Mineralization of England and Wales

R.E. Bevins
Department of Geology, National Museum Wales, Cardiff

B. Young
Department of Earth Sciences, University of Durham
(formerly British Geological Survey)

J.S. Mason
Department of Geology, National Museum Wales, Cardiff

D.A.C. Manning
Institute for Research on Environment and Sustainability, Newcastle University

and

R.F. Symes
Geologist/Mineralogist, Sidmouth

with contributions from
R.A.D. Pattrick (University of Manchester)
A. Clark (Mineral Solutions Ltd)
A. Thurston (Mineral Solutions Ltd)
J. Vetterlein (Mineral Solutions Ltd)
J. Aumônier (The Mineral Industry Research Organisation (MIRO))
M.L. White (Mineral Solutions Ltd)
G. Warrington (formerly British Geological Survey)

Based in part on primary work by Dr L. Haynes

GCR Editors: L.P. Thomas and E.L. Durham

Chapter 2

The Lake District

B. Young

INTRODUCTION

The Lake District GCR Mineralogy Block is taken to include the mountainous fell country of the central Lake District, together with the adjoining iron orefield of west and south Cumbria.

This is an area of remarkably varied geology (Figure 2.1). The area has a long history of geological research with a very extensive literature. Excellent summaries of the essential features of the geology, with extensive references to earlier work, include those by Moseley (1978), and the British Geological Survey (1992). The following very brief summary, which draws on this extensive literature, provides a framework for the description of the mineralogical sites.

Within the central Lake District fells occurs a thick three-fold subdivision of Ordovician and Silurian sedimentary and volcanic rocks. The oldest of these, the Skiddaw Group, comprises a complex succession of more than 5 km of generally poorly fossiliferous marine turbiditic mudstones, siltstones and greywackes which range in age from Tremadoc to Llanvirn. The Skiddaw Group rocks occupy a wide outcrop across the north central Lake District, including Skiddaw itself, Blencathra and the Buttermere fells. Smaller outcrops of Skiddaw Group rocks occur in the south of the district, in the Black Combe area and in Furness. In the north of the Lake District the Skiddaw Group is overlain unconformably by the Eycott Volcanic Group, believed to be of Llandeilo to early Caradoc age. The succession comprises at least 3 km of tholeiitic volcanic rocks in which a variety of lavas and volcanic sediments occur. The Eycott Volcanic Group crops out on the Caldbeck Fells, on Eycott Hill and Binsey. In the central part of the Lake District, the Skiddaw Group is overlain unconformably by the Borrowdale Volcanic Group, also of possible Llandeilo to Caradoc age.

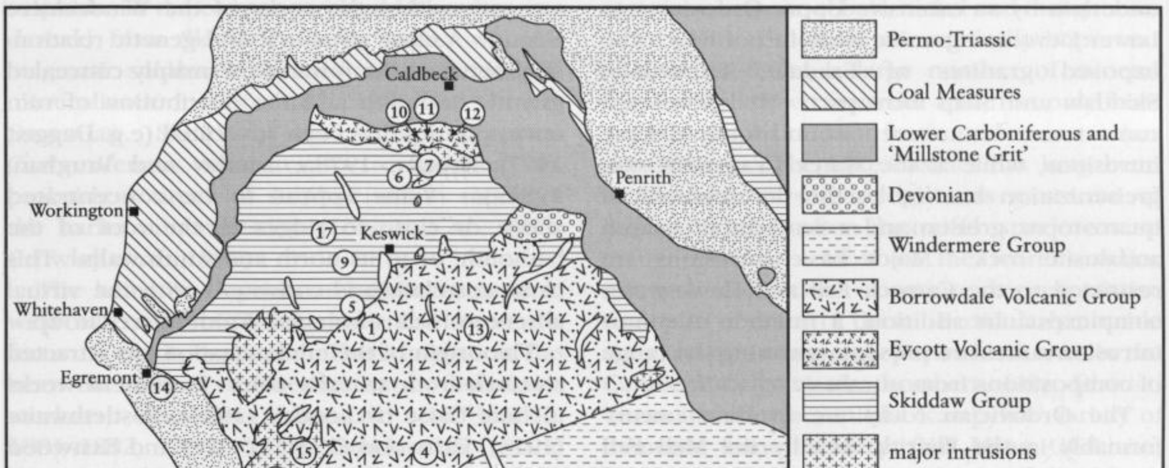

Figure 2.1 Geological sketch map showing locations of GCR sites. 1 – **Seathwaite Graphite Mine**; 2 – **Water Crag**; 3 – **Coniston Copper Mines**; 4 – **Birk Fell Hawse Mine**; 5 – **Dale Head North and South Veins**; 6 – **Wet Swine Gill**; 7 – **Carrock Mine–Brandy Gill**; 8 – **Buckbarrow Beck**; 9 – **Long Comb**; 10 – **Red Gill Mine**; 11 – **Roughtongill Mine**; 12 – **Dry Gill Mine**; 13 – **Eagle Crag**; 14 – **Florence Mine**; 15 – **Nab Gill Mine**; 16 – **Seathwaite Copper Mines**; 17 – **Force Crag Mine**.

The sequence is at least 6 km thick and comprises a complex succession of dominantly subaerial, calc-alkaline lavas and volcaniclastic rocks. It is divisible into a lower, pre-caldera sequence composed dominantly of basalt, andesite and dacite sheets, and an upper probably intra-caldera sequence of ignimbrites and volcaniclastic rocks including a thin unit of marine mudstone known as the 'Holehouse Gill Formation'. Rocks of the Borrowdale Volcanic Group give rise to the spectacular mountain country of the central Lake District including the Sca Fells, the Coniston Fells, the Langdale Pikes, Helvellyn and the High Street ranges. Overlying the Borrowdale Volcanic Group rocks unconformably in the southern Lake District is a thick succession of mudstones, siltstones and sandstones, collectively known as the 'Windermere Group'. This comprises a succession, more than 8 km thick, which records a resumption of marine sedimentation during late Ordovician and early Silurian times.

Much of the central part of the Lake District is underlain by an extensive Upper Ordovician to Lower Devonian granitic batholith of which the exposed granites of Eskdale, Ennerdale, Skiddaw and Shap form part. Well-developed contact aureoles are seen around some of these intrusions, while at the **Water Crag** GCR site, greisenization has led to the development of quartz-topaz greisen and a remarkable quartz-andalusite rock. Major basic intrusions are restricted to the Carrock Fell and Haweswater complexes. In addition, a number of minor intrusion suites are present, spanning the range of compositions from ultrabasic to acidic.

The Ordovician rocks are overlain unconformably in the Penrith area by the Mell Fell Conglomerate, of probable Devonian age. This is in turn unconformably overlain by conglomerates of the Carboniferous Basement Beds. A thick succession of Carboniferous rocks follows and forms an almost continuous outcrop surrounding the Ordovician and Silurian rocks of the central Lake District. Marine limestones, locally with some contemporaneous lavas, make up the greater part of the lower Carboniferous sequence. They are succeeded upwards by rocks exhibiting increasingly deltaic influences with a significant clastic component, culminating in the predominantly non-marine sediments of the Coal Measures of the Cumbrian Coalfield.

These Palaeozoic rocks are unconformably overlain by a thick succession of sedimentary rocks of Permo–Triassic age. In west and south Cumbria the lowest members of the succession are breccias, known locally as 'brockram'. Similar breccias are present in east Cumbria although in much of this area an aeolian sandstone, the Penrith Sandstone, directly overlies the sub-Permo–Triassic surface. These deposits are overlain by mudstones and siltstones, locally with formerly economically important beds of anhydrite and gypsum, and these are in turn followed by the thick red sandstones and mudstones of the Sherwood Sandstone and Mercia Mudstone groups, known locally as the 'St Bees Sandstone Formation' and the 'Stanwix Shales Formation' respectively.

Within this broad geological framework there occurs a great diversity of rock types, some of which host a variety of mineral deposits, prominent amongst which are the metalliferous vein deposits of the central Lake District. Mineralized veins are numerous within the Skiddaw, Eycott Volcanic and Borrowdale Volcanic groups and the major intrusions, but are rare within the rocks of the Windermere Group. A close structural and genetic relationship between the form of the mainly concealed granitic batholith and the distribution of vein mineralization has been advocated (e.g. Dagger, 1977; Firman, 1978a; Stanley and Vaughan, 1982a). Veins appear to be concentrated above or close to ridges in the roof of the batholith, or to its north and south walls. This close correlation is consistent with the virtual absence of veins from the Windermere Group.

The origin of the mineralization has attracted research from an early date. Prominent works include those by Kendall (1884), Postlethwaite (1913), Eastwood (1921), Dewey and Eastwood (1925), Rastall (1942), Dunham (1952a), Ineson and Mitchell (1974), Shepherd *et al.* (1976), Firman (1978a), Stanley (1979), Stanley and Vaughan (1980, 1982a), Lowry *et al.* (1991), and Millward *et al.* (1999). The geochemical atlas for the area (British Geological Survey, 1992) provides a useful descriptive and genetic summary of the main types of mineralization.

In the most widely accepted classification of Lake District mineralization, Stanley and Vaughan (1982a) recognized several mineralizing episodes. These range in age from early Devonian copper- and tungsten-bearing veins, through early Carboniferous lead-zinc mineralization, some barite emplacement in the late Carboniferous and the later formation of supergene assemblages, perhaps in part as early as the

Jurassic. Millward *et al.* (1999) have presented evidence for the emplacement of at least some of the copper mineralization pre-dating the early Devonian regional cleavage-forming event, as for example at the **Coniston Copper Mines**, the **Dale Head North and South Veins** and the **Seathwaite Copper Mines** GCR sites, whilst the **Birk Fell Hawse Mine** GCR site exposes copper mineralization dominated by bornite of probable supergene origin. The major phases of mineralization are probably related to episodes of hydrothermal activity within the batholith. Studies of each of the major suites of mineralization have revealed evidence of different temperatures and fluid compositions for each episode. D.C. Cooper *et al.* (1988) have demonstrated that Skiddaw Group sedimentary rocks within the Crummock Water thermal aureole may have provided a source of ore metals in at least part of the area, as seen at the **Long Comb** GCR site. Isotopic studies by Lowry *et al.* (1991) have shown that sulphur in sulphides in the copper and lead-zinc suites was derived from Skiddaw Group rocks, whereas magmatic sulphur is a major component of the mineralization associated with the Lower Devonian Skiddaw and Shap granites. Carboniferous seawater or evaporites are probable sources of sulphur within much of the barite mineralization (Lowry *et al.*, 1991; Crowley *et al.*, 1997).

