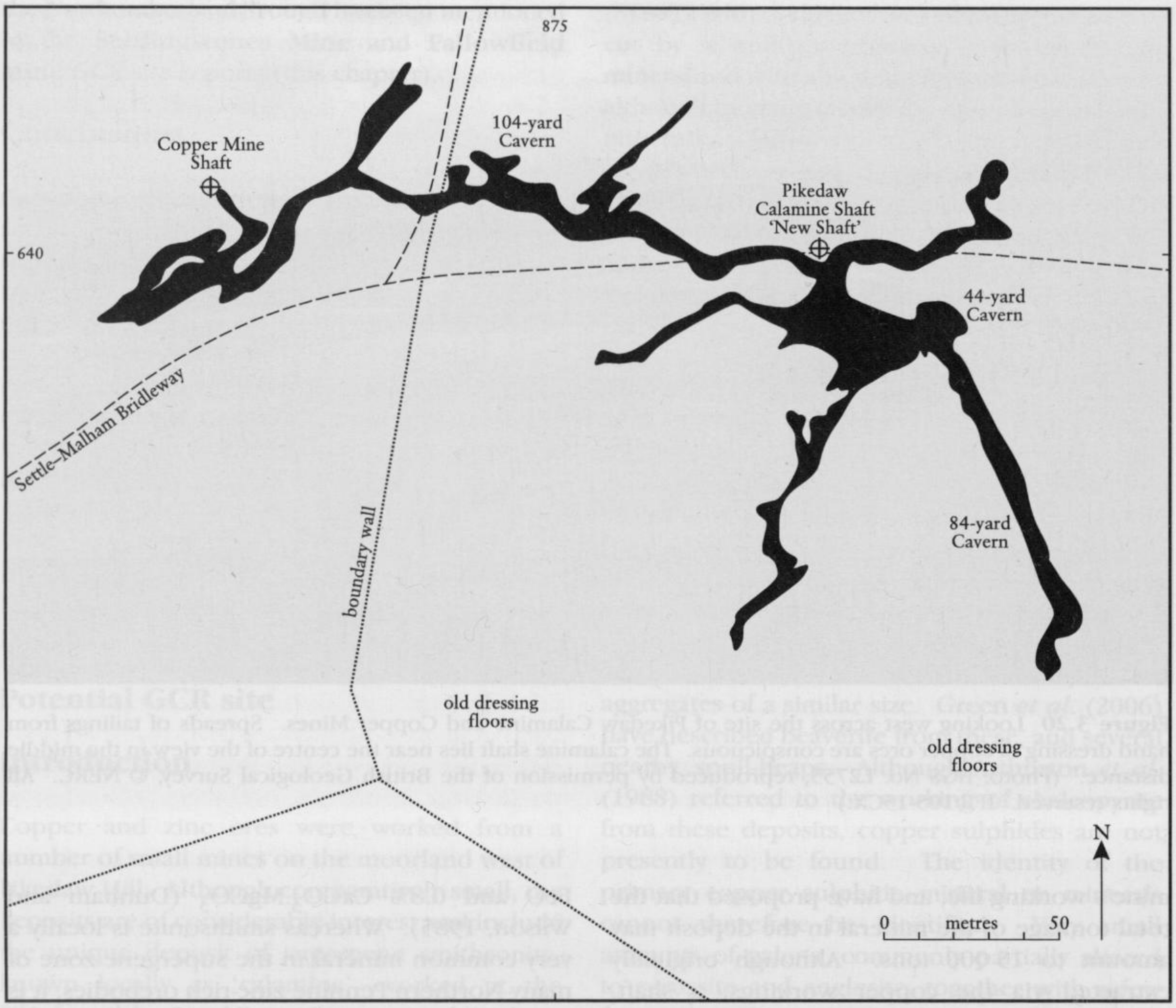

Figure 3.21 Sketch plan of Pikedaw Calamine and Copper Mines showing the extent of the calamine-bearing caverns. After Raistrick (1983).

Craven Fault System, including the copper and zinc mineralization at Pikedaw, has led to speculation, and some exploration interest, in the potential for so-called 'Irish Style' mineralization associated with the Mid Craven Fault (Dunham and Wilson, 1985; Arthurton *et al.*, 1988).