The hematite deposits of adjoining parts of west and south Cumbria have also been the focus of much research. Their formation has been the subject of investigation by numerous workers, including Kendall (1873–1875, 1881–1882, 1893, 1921), Smith (1924), and Trotter (1945). More recently Shepherd (1973), Rose and Dunham (1977), Evans and El-Nikhely (1982), Dunham (1984), Shepherd and Goldring (1993), and Rowe *et al.* (1998) have offered models for their genesis based in part upon geochemical, fluid-inclusion and palaeomagnetic studies. This mineralization is seen best at the **Florence Mine** and **Nab Gill Mine** GCR sites.

The area has had a long history as a producer of mineral products. The celebrated graphite deposit at the **Seathwaite Graphite Mine** GCR site, in Borrowdale, was worked by the Elizabethans and was productive for many years in the 18th and 19th centuries. The central Lake District was a major source of copper in Elizabethan times and again in the latter half of the 19th century. Lead and zinc were mined well into the 20th century, seen for example at the **Eagle Crag** and **Force Crag Mine** GCR sites. The northern Lake District includes Britain's only worked tungsten deposit outside of the South-west England province, at the **Carrock Mine–Brandy Gill** GCR site, where the mineralization is related to the intrusion of the Skiddaw Granite, and is probably related also to minor antimony mineralization at the **Wet Swine Gill** GCR site. Although never exploited commercially, further tungsten mineralization is present in the extreme west of the area, at the **Buckbarrow Beck** GCR site, associated with the Eskdale Granodiorite.

The area has also yielded a large tonnage of barite. The huge hematite deposits of west and south Cumbria provided many millions of tons of high-grade iron ore and formed the basis of the formerly important Cumbrian iron and steel industry. Small-scale extraction of hematite continued until 2007 at **Florence Mine**, near Egremont. Other mineral products, formerly worked on a small scale include ores of antimony, arsenic, cobalt, nickel and manganese.

In addition to these economically important mineral products, a large number of mineral species are known from the area, not only from worked deposits but from numerous other occurrences. The Lake District has long been well-known to mineralogists as a source of important and often beautiful specimens of many minerals. Most of the world's major mineral collections contain representative examples of many of these. Particularly notable are examples of several species from sites in the Caldbeck Fells in the northern Lake District. These include the unique 'campylite' variety of mimetite from the **Dry Gill Mine** GCR site, fine examples of linarite and leadhillite from the **Red Gill Mine** GCR site, pyromorphite, plumbogummite, hemimorphite and brochantite from the **Roughtongill Mine** GCR site, and scheelite and other minerals from the **Carrock Mine–Brandy Gill** GCR site. The hematite mines of west and south Cumbria are world-renowned for spectacular examples of 'kidney ore' and 'specular' hematite as well as superb specimens of associated gangue minerals including calcite, barite, fluorite and quartz, especially from the **Florence Mine** GCR site.

In a comprehensive review of the area's minerals and their distribution, Young (1987a) noted that approximately half of the mineral species then known to be present within Great Britain are to be found within the Lake District.

Cooper and Stanley (1990) have produced a detailed description of the minerals of the Calbeck Fells mines and illustrate striking examples of many of them.

Ryback *et al.* (2001) have shown that the late A.W.G. Kingsbury falsified the localities of numerous rare mineral species. It seems that from about 1951 he began to pass off classic foreign material from old collections as having been found by him at British localities, including many in the Lake District. Discredited reports of several species from Carrock Mine are discussed below. In addition to these, in their detailed investigation of parts of the Kingsbury collection, held at the Natural History Museum, London, Ryback *et al.* (2001) have demonstrated undoubted false claims of adamite from the Sandbed, Netherow Brow, Potts Gill and Wanthwaite mines; and plancheite from Driggith Mine. Although not yet investigated in detail, it seems likely that many other falsely labelled specimens await discovery in this collection. This is almost certainly so in the case of many, if not all, of Kingsbury's specimens of gold said to have been obtained from numerous Lake District locations. Serious doubt must therefore be attached to many of Kingsbury's claims, especially where these have not been duplicated or substantiated by more-recent collectors.

SEATHWAITE GRAPHITE MINE, CUMBRIA (NY 234 127)

Introduction

The long-abandoned mine at the Seathwaite Graphite Mine GCR site at the head of Borrowdale is perhaps one of Britain's most famous old mines. This deposit of remarkably pure graphite, which is associated with a dolerite intruded into the Borrowdale Volcanic Group, appears to lack any counterpart in Britain or elsewhere.

Mining for graphite at Seathwaite can be traced back several centuries and it is likely that Seathwaite was the world's first commercial producer of graphite. Over this period the mineral has been known by a variety of names including 'black cawke', 'wad', 'black lead' and 'plumbago'. It has found a variety of uses, ranging from the marking of sheep, as a rust-proof coating of metal, and even as a medicine. It was principally employed, however, in the making of crucibles and moulds for metal casting and in pencil making, although this latter use appears to have come comparatively late in the mine's working life. It was the availability of Borrowdale graphite which gave rise to the important pencil-making industry at Keswick. The date of the discovery of the deposit is not known, although the first documentary evidence of graphite working here dates from 1540 (Tyler, 1995). The mine was worked vigorously by the Elizabethans, and working continued, although with some short periods of inactivity, until 1891 when the workings were finally abandoned. The history of graphite mining at Seathwaite has been outlined by Postlethwaite (1913), and more recently by Adams (1988), Bridge (1992), and Tyler (1995).

The uniqueness of the deposit has attracted geological and mineralogical attention from an early date. Some of the earliest geological references to this occurrence are those of Woodward (1729), and Phillips (1819, 1844). Other important descriptions include those of Ward (1876b), Goodchild (1882), Postlethwaite (1913), and Strahan *et al.* (1917). In addition to giving descriptions of the deposit Strens (1962, 1965), Weis *et al.* (1981), and Parnell (1981) have all offered explanations of its origin.

Description

Ward (1876b) referred to the occurrence of graphite within eight 'veins' and inclined 'pipes' up to 1–3 m in cross-section and from 2 m to over 100 m deep. These are shown on the mine plan and sections (Figure 2.2). They occur as part of a complex fracture-system in a doleritic intrusion within the tuffs and andesites of the Whorneyside Formation of the Ordovician Borrowdale Volcanic Group. Strens (1965) recorded that graphite mineralization is confined to a 400 m length of the vein system within the intrusion, and commented that the mine plans suggest that the richest concentrations occurred at the junction with the volcanic rocks.

Strens (1965) noted considerable alteration of the dolerite which hosts the graphite mineralization. He recognized a zone of relatively high-temperature alteration distinguished by a biotite-chlorite-quartz-albite-magnetite assemblage within, and extending for some distance beyond, the 'zone' of graphite mineralization. Low-temperature alteration, with the develop-

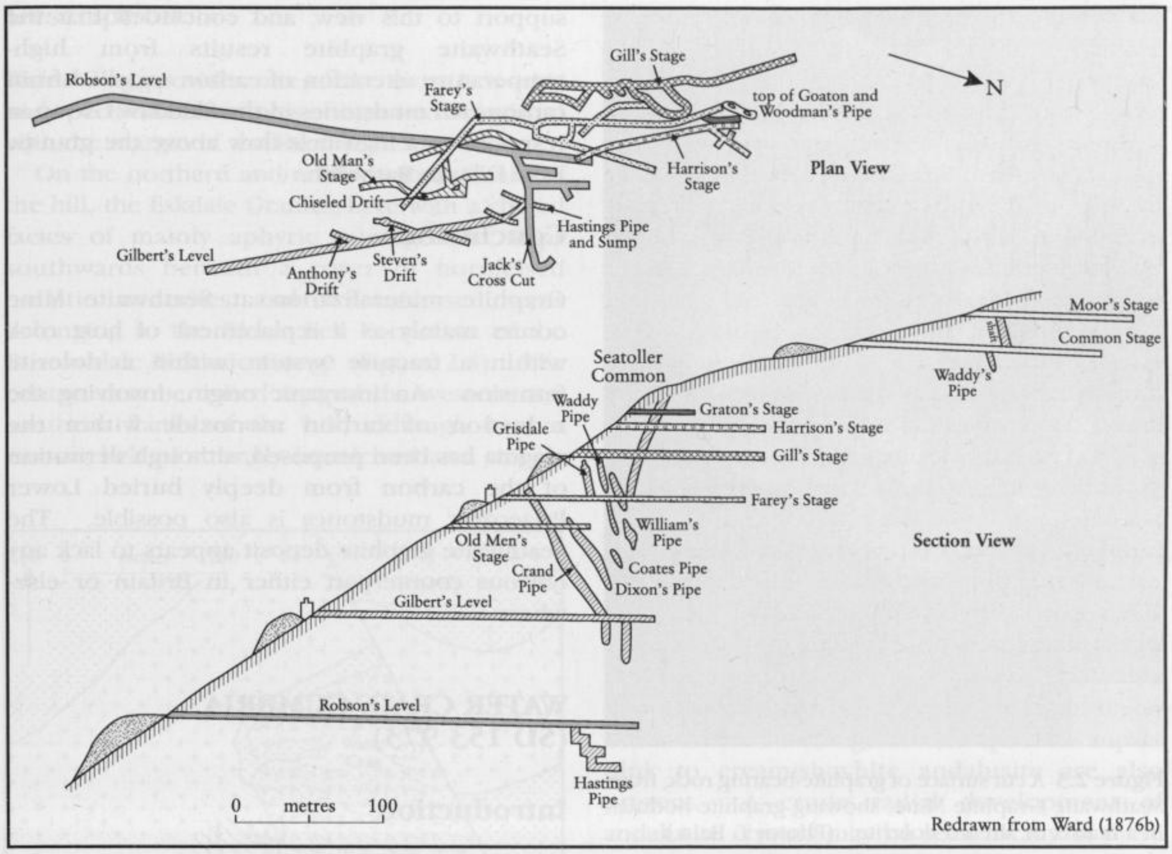

Figure 2.2 Plan and section of the workings at Seathwaite Graphite Mine. After Ward (1876b).

ment of hematite-chlorite-quartz-calcite-mica-orthoclase rock, extends for up to 2 km beyond the belt of high-temperature alteration. Strens (1965) also drew attention to the presence of an extensive fault system parallel with the graphite vein system and carrying galena, chalcopyrite, sphalerite, quartz and hematite veins.

According to Strens (1965) the altered dolerite, or 'veinstone', consists of numerous graphite nodules, mainly from 1 mm to 5 cm in diameter, embedded in a buff-coloured matrix of mica, chlorite and quartz (Figure 2.3). Most of the graphite nodules exhibit rims of brown chlorite up to 0.5 mm across and contain numerous inclusions of dark-brown chlorite and mica. The presence of chlorite and mica inclusions in these nodules, the occurrence of graphitized dolerite, especially in parts of the upper workings, and the appearance of the rock in hand specimen, all indicate that the graphite has replaced the rock, and was not deposited as a fissure-filling. Some inclusion-free graphite nodules were interpreted by Strens (1965) as filling hollows formed by dissolution of the dolerite during the alteration process. Firman (1978a) noted graphite nodules up to 1 m in diameter. Representative specimens of Seathwaite graphite are present in many mineralogical collections. A fine set of samples, together with examples of its use in pencil making, can be seen in Keswick Museum.

Parts of the underground workings remain accessible and are commonly visited by mine explorers, although there are understood to be few good exposures of graphite mineralization. Good specimens of graphite-rich rock, including comparatively pure nodules, are abundant on many of the spoil heaps.

Interpretation

The Seathwaite graphite deposit is almost certainly unique amongst such deposits in that it is clearly not associated with either regional or thermal metamorphism of carbonaceous material. Graphite mineralization here is intimately

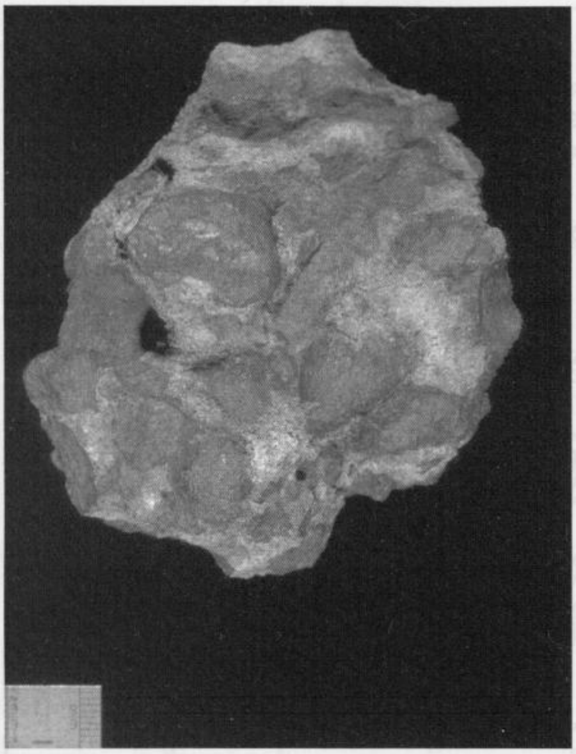

Figure 2.3 A cut surface of graphite-bearing rock, from Seathwaite Graphite Mine, showing graphite nodules in a matrix of altered dolerite. (Photo: T. Bain.)

associated with a doleritic intrusion. A genetic association is suggested by K-Ar dating of the intrusion and vein alteration at 382 Ma and 376 Ma respectively, by Mitchell and Ineson (1975), and by the absence of graphite in veins remote from the intrusion.

Early hypotheses on the origin of the graphite (e.g. Marr, 1916) suggested that mudstones of the Skiddaw Group, which underlie the Borrowdale Volcanic Group, could have been the source of the necessary carbon. This view was discounted by Strens (1965), who advocated the reduction to elemental carbon of large volumes of carbon monoxide catalysed by pyrite, iron oxides, iron silicates and quartz at pressures of up to about 1000 bar and temperatures of between 400°C and 600°C. The common occurrence of pyrite or hematite replacing pyrite, and more rarely of cores of quartz, chlorite and mica, as cores to many of the graphite nodules was cited by Strens (1965) in support of this theory.

Weis *et al*. (1981) presented isotopic evidence for the organic origin of the carbon within the Seathwaite deposit. Parnell (1981) provided support to this view, and concluded that the Seathwaite graphite results from high-temperature alteration of carbon expelled from carbon-rich mudstones in the Skiddaw Group in response to a high heat-flow above the granitic Lake District Batholith.

Conclusions

Graphite mineralization at Seathwaite Mine occurs mainly as a replacement of host rock within a fracture system within a dolerite intrusion. An inorganic origin, involving the reduction of carbon monoxide within the magma has been proposed, although derivation of the carbon from deeply buried Lower Palaeozoic mudstones is also possible. The Seathwaite graphite deposit appears to lack any obvious counterpart either in Britain or elsewhere.

WATER CRAG, CUMBRIA (SD 153 973)

Introduction

At Water Crag, west of Devoke Water, the Eskdale Granite, the largest exposed portion of the granitic Lake District Batholith, is in contact with rocks of the Ordovician Skiddaw Group and Borrowdale Volcanic Group. Adjacent to the contact the granite has been altered to a quartz-topaz greisen, and locally a remarkable quartz-andalusite rock is present adjacent to mudstones of the Skiddaw Group. Local concentrations of disseminated arsenic, bismuth and molybdenum minerals occur within the greisen.

The Eskdale Granite has been the subject of studies by Dwerryhouse (1909), Simpson (1934), Trotter *et al.* (1937), Firman (1978b), Rundle (1979, 1981), Ansari (1983), O'Brien *et al.* (1985), Firman and Lee (1986), and Young *et al.* (1988). Although the occurrence of greisens was noted by Dwerryhouse (1909), Simpson (1934), and Ansari (1983), their widespread occurrence was first described by Young (1985a). The unusual quartz-andalusite rock was first noted by Ansari (1983) and was described in greater detail by Young *et al*. (1988). The presence of metalliferous mineralization within the greisen was reported by Young (1985b).

Description

Water Crag provides one of the most extensive and spectacular examples of a greisen associated with the margin of the Eskdale Granite.

On the northern and north-western flanks of the hill, the Eskdale Granite, here with a chilled facies of mainly aphyric microgranite, dips southwards beneath a cover of hornfelsed basaltic andesites and volcanic sediments belonging to the Birker Fell Formation of the Borrowdale Volcanic Group (Figure 2.4). The contact may be traced around the western and southern flanks of the hill, although here a narrow belt of strongly hornfelsed and steeply

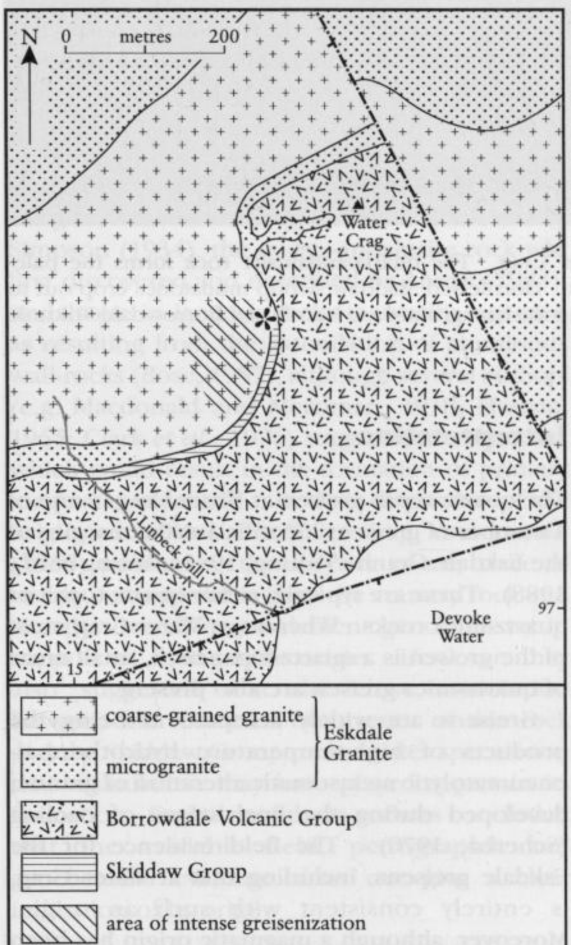

Figure 2.4 Geological sketch map of Water Crag.

inclined and cleaved slates, referred by Trotter *et al.* (1937) to the Skiddaw Group, intervenes between the granite and volcanic rocks. The slates are well exposed at several places on the hill, although their junction with the volcanic rocks is nowhere exposed, and their relationship with these rocks is unclear.

Near the summit of the hill a remarkable quartz-andalusite rock forms a prominent rib up to 1 m wide and 4 m long which separates coarse-grained granite and its greisenized equivalent from the hornfelsed slates (Figure 2.5). The junction of this andalusite-quartz rock with the adjacent rocks is not exposed. This rock was first recognized by Ansari (1983), although the presence of andalusite within the nearby greisen was first noted by Simpson (1934). Young (1985a), and Young *et al.* (1988) provided detailed descriptions of this rock. In hand specimen it is seen to comprise coarse-grained colourless quartz in which occur numerous patches, up to 8 mm across, of rose-pink andalusite. Lenticular pockets, up to 0.2 m across and 0.5 m long, of much purer compact pink to creamish-white andalusite are also present. A crude radial development of andalusite crystals may be seen locally in these lenses. A little white mica occurs along minor shears. Thin-sections of this rock reveal that much of the andalusite is fresh and unaltered, although locally some alteration to fine-grained sericite may be seen. Young *et al* (1988) figured thin-sections of this andalusite-quartz rock.