The origins, and possible significance, of the Pikedaw 'calamine' deposit is of particular interest. The occurrence of smithsonite as a powdery sediment within the filling of solution caverns is clear evidence of its supergene origin. It is well known that carbonate-rich phreatic waters are capable of transporting zinc in solution for considerable distances from a primary sphalerite source during oxidation (Loughlin, 1914). However, where deposition from such waters takes place in caverns or mine workings, it is normal for zinc to be deposited either as encrustations of 'dry bone' smithsonite or as hydrozincite. Dunham and Wilson (1985) suggested two possibilities to explain the formation of this extremely unusual form of smithsonite at Pikedaw. The first is that it results from deposition of smithsonite particles derived from erosion of a nearby, although unidentified, deposit of massive smithsonite. The second is that the mineral may be a direct chemical precipitate from carbonated water carrying zinc, perhaps as a result of a change in oxygen fugacity, although the authors admitted that it was difficult to explain why in such circumstances a solid crystalline deposit was not produced. Whatever process generated the deposit, it seems clear that a substantial body of sphalerite is, or was, present in the vicinity and was undergoing active oxidation, with export of the zinc and its subsequent deposition in solution caverns. Dunham and Wilson (1985) suggested that the smithsonite sediment is almost certainly of Quaternary age. In view of Raistrick's (1954) observation that parts of the smithsonite deposit were buried beneath a calcite stalagmite, Dunham and Wilson (1985) concluded that deposition of smithsonite was no longer active. The inferred presence of a substantial primary sphalerite orebody in the vicinity lends support to the hypothesis of hitherto unknown metalliferous mineralization, including possible 'Irish-Style' deposits in the neighbourhood.

Conclusions

Unlike most parts of the Northern Pennines, several deposits here are dominated by abundant copper minerals. Although supergene malachite and azurite are abundant, the nature of the primary sulphide assemblage cannot be established.

The area includes the remarkable smithsonite deposit of the Pikedaw Calamine Mine. Although the precise mode of origin of this deposit is unclear, the presence of abundant smithsonite as a sediment in solution caverns appears to be without parallel in Great Britain. The remnants of the deposit offer important opportunities for further research into supergene processes in metalliferous orebodies.

The mineralization at Pikedaw may hold important clues to the area's potential for 'Irish-Style' deposits of base-metals adjacent to, or within, the Craven Fault System.

GUNNERSIDE GILL, SWALEDALE, NORTH YORKSHIRE (NY 939 012)

Potential GCR site

Introduction

In the headwaters of Gunnerside Gill, a left bank tributary of the River Swale, uppermost Dinantian and Namurian limestones, sandstones, cherts and shales are cut by a closely spaced belt of mineralized faults which comprise part of the most intensely mineralized parts of the Askrigg Block of the Northern Pennines, collectively termed the 'North Swaledale Mineral Belt' by Dunham and Wilson (1985). The geology and the main mineralized veins are shown on Figure 3.22. The area has a very long history of lead mining, dating back to the 17th, and perhaps 16th, centuries, although the most extensive working was in the 19th century. Over this period very substantial tonnages of ore must have been raised, although no figures are recorded. In addition to lead ore, significant, although unrecorded, amounts of barite have been extracted from spoil heaps between the 1950s and 1980s. Dunham and Wilson (1985) gave detailed descriptions of the geology and mineralization, together with comments on the history of working. Crabtree and Foster (1963), and Raistrick (1975) have provided more details of mining history, including photographs of key features.

Description

The North Swaledale Mineral Belt of Dunham and Wilson (1985) comprises a linked system of mineralized faults which extends for at least 29 km from Great Sleddale at the head of Swaledale, to Feldom, near Richmond. It is the most highly mineralized zone within the Askrigg Block and has been exploited at numerous points. In Gunnerside Gill veins within this belt cut beds ranging from the shale above the Ten Fathom Grit (Namurian) down to the Five Yard Limestone (Dinantian). They have been extensively worked at the surface and underground on the west side of the valley at the Lownathwaite mines, and on the east side of the valley from a complex of workings which connected with and formed part of the Old Gang mines, the main access to which lay almost 3 km to the east, in Hard Level Gill. Detailed descriptions of the structural and stratigraphical relationships of the veins and their orebodies, including observations made underground, are given in Dunham and Wilson (1985). .

Although no good surface exposures of veins remain, and although none of the underground workings are today safely accessible, the area offers one of the finest opportunities to appreciate the extent and nature of mineralization typical of this part of the Pennines. Within both sides of Gunnerside Gill the courses of the major veins are clearly apparent in the spectacular opencasts excavated along them. Known locally as 'hushes', these vast gullies were in part created by a form of hydraulic mining, known as 'hushing', in which torrents of water were periodically released from specially

Figure 3.22 Map of the geology and mine workings in Gunnerside Gill. After Dunham and Wilson (1985).

constructed dams high on the hillsides. Although previously considered to be the main agent in creating these features, it is now realized that the scouring effects of water alone could not satisfactorily account for the great size of the excavations. It seems much more probable that water was periodically released to flush from the workings debris created by conventional excavation. Whatever their precise origins, these 'hushes' in Gunnerside Gill are amongst the finest in the Askrigg Block. Underground mining was via a number of adit-levels driven directly on the veins, or as cross-cuts through barren rock. The most notable of the latter was the Sir Francis Level (NY 9399 0001), driven beneath the Five Yard Limestone, and which gave access to veins on both sides of the valley. A sublevel beneath this adit worked ore-shoots in the Middle Limestone. Several veins were also worked from surface shafts sunk directly on their outcrops on the moorland, especially to the east of Gunnerside Gill (Figure 3.23).