On the southern slopes of Water Crag large ice-smoothed surfaces of the granite exhibit patchy alteration to a coarse-grained greisen in roughly vertical ribs up to 2 m wide. Young (1985a) and Young *et al.* (1988) have given detailed descriptions of this rock. These ribs tend to parallel the granite contact, although several ribs up to 1 m wide run almost at right-angles to it. The greisen appears to have developed adjacent to, and in association with, a major set of joints. Greisenization may be seen up to 30 m from the granite contact. Much of the greisen at Water Crag consists of a coarse-grained quartz-topaz rock, mainly of a grain-size comparable with the parent granite. In hand specimen the quartz varies from colourless to smoky grey. Topaz is conspicuous as white or pale-cream rather saccharoidal patches and isolated anhedral crystals up to 8 mm across which commonly display a characteristic basal

Figure 2.5 Outcrop of quartz-andalusite rock at Water Crag. The quartz-andalusite rock forms the pale-coloured outcrop immediately to the left of the map case. Hornfelsed Skiddaw Group mudstones crop out to the right of the map case. The rather rounded outcrops in the background are hornfelsed Borrowdale Volcanic Group rocks. (Photo: B. Young.)

cleavage. A few scattered grains of pink andalusite occur locally and these appear to become more numerous as the contact with the hornfelsed slate is approached. Rarely, a little deep-purple fluorite is seen coating joint-surfaces. The junction with the unaltered granite is transitional over a few centimetres. In places, quartz-mica greisen is present in this transition zone. Young *et al.* (1988) figured a thin-section of the quartz-topaz greisen.

Locally a few streaks and pockets, up to 1 cm across, within the quartz-topaz greisen contain a fine-grained mixture of metallic minerals including arsenopyrite, bismuthinite, native bismuth and molybdenite. The latter mineral occurs as rare isolated flakes up to 0.5 mm across, scattered through the quartz-topaz greisen. Traces of the supergene minerals scorodite and ferrimolybdite have been identified and very small specimens have been obtained which show affinities with the rare bismuth supergene minerals zavaritskite (BiOF) and rooseveltite ($BiAsO_4$) (Young, 1985a,b).

Interpretation

The quartz-topaz greisen at Water Crag is one of a number of greisens identified at the margins of the Eskdale Granite (Young, 1985a; Young *et al.*, 1988). These are typically either quartz-topaz or quartz-mica rocks. Whereas at Water Crag most of the greisen is a quartz-topaz rock, small areas of quartz-mica greisen are also present.

Greisens are widely accepted as being the products of high-temperature hydrothermal-pneumatolytic metasomatic alteration of granite, developed during the final stages of cooling (Scherba, 1970). The field evidence for the Eskdale greisens, including that at Water Crag, is entirely consistent with such an origin. Moreover, although a magmatic origin has been proposed for certain quartz-topaz rocks found in association with granites (e.g. Collins and Coon, 1914; Scrivenor, 1914; Eadington and Nashar, 1978), the evidence at Water Crag and elsewhere in Eskdale points to a hydrothermal/metasomatic origin for the quartz-topaz rocks. Young *et al.* (1988) suggested that the widespread occurrence of greisens at the margins of the Eskdale Granite results from a concentration of volatile components ponded back by the relatively impervious hornfelsed country rocks near the roof of the intrusion. Ansari (1983) noted that compared to the parent granite, the greisens typically are enriched in SiO_2 and depleted in Al_2O_3, total iron, CaO, Na_2O and K_2O. There is evidence for local enrichment in Sn (Ansari, 1983), W and B (O'Brien *et al*., 1985). Young *et al*. (1988) commented that the depletion in Li noted locally by O'Brien *et al*. (1985) is unusual, as in the greisens of South-west England and many other parts of the world enrichment in Li is more usual.

Young (1985a,b) proposed that the small amount of metalliferous mineralization within the greisen at Water Crag developed during the final consolidation of the granite, and commented on a possible genetic link with the copper and tungsten mineralization at **Buckbarrow Beck** (see GCR site report, this chapter).

Although the presence of andalusite within the greisen at Water Crag was first mentioned by Simpson (1934), the quartz-andalusite rock was first discovered and described by Ansari (1983). Andalusite in igneous rocks is usually regarded as resulting from the assimilation of aluminous wall-rocks (Rose, 1957), although several authors (e.g. Macdonald and Merriman, 1938; Haslam, 1965; Clark *et al*., 1976) suggested mechanisms which could result in the formation of primary magmatic andalusite. In their discussion of the origins of andalusite at Water Crag, Young *et al*. (1988) pointed to the absence of any trace of visible contamination from the country rock and cite the overall major-element geochemistry in support of a magmatic origin. However, they also suggested that the close association between the restricted occurrence of this rock and the Skiddaw Group rocks invites speculation that assimilation may have played a part in its formation. On balance these authors concluded that the available field, petrographic and geochemical evidence does not give a clear indication of its origin.

Conclusions

Water Crag provides clear exposures of quartz-topaz greisen and quartz-andalusite rock, both at the margins of the Eskdale Granite. The greisen is interpreted as the product of high-temperature metasomatism of the granite during its final stages of cooling. Associated minor metalliferous mineralization may also be a product of this process. The unique quartz-andalusite rock may be a highly unusual modification of the granite, although whether the andalusite is the result of assimilation of adjacent slate or a primary magmatic product remains unclear.

CONISTON COPPER MINES, CUMBRIA (SD 281 991–SD 290 985)

Introduction

Coniston Copper Mines comprise an extensive group of workings in and around the Copper Mines Valley at the head of Church Beck, south-east of Levers Water. Large tonnages of copper ores, together with smaller amounts of lead, zinc, nickel and cobalt ores, have been mined over a long period from two principal veins and a number of minor veins.

Coniston was one of the major centres of copper production within the Lake District. Copper mining here may be traced back over many centuries. It has been suggested that the earliest workings may be Roman or even earlier. It is known that some of the workings were already abandoned when the major revival of metal mining in the Lake District took place in Elizabethan times. Since then the mines were worked intermittently until the 19th century when they were developed on a large scale. A rapid decline in production from about 1874 culminated in the closure of the mines in 1889. Attempts to revive mining in the early years of the 20th century failed and the mines were abandoned in 1908. An unsuccessful attempt was made between 1912 and 1914 to recover copper from the dumps. Underground exploration and rehabilitation of some of the workings in 1954 did not lead to a resumption of mining. Important histories of mining at Coniston include those by Dewey and Eastwood (1925), Shaw (1970), Holland (1986), Flemming (1992), and Donald (1994).

The Coniston deposits occur as veins within rocks of the Ordovician Borrowdale Volcanic Group. There are two principal veins, although a number of associated veins have also been worked. Copper ore was the main product. The main ore mineral was chalcopyrite, although minor amounts of tennantite and bornite are locally present. Much smaller amounts of lead, zinc, nickel and cobalt ores were also raised. In addition to these, the veins contain a great variety of other minerals including arsenopyrite, pyrite, pyrrhotite and traces of rare bismuth-, tellurium- and selenium-bearing minerals. Substantial quantities of magnetite occur locally. The geology of the Coniston deposits has been described by Postlethwaite (1913), Dewey and Eastwood (1925), Wheatley (1971a), Dagger (1977), and Millward *et al.* (1999, 2000). The mineralogy has been the subject of work by Russell (1925), Stanley and Vaughan (1982a,b), Young and Johnson (1985), and Young (1987a).

Parts of the underground workings are accessible and are regularly visited by mine explorers. Important exposures of mineralization are available in parts of these workings. Holland (1981) provided a detailed guide to some of these. There are limited surface exposures of mineralization *in situ*, although huge quantities of veinstone on the extensive spoil-heaps provide abundant material for study.

Description

The geology and principal veins of the Coniston area are shown in Figure 2.6. The roughly NW–SE-trending Bonser Vein is one of the area's

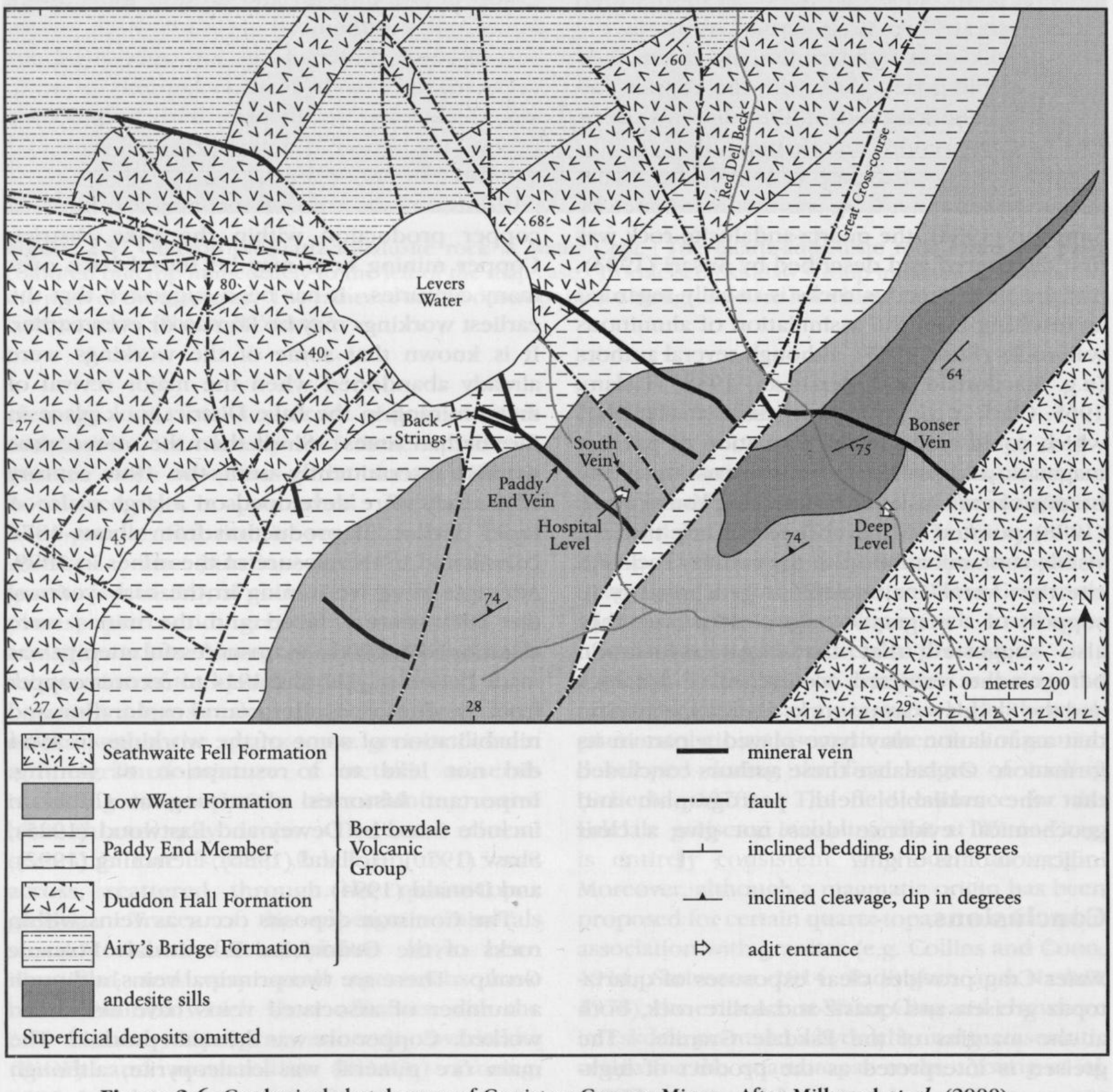

Figure 2.6 Geological sketch map of Coniston Copper Mines. After Millward *et al.* (2000).

two main veins. Over the western part of its course, from Levers Water to Kernal Crag, it is referred to on contemporary plans and reports by its alternative name of 'Thriddle (or Triddle) Vein'. East of Kernal Crag the vein is displaced about 80 m sinistrally by a NNE–SSW-trending fault belt, here in the form of a narrow horst, known as the 'Great Cross-course'. Over much of its course between Levers Water and Kernal Crag, and within the Great Cross-course horst, the vein at outcrop cuts ignimbrites of the Paddy End Member. In most surface outcrops the vein consists of up to 1.5 m of quartz-veined brecciated wall-rock. However, in a large cave-like excavation, known as the 'Glory Hole' (SD 2840 9917), the vein is up to 2.7 m wide and consists of quartz, chlorite, pyrite and chalcopyrite in crude bands parallel to the vein walls. Abundant dark-brown 'gossany' iron oxides encrust much of the outcrop. East of the Great Cross-course the vein passes into volcaniclastic sandstones of the Low Water Formation and immediately narrows to a belt of hematite-stained fractures with very little mineralization. Little information is available on the wall-rocks in the underground workings, although it seems likely that ignimbrites formed the walls in the most productive sections.

Bonser Vein, or a parallel branch from it, was tried beneath Levers Water in a branch from Hospital Level. Millward *et al.* (1999) described a section of the vein in the forehead of these workings which is here within andesitic tuffs of the Duddon Hall Formation of the Borrowdale Volcanic Group. Well-developed cleavage within the tuff wall-rocks is refracted through the vein. A similarly strong wall-rock cleavage fabric passes through the South Vein exposed in Courtney's Cross-cut, near the entrance to Hospital Level.

Bonser Vein has been worked from outcrop down to at least 457 m below the surface over a strike length of about 0.5 km. When followed downwards the hade of the vein changed from southwards at the surface to a northerly hade in the lowermost workings. Throughout the underground workings vein widths varied from 0.3 m up to several metres. Dewey and Eastwood (1925) recorded that in the lower levels the vein was about 1.0 m wide with nearly half of the filling being copper ore.

Chalcopyrite is the main copper ore mineral in the Bonser Vein. It is accompanied by abundant arsenopyrite, some pyrite and marcasite and a little pyrrhotite, galena and sphalerite. Magnetite, at least some of which appears to replace earlier hematite, is an important constituent of the vein, especially in the deeper levels where it became progressively more abundant, apparently at the expense of chalcopyrite (Shaw, 1970) (Figure 2.7). Other metallic minerals, commonly associated with the magnetite, are native bismuth, bismuthinite, josëite, cosalite and laitakarite. The nickel and cobalt minerals niccolite, nickel skutterudite, rammelsbergite and safflorite were found locally in the Bonser Vein or in a branch of it (Russell, 1925; Stanley, 1979; Young, 1987a). Non-metalliferous gangue minerals include quartz, chlorite, stilpnomelane, calcite and dolomite.

Dewey and Eastwood (1925) recorded a vein carrying galena and sphalerite in an exploratory drive from the Bonser Deep Level. The exact position of this is unknown, although Eastwood (1959) suggested that these minerals were

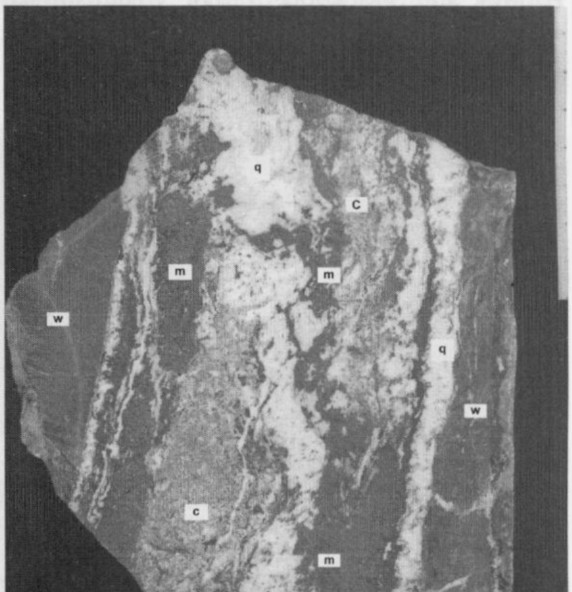

Figure 2.7 A cut section of a large specimen from Bonser Vein, Coniston Copper Mines, showing crude bands of white quartz (q), magnetite (m), and chalcopyrite (c), between Borrowdale Volcanic Group wall-rock (w). The scale bar is 10 cm. (Photo: T. Bain, BGS No. MNS 5932, reproduced by permission of the British Geological Survey, © NERC. All rights reserved. IPR/116-33CY.)

found in the easterly parts of the mine. Firman (1978a) noted that the Coniston copper veins are cut and shifted by barren cross-courses or by lead-bearing cross-veins which strike north–south or north-east–south-west.

Sections of Bonser Vein with abundant iron sulphides are exposed in workings accessible via Bonser Deep Level, and the large dumps adjacent to the Bonser Deep Level entrance contain abundant examples of apparently typical chalcopyrite-bearing veinstone, much of it rich in magnetite. Small concentrations of veinstone distinguished by carrying abundant galena and sphalerite, in association with arsenopyrite and chalcopyrite, may be seen locally on parts of the old dressing floors. This material may have been derived from one or more of the lead-bearing cross-veins.

Roughly parallel to Bonser Vein, and approximately 300 m to the south-west, lies the Paddy End Vein, the second major vein of the Coniston area, and said to have yielded richer ores (Dewey and Eastwood, 1925). The surface geology of the Paddy End Vein resembles that of the Bonser Vein (Figure 2.8). At its western extremity, near Levers Water, the vein splits into a number of roughly parallel branches. These have been worked out to surface within ignimbrites of the Paddy End Member in a series of ancient, deep open stopes known as the 'Back Strings'. One of these open workings on Paddy End Vein forms the prominent gully known as 'Simon's Nick'. The wall-rocks adjacent to these veins show considerable metasomatism to a relatively soft clay-rich rock. A branch vein, known as 'Belman Hole Vein', diverges north from Paddy End Vein near Levers Water. According to Dewey and Eastwood (1925) the vein was particularly rich at the junction which was referred to by the miners as the 'Californian Bunch'. Whereas there are few records of the wall-rock in the underground workings at Paddy End, Millward *et al.* (1999) concluded that payable mineralization is likely to have been concentrated within ignimbrite wall-rocks. According to Dewey and Eastwood (1925) much

Figure 2.8 View of the Paddy End workings at Coniston Copper Mines. The large dumps in the foreground adjoin Hospital (H) and Grey Crag (G) levels. Dumps from higher levels may be seen to the left of the stream. Ancient surface workings, including Simon's Nick, are visible on the skyline above these dumps. The modern buildings are part of a water-treatment plant. (Photo: B. Young.)

of Paddy End Vein has been removed by stoping down to about 110 m below the Grey Crag Level.

As at Bonser the main copper ore mineral at Paddy End was chalcopyrite, although small amounts of tennantite were present locally. Arsenopyrite and pyrite are also common. Traces of native bismuth and bismuthinite have also been found (Stanley and Criddle, 1979). Stanley (1979) recorded traces of gold associated with a bismuth telluride tentatively identified as wehrlite. Ores of nickel and cobalt were also reported (Russell, 1925). Gangue minerals include quartz, chlorite, calcite and dolomite. In contrast to the Bonser workings, those at Paddy End contain a number of supergene species. Russell (1925) noted the occurrence of erythrite on the dumps. The mineral remains comparatively common here today and, in addition, is locally common in some sections of the underground workings. Young and Johnson (1985) recorded langite and posnjakite in crusts of post-mining origin in some of the upper stopes.

Limited sections of the underground workings which remain accessible provide sections of veinstone *in situ*. Representative examples of vein material are, however, very abundant on the extensive dumps along the course of Paddy End Vein, especially adjacent to the entrances of Grey Crag and Hospital levels.

Interpretation

The copper-bearing veins at Coniston belong within the widespread chalcopyrite-pyrite-arsenopyrite-type suite of Lake District veins described by Stanley and Vaughan (1982a). These authors proposed a Lower Devonian age for the emplacement of these deposits, based in part on K-Ar isotopic dating of veinstone samples by Ineson and Mitchell (1974).