Very large volumes of mineralized spoil within the hushes, on adit dumps, and adjacent to the numerous shafts, provide excellent opportunities to study the mineralogy characteristic of these deposits. Galena, the

Figure 3.23 View east along old workings on Old Rake. (Photo: B. Young.)

only ore mineral recovered from these workings, remains common in much of the spoil. Sphalerite is also present locally, although it was never worked. Most abundant of the gangue, or 'spar', minerals was barite, which comprises a major proportion of most of the spoil heaps. Much of the barite occurs as cellular, often rather coral-like, crystalline masses composed of small, sharply pointed crystals in which the dominant faces are (110) combined with (001). The mineral commonly forms comparatively fine-grained stalagmitic masses full of reticulated tubes. Limonite staining is common. This form is characteristic of barite formed by alteration of a primary barium carbonate mineral such as witherite or barytocalcite, and contrasts strikingly with the generally much more coarsely crystallized tabular form in which the dominant faces are (001) (102) and (102) (Dunham and Wilson, 1985; Dunham, 1990). Only very small amounts of barite showing the latter morphology are present here. Witherite is present locally, commonly forming the core to large blocks of cellular barite. Barytocalcite has been said to be present, particularly in parts of Old Rake and Friarfold Vein (Dunham and Wilson, 1985), although these authors were unable to confirm its presence by microscopical and X-ray diffraction examination of veinstone samples. They did, however, record a single specimen of the mineral from the spoil heaps of Sir Francis Level. Fluorite occurs locally in association with barite, particularly in spoil from workings on Old Rake. In common with much of the Askrigg Block, the fluorite is typically colourless or white and, where barium minerals are present, invariably pre-dates these minerals. Strontianite has been recorded from the Sir Francis Level dump (Young, 1987b). Supergene minerals include cerussite, 'limonite', rare traces of cinnabar accompanied by smithsonite, hemimorphite and aurichalcite (Young *et al.*, 1989), and, in places in spoil from workings on Old Rake, pyromorphite (Small, 1982).

Interpretation

The North Swaledale Mineral Belt is unique in the Northern Pennines for its structural relationships and continuity of mineralization. The proved vertical range of mineralization at Lownathwaite, of almost 230 m, is roughly twice that found elsewhere in the belt, and led Dunham (1952b) to speculate that Lownathwaite may lie above one of the foci from which mineralizing fluids were distributed. The possibility of further workable ore deposits beneath the area was tested by a single borehole drilled on the west side of Gunnerside Gill in 1968, although the results did not lead to further investigation (Dunham and Wilson, 1985).

Whereas a zonal distribution of fluorite and barium minerals is locally discernible in the Askrigg Block, this distinction is generally by no means as clear as in the Alston Pennines. Moreover, unlike the Alston Block, where fluorite and barium minerals generally exhibit a mutually exclusive relationship, in the Askrigg Block it is common to find fluorite and barium minerals in close juxtaposition in the same deposit; where this is so fluorite is invariably the earliest phase. Dunham and Wilson (1985) have demonstrated a concentration of fluorite mineralization within the North Swaledale Mineral Belt which embraces parts of the veins which crop out in and around Gunnerside Gill. Fluorite is present locally, notably in spoil from Old Rake, although the gangue assemblage throughout the deposits described here is dominated by barite, in places accompanied by a little witherite. As noted above, the bulk of the barite occurs in a form indicative of late-stage alteration of a barium carbonate mineral, leading Dunham and Wilson (1985) to suggest that prior to this alteration, witherite was very abundant, especially in veins such as Old Rake and Friarfold Vein. The date of this alteration is unclear. Although barite with this morphology can be found as an alteration of witherite related to present-day supergene activity, its great abundance here from workings which extended far beneath present zones of supergene influence suggests a much earlier widespread alteration of barium carbonate minerals. Young *et al*. (1989) suggested that the close association of cinnabar with supergene zinc minerals may indicate that a small amount of mercury may be present within primary sphalerite, although they were unable to cite any analyses of local sphalerite for mercury.

Conclusions

Gunnerside Gill provides one of the finest opportunities to study the mineralogy and geological setting of deposits characteristic of this part of the Askrigg Block of the Northern Pennines.