A close relationship between vein productivity and wall-rock lithology has long been recognized in the Coniston veins where economic copper mineralization appears, in most places, to have been restricted to veins within ignimbrite wall-rocks (the rhyolites of Mitchell, 1940). Dewey and Eastwood (1925) noted that the 'slates' worked in the Coniston area effectively limit the area of productive mineralization within the veins. In his structural study of these veins Dagger (1977) explained this relationship in terms of the greater tendency of the hard ignimbritic rocks to form open fractures in response to faulting than the associated volcaniclastic sandstones. Whereas there are few contemporary descriptions of vein wall-rocks, and most sections of the mines are now inaccessible for study, Millward *et al.* (1999, 2000) suggested that there are good grounds for accepting this relationship.

Work by several authors (e.g. Dagger, 1977; Stanley and Criddle, 1979; Stanley and Vaughan, 1982a,b) on the parageneses of these veins has suggested that many may be the result of several mineralizing episodes. It has been claimed that the Coniston veins exhibited a vertical zonation of constituent minerals, with pyrite and chalcopyrite at higher levels, and arsenopyrite increasing in abundance with depth and being progressively replaced by magnetite at even deeper levels (Dagger, 1977). This suggestion must, however, be viewed with some caution as only the Bonser and Paddy End veins have been systematically explored by mining over a significant vertical interval and in neither instance are reliable mineralogical observations known to have been recorded during mine development. Whereas magnetite seems to be present only at depth in the Bonser Vein it occurs at high levels in the Long Crag Vein in the nearby Greenburn Valley. In the Bonser Vein, magnetite, together with specular hematite, which it appears to replace, occupy an early position in the vein's paragenesis and may not be a reliable indicator of increasing depth.

Stanley and Vaughan (1980, 1982a,b) have provided data for the likely formation temperatures of minerals within the Lake District copper veins and on the composition of the fluids from which they were deposited. For the Bonser Vein they suggested (1982b) that replacement of the original hematite by magnetite, and deposition of early arsenopyrite, which post-dates magnetite, may have occurred at 350°–400°C. Quartz, chlorite, stilpnomelane, calcite, dolomite, pyrrhotite, chalcopyrite, sphalerite and late arsenopyrite were probably deposited at about 240°C. Later minerals, including pyrite, native bismuth, bismuthinite, laitakarite, joseïte, galena and cosalite are considered to have formed at temperatures as low as 200°C.

No fluid-inclusion data are available for the Coniston veins. However, inclusions in quartz from Castle Nook Vein in the Vale of Newlands, and likely to be a member of the same suite of deposits as those at Coniston, suggest that the mineralizing fluids were moderately saline brines (T. Shepherd, pers. comm. in Stanley and Vaughan, 1982a). The Borrowdale Volcanic Group has been proposed as a source of the introduced metals, the remobilization and re-distribution of which may have been brought about by heat flow from the batholith (Firman, 1978b; Stanley and Vaughan, 1982a). Lowry *et al*. (1991) demonstrated from sulphur isotope studies that Skiddaw Group rocks were the most likely source of sulphur. These authors have attempted, although with some difficulty, to relate the distribution of copper mineralization to features in the underlying batholith. However, Millward *et al*. (1999) have noted that at least some of the faults now occupied by mineralized veins at Coniston may have been active during volcanism. In addition, they have described cleavage fabrics within the wall-rocks passing through the veins, indicating that at least some of the mineralization pre-dates the Acadian cleavage-forming event. They have further pointed to similarities, including the local abundance of magnetite within the veins, with broadly contemporaneous copper deposits in North Wales (see Chapter 5), which Reedman *et al*. (1985) regarded as being genetically related to hydrothermal activity late in the process of caldera evolution. There are thus grounds to suggest that copper mineralization here may be genetically linked with the final phase of Ordovician magmatism.

Conclusions

The copper deposits at Coniston are important examples of the chalcopyrite-pyrite-arsenopyrite suite of Lake District veins. Limited surface and underground exposures of veins and an abundance of mine spoil provide excellent opportunities to study the mineral parageneses. The relationships of the veins, and their economic mineral content, to wall-rock lithology may also be demonstrated. Recently described cleavage fabrics within the veins give evidence of pre-Acadian emplacement for at least part of the mineralization, perhaps linked to the final stages of Ordovician magmatism. The local abundance of magnetite suggests similarities with the caldera-related mineralization in North Wales.

BIRK FELL HAWSE MINE, CUMBRIA (NY 294 015)

Introduction

A small quartz vein, which crosses Birk Fell Hawse at the head of Tilberthwaite Gill, carries abundant copper minerals, prominent amongst which is bornite. The vein has been worked for copper ores both underground and opencast. The date of most of these small workings is unknown, although Shaw (1970) commented that the opencast pit on the summit of Birk Fell Hawse yielded several tons of 'rich erubescite [bornite] ore' in about 1900.

Description

Birk Fell Hawse, the ridge which separates the Tilberthwaite and Greenburn valleys, is crossed by at least two roughly E–W-trending faults which throw down to the north. These locally carry copper mineralization. The northernmost fault, known as the 'Pave York Vein', has been worked from levels driven to it from the sides of the Greenburn Valley to the north. Birk Fell Hawse Vein, the southernmost of these faults, carries copper mineralization where it cuts acid lapilli tuffs of the Airy's Bridge Formation of the Borrowdale Volcanic Group near the summit of Birk Fell Hawse. At least three short levels have been driven into the vein from the steep slopes east of Birk Fell Hawse. Spoil from these shows chalcopyrite in a gangue of broken country rock, quartz and chlorite. A small opencut (Figure 2.9) on the summit of Birk Fell Hawse exposes the vein which is here up to 0.6 m wide and consits mainly of quartz with bornite as the most abundant copper mineral. Shaw (1970) recorded that several tons of this mineral were obtained here early in the 20th century. A little chalcopyrite, tennantite and arsenopyrite are also present, and thin bright-green coatings of malachite are locally conspicuous. Whereas a small amount of copper-bearing veinstone remains exposed *in situ*, the mineralization is most easily examined in the abundant material on the small spoil-heaps alongside the opencut.

Stanley (1979) described the veinstone as consisting of fractured quartz cemented by bornite, together with smaller amounts of arsenopyrite and chalcopyrite. He noted that polished sections reveal that tennantite forms veinlets in arsenopyrite and also occurs at the

Figure 2.9 The Birk Fell Hawse Vein between Borrowdale Volcanic Group wall-rocks, exposed in the old opencut working at Birk Fell Hawse Mine. The vein is composed mainly of quartz with abundant bornite and minor chalcopyrite and arsenopyrite. (Photo: B. Young.)

margins between arsenopyrite and bornite. Arsenopyrite is locally replaced along fractures by fine-grained chalcocite, and both bornite and chalcocite have also been observed along fractures in chalcopyrite. He further noted that the tennantite is similar in composition to that from the nearby Pave York and Paddy End veins.

Interpretation

The copper-bearing veins of the Birk Fell Hawse and Tilberthwaite area belong, like those of the adjoining Coniston area, to the widespread chalcopyrite-pyrite-arsenopyrite suite of veins of Stanley and Vaughan's (1982a) classification, for which these authors propose a Lower Devonian age of emplacement. Millward *et al*. (1999) presented grounds for regarding some of this mineralization as significantly older, possibly related to the final phases of Ordovician magmatism.

The Birk Fell Hawse Vein is unusual in containing abundant bornite in addition to chalcopyrite and arsenopyrite. Bornite appears to be confined to the vein exposed in the opencut on the summit of Birk Fell Hawse. Spoil from the levels driven on the vein from the hillside east of and below the opencut show abundant chalcopyrite but no bornite. Stanley's (1979) descriptions of the bornite-bearing veinstone clearly show that the bornite is of secondary origin. Millward *et al*. (2000) have suggested that the occurrence of bornite at Birk Fell Hawse appears consistent with it being the product of supergene enrichment. It is perhaps worth noting that in other Lake District localities, for example at Black Scar, Levers Water (Stanley, 1979), Seathwaite Tarn, Coniston (Stanley and Criddle, 1979), Dale Head (Stanley, 1979; see also **Dale Head North and South Veins** GCR site report, this chapter) and elsewhere (Young, 1987a), bornite also occurs in situations consistent with its formation by supergene enrichment, although this mineralization is exposed *in situ* only at Birk Fell Hawse.

Conclusions

The outcrops of the Birk Fell Hawse Vein exposed in the old opencut provide a unique opportunity in the Lake District to study a copper-bearing vein in which bornite is the dominant copper mineral. The distribution of this mineral within the vein and its relationship with other minerals is consistent with its origin by supergene enrichment.

DALE HEAD NORTH AND SOUTH VEINS, CUMBRIA (NY 223 155, NY 222 156, NY 22 71)

Introduction

The Vale of Newlands, south-west of Keswick, contains a number of metalliferous veins, two of which, the Dale Head North Vein and the Dale Head South Vein, belong to the widespread chalcopyrite-pyrite-arsenopyrite suite of Lake District veins.

Mining at Dale Head, as at a number of sites in the Vale of Newlands, may be traced back with certainty to Elizabethan times, although earlier working is possible. Working is known to have been active during the 17th century, and it is said that significant amounts of copper ore were raised here at various times during the 19th century. The history of mining in the Vale of Newlands and at Dale Head has been outlined by Postlethwaite (1913), and Donald (1994). Shaw (1970), and Stanley and Vaughan (1980) commented on more-recent proposals to attempt to re-open the mines.

The geology and mineralization of the Dale Head veins has been described by Dewey and Eastwood (1925), Rastall (1942), Strens (1962), Stanley (1979), and Stanley and Vaughan (1980).

Description

At Dale Head, mudstones belonging to the Buttermere Formation of the Ordovician Skiddaw Group are overlain by andesitic lavas and volcaniclastic rocks of the Birker Fell Formation at the base of the Ordovician Borrowdale Volcanic Group. The site includes exposures and spoil heaps from two separate, but almost certainly related, veins, namely the Dale Head North Vein and the Dale Head South Vein. The Dale Head North Vein is mineralized within Skiddaw Group rocks: the Dale Head South Vein occurs entirely within Borrowdale Volcanic Group rocks (Figure 2.10). These veins are described separately but their interpretation and genetic significance are considered together.

The Dale Head North Vein (also known as the 'Long Work') occupies an approximately E–W-trending fault. The vein is exposed in Newlands Beck where it dips south at about 70°, and is 0.5 m wide and composed mainly of quartz. Mineralization can be traced along strike for almost 0.75 km westwards onto the lower slopes of Hindscarth. It has been worked in surface trenches and stoped out to surface from shallow underground workings at several points (Figure 2.11). In these workings the vein is up to 1 m wide and comprises ribs and veins of quartz with bands rich in pyrite, chalcopyrite and arsenopyrite. Veinlets of quartz which carry these sulphide minerals penetrate the wall-rocks locally. Millward *et al*. (1999) described a strong cleavage fabric in the wall-rocks passing through and refracted by the vein and its included wall-rock clasts. Stanley and Vaughan (1980) described extensive chloritization of slate wall-rock with the development of zircon, rutile and graphite.

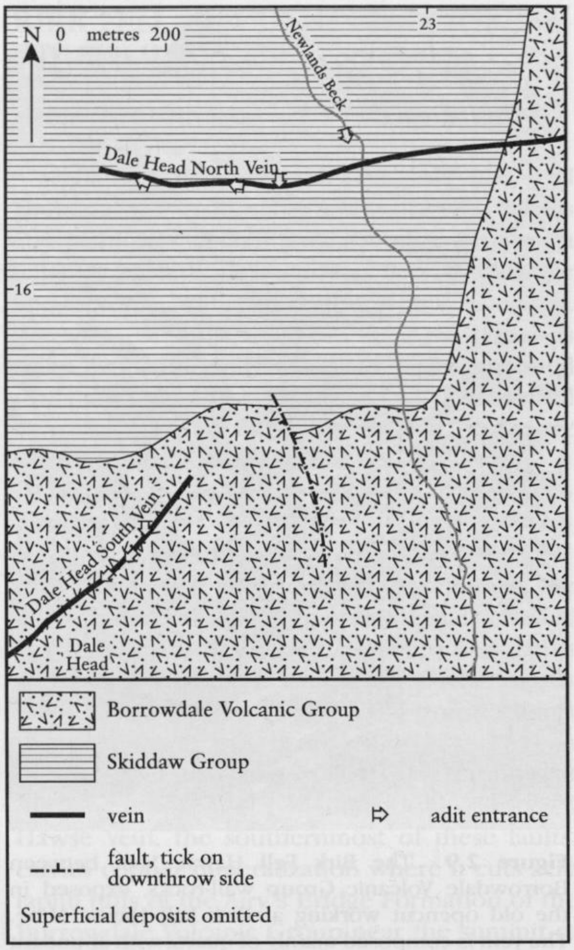

Figure 2.10 Geological sketch map of the Dale Head North and South Veins GCR site.

Sulphide-rich veinstone is abundant in small spoil-heaps adjoining most of these workings. Larger quantities of veinstone occur on the spoil heap from a level driven into the vein from the west bank of Newlands Beck. Stanley (1979), and Stanley and Vaughan (1980) presented detailed descriptions of the mineralogy and paragenesis of veinstone from this working. The most abundant and conspicuous minerals are quartz, pyrite, arsenopyrite and chalcopyrite. The vein differs from most Lake District copper veins in the abundance of pyrrhotite. In most veins of this type pyrrhotite occurs as minute inclusions usually enclosed within pyrite or arsenopyrite. The pyrrhotite at Dale Head is the monoclinic form. Other metalliferous minerals identified within the Dale Head North Vein by Stanley and Vaughan (1980) include cobaltite, cobaltiferous pyrite, native bismuth, bismuthinite,

Figure 2.11 Dale Head North and South Veins. Old opencast working in the North Vein, here between strongly cleaved Skiddaw Group wall-rocks. (Photo: B. Young.)

sphalerite, marcasite, tennantite and galena. A few inclusions of gold were recorded in one specimen. In addition to quartz, non-metalliferous minerals include rutile, muscovite and chlorite.

Dale Head South Vein occupies a NE–SW-trending fault which cuts the andesites and volcaniclastic rocks of the Birker Fell Formation at the base of the Borrowdale Volcanic Group on Dale Head Crags. The vein exposure in the crags is inaccessible. However, its course may be followed as a cleft in the crags adjacent to at least two levels which have been driven on it. The underground workings are inaccessible. The mineralogy of the vein is most easily studied in the abundant mineralized spoil from these levels and on the site of an old, perhaps Elizabethan, dressing floor. Veinstone remaining here shows abundant quartz in which occur concentrations of djurleite (Stanley, 1979). It is likely that much, if not all, of the 'copper glance' described from here by Dewey and Eastwood (1925) may be djurleite. Bornite is also comparatively common. Stanley (1979) observed the alteration of bornite to chalcopyrite in some specimens and the presence of covellite along late fractures. He also commented on the fractured nature of many of the sulphides intimately mixed with finely brecciated country rock. Other sulphide minerals present in small amounts in the Dale Head South Vein include pyrite, arsenopyrite, galena and sphalerite. Most conspicuous of the copper minerals in the Dale Head South Vein are brightly coloured supergene species, the most abundant of which are malachite and chrysocolla. Ward (1876b) noted that the vein contained an abundance of 'green carbonate' (malachite) but very little 'yellow copper' (chalcopyrite). Dark-brown goethite is also common in most samples of veinstone.

Interpretation

The mineralogy of the Dale Head North Vein is generally characteristic of the assemblages present within the widespread suite of chalcopyrite-pyrite-arsenopyrite veins found throughout much of the Lake District (Stanley and Vaughan, 1982a). In their detailed studies of this vein, Stanley and Vaughan (1980) demonstrated that deposition of quartz, muscovite, chlorite and rutile was followed by pyrite, some of which contains cobaltiferous zones, at temperatures of 300°–350°C; arsenopyrite was deposited at 295°–275°C; bismuthinite, monoclinic pyrrhotite, chalcopyrite and sphalerite followed at 240°–250°C, with late marcasite, pyrite and galena at about 235°C. The Dale Head North Vein thus exhibits some broad similarities to the copper-bearing veins of the **Coniston Copper Mines** (see GCR site report, this chapter). Stanley and Vaughan (1982a) proposed a Lower Devonian age for these veins, based in part on K-Ar isotopic dating of veinstone samples by Ineson and Mitchell (1974). However, the discovery by Millward *et al.* (1999) of cleavage within the Dale Head and Coniston copper veins indicates that mineralization, at least in part, pre-dates the Acadian cleavage-forming event and may be genetically related to the final phases of Ordovician magmatism.

Borrowdale Volcanic Group rocks have been suggested as a source of the introduced metals in these deposits (Firman, 1978a; Stanley and Vaughan, 1982a). More recently Lowry *et al.* (1991) demonstrated from sulphur isotope studies that Skiddaw Group rocks were the most likely source of sulphur. These and other authors have suggested that the underlying granitic batholith may have provided the heat source for the mineralization, and have also suggested that the distribution of copper mineralization within the Lake District is related to features in the batholith.

The relationship between the Dale Head South Vein and the majority of Lake District copper veins is not clear. A striking feature of this vein is the abundance within it of copper sulphides such as djurleite and bornite which are commonly found in zones of enrichment. Stanley (1979) described a number of replacement textures in sulphide minerals within this vein, although a detailed paragenetic sequence has not been established. He suggested that the South Vein was probably originally a chalcopyrite-pyrite-arsenopyrite vein similar to others in the Newlands Valley, including the North Vein, which has undergone considerable supergene alteration resulting from the circulation of oxidizing fluids through brecciated veinstone. The date of this brecciation and alteration is not known. The occurrence of abundant bornite in the uppermost exposed sections of the Birk Fell Hawse Vein, near Coniston, may be a similar example of supergene alteration within the upper levels of a copper vein (see **Birk Fell Hawse Mine** GCR site report, this chapter).

The presence of large quantities of minerals such as malachite and chrysocolla in the South Vein clearly results from supergene oxidation, although the timing of this alteration has not been established.

Conclusions

The Dale Head North Vein is an example of the widespread suite of chalcopyrite-pyrite-arsenopyrite veins within the Lake District, for which a Lower Devonian age has been proposed, although recent work by Millward *et al.* (1999) indicates that mineralization pre-dates the Acadian cleavage. This vein is hosted by Skiddaw Group rocks in which wall-rock alteration may be studied. Exposures of the vein *in situ* are supplemented by an abundance of mineralized veinstone in spoil heaps.

The mineral assemblage seen today in the Dale Head South Vein, which is hosted by Borrowdale Volcanic Group rocks, is believed to be the result of supergene alteration of an original chalcopyrite-pyrite-arsenopyrite vein.

WET SWINE GILL, CUMBRIA (NY 314 322)

Introduction

A small antimony-bearing vein which cuts rocks of the Ordovician Skiddaw Group is exposed in Wet Swine Gill, a left bank tributary of the River Caldew, near the head of Mosedale. The mineralization demonstrates a progression from an early Sb-Fe-As association characterized by stibnite and berthierite, to a later Sb-Pb assemblage with zinkenite and rare semseyite and fülöppite. A variety of supergene antimony minerals occurs. The vein may be an expression of the nearby early Devonian W-As mineralization at Carrock Fell Mine.

Description

The Wet Swine Gill Vein is exposed in the bed and banks of Wet Swine Gill, although its continuation beyond the stream cannot be determined. The vein cuts hornfelsed silty mudstones of the Kirk Stile Slates of the Ordovician Skiddaw Group (Jackson, 1978), within the aureole of the Skiddaw Granite. The vein is up to about 0.5 m wide in the stream, where it strikes north-east–south-west and dips steeply to the south-east. The site lies about 1 km south-west of the workings of the **Carrock Mine–Brandy Gill** GCR site.

The Wet Swine Gill Vein is unusual in the Lake District in having been discovered only within the past few years. There are no signs of any excavations or trials on it.

The veinstone typically consists of fine- to medium-grained quartz in which are scattered irregular patches of fine-grained ore minerals. Fortey *et al.* (1984) provided a detailed description of the vein and its mineralogy. The principal ore minerals include, in order of abundance, stibnite, zinkenite and berthierite. In addition, jamesonite is present in small amounts accompanied by very small quantities of native antimony, semseyite and fülöppite, the latter reported here for the first time from a British locality. More recently, Green *et al.* (2005b) have presented analyses of equant, subhedral crystals of füllöppite. A little sphalerite and arsenopyrite occur within the ore assemblage. Weathered surfaces of the vein-stone are encrusted with supergene antimony minerals including yellow bindheimite, greyish-white stibiconite and traces of senarmonitite and kermesite.

Rare supergene species found at Wet Swine Gill include antimonian claudetite (Leppington and Green, 1998), and scorodite, pharmacosiderite, beudantite and valentinite, in addition to parasymplesite, reported here for the first time from a British locality (Neall and Green, 2001a).

In recent years the outcrop of the vein has been considerably excavated by mineral collectors and much of the richer ore-bearing parts of the vein have been removed or damaged. However, substantial amounts of ore-bearing material remain in and around these excavations. The site lies within the area in which mineral collecting is controlled by a permit system administered by the Lake District National Park Authority.

Interpretation

Fortey *et al.* (1984) showed that the earliest mineralization at Wet Swine Gill comprises two generations of vein quartz. The ore mineral assemblage demonstrates a progression from an Sb-Fe-As paragenesis consisting of stibnite, berthierite, jamesonite, native antimony, antimony-rich arsenopyrite and sphalerite to an Sb-Pb paragenesis consisting of zinkenite, fülöppite and semseyite.

In their studies of this mineralization Fortey *et al.* (1984) drew attention to several points of similarity with the deposits of the tungsten-bearing veins of the nearby Carrock Fell Mine, where small amounts of antimony minerals have also been recorded (Kingsbury and Hartley, 1956a). They concluded that the early quartz and Sb-Fe-As assemblages at Wet Swine Gill were synchronous with the early sulphide mineralization within the Carrock Fell veins and thus of early Devonian age. The identification of wolframite and scheelite in panned concentrates from Wet Swine Gill and adjacent streams may be significant in suggesting that hitherto undetected mineralization related to the Carrock Fell deposits may be present in this area (Appleton and Wadge, 1976). A small jamesonite-bearing quartz vein, on strike with the Carrock Fell veins, described briefly by Fortey *et al.* (1984) may offer further evidence of a genetic association between the Wet Swine Gill and Carrock Fell veins.

Small antimony-rich veins have been reported from elsewhere in the Lake District, including that formerly worked for antimony at Robin Hood Mine, near Bassenthwaite several kilometres west of Wet Swine Gill (Postlethwaite, 1913; Young, 1987a). There are, however, few descriptions of these occurrences, or of the mineral assemblages present, and relatively little is known of their place in the evolution of Lake District mineralization and metallogenesis. In their classification of Lake District mineralization Stanley and Vaughan (1982a) placed these deposits in a separate category of uncertain age. If the Wet Swine Gill Vein is genetically related to the Carrock Fell tungsten deposits it is possible that at least some of the other Lake District antimony veins may also be the result of early Devonian mineralization.

Elsewhere in the Lake District lead-rich veins, generally regarded as of early Carboniferous age, typically contain an abundance of antimony minerals as minute inclusions in, or associated with, galena (Stanley and Vaughan, 1982a). Fortey *et al.* (1984) have suggested that the later Sb-Pb-rich assemblage within the Wet Swine Gill

Vein may result from a remobilization of earlier deposited antimony by lead-rich fluids during this early Carboniferous mineralizing episode.

The crusts of supergene minerals in the Wet Swine Gill Vein are almost certainly the product of oxidation since the vein was exposed to weathering.

Conclusions

The Wet Swine Gill Vein provides the finest example of an antimony-bearing vein exposed within the Lake District. The work of Fortey *et al.* (1984) suggests that the earliest ore mineral assemblage in the vein is genetically linked with the early Devonian sulphide-rich mineralization in the nearby Carrock Fell tungsten veins. The vein is thus important in the understanding and interpretation of these deposits. The presence of a separate, later phase of lead-rich antimony mineralization provides evidence for remobilization of previously deposited antimony by early Carboniferous lead-rich mineralizing fluids.

CARROCK MINE–BRANDY GILL, CUMBRIA (NY 323 335)

Introduction

Tungsten mineralization at the Carrock Mine–Brandy Gill GCR site occurs mainly in three major roughly N–S-trending veins which cut a variety of rock types including the greisen within the northern portion of the Skiddaw Granite, hornfelsed Skiddaw Group rocks, and various members of the Carrock Fell Intrusive Complex. The mineralization is genetically associated with extensive greisenization of the Skiddaw Granite. The veins record a number of stages of fracturing and mineralization, each characterized by a distinctive mineral assemblage. The main tungsten-bearing veins are cut, and displaced, by a later set of lead-bearing veins.

Although the presence at this site of several conspicuous quartz veins must have attracted early prospecting, the absence of workable lead and copper minerals in the tungsten veins would have soon been recognized. Trial workings on the lead veins, which are now known to intersect the tungsten veins, began in the middle years of the 19th century although output is likely to have been small. Attempts at tungsten mining began in 1901 and continued intermittently until 1919. Investigation of the mine's potential during World War II did not lead to a resumption of production. Mining restarted in the 1970s and although a new mill was built, the mine became uneconomic and was closed down finally in 1981. The Carrock Fell veins comprise the only known economic concentration of tungsten mineralization within Britain outside of South-west England. The total output of tungsten minerals is not known but is small. The mine's history has been outlined by Postlethwaite (1913), Abraham (1917), Shaw (1970), Adams (1988), and Blundell (1992).

The Carrock Fell veins have been the subject of much research. Important descriptions of the deposits and interpretations of their formation include those by Finlayson (1910a), Hitchen (1934), Ewart (1962), Appleton and Wadge (1976), Shepherd *et al.* (1976), Fortey (1978), Beddoe-Stephens and Fortey (1981), Brown (1983), Roberts (1983), Shepherd and Waters (1984), and Ball *et al.* (1985). The great variety of minerals found within the veins has long attracted mineralogists. Comprehensive lists of the minerals and references to individual descriptions are to be found in Young (1987a), and Cooper and Stanley (1990).

Since its abandonment the site has been cleared of buildings and parts of the spoil-heaps levelled. The main entrance adit has been closed and none of the underground workings are safely accessible. Good surface exposures of parts of the veins remain, and representative examples of mineralized veinstone may be seen in the remaining spoil-heaps. The site lies within the area in which mineral collecting is controlled by a permit system administered by the Lake District National Park Authority.

Description

The geology of the site is summarized in Figure 2.12, which incorporates the results of the most recent mapping by the British Geological Survey.

The deposits occur within a small area on the northern margin of the Grainsgill Cupola of the Skiddaw Granite. This partially unroofed intrusion has an extensive thermal metamorphic aureole in Ordovician rocks which include highly deformed slates of the Skiddaw Group, volcanic rocks of the Eycott Volcanic Group, and parts of the Carrock Fell Intrusive Complex, including gabbro and granophyre. In its northernmost outcrop in Grainsgill, the Skiddaw

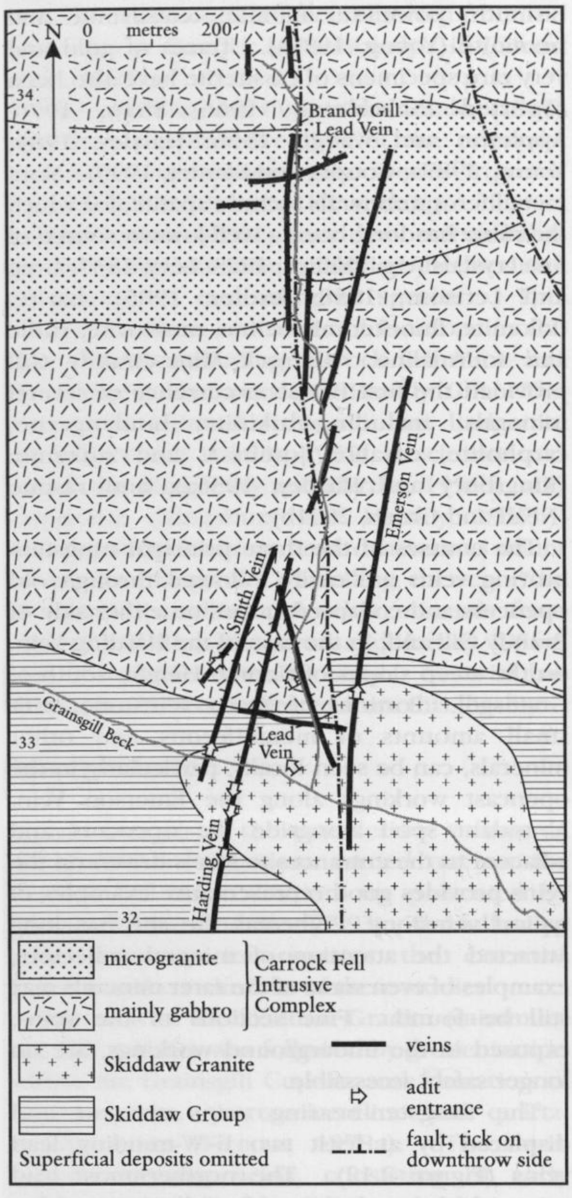

Figure 2.12 Geological sketch map of the Carrock Mine–Brandy Gill GCR site.

Granite exhibits intense alteration which culminates in the quartz-muscovite greisen of the Carrock Mine–Brandy Gill area.

Two principal sets of veins are present at Carrock Mine–Brandy Gill, namely the tungsten veins and a cross-cutting set of lead veins.

The tungsten veins strike approximately north–south on either side of Brandy Gill, the left bank tributary of Grainsgill Beck. From west to east these are known as the 'Smith', 'Harding' and 'Emerson' veins. Other minor tungsten-bearing veins are associated with these and are known mainly from underground workings. Harding and Emerson veins were the main sources of tungsten minerals. Smith Vein is said by Shaw (1970) to have contained only poor tungsten values. The main workings on these veins lie on the north side of Grainsgill Beck. The only significant workings south of Grainsgill Beck are those in the Harding Vein on the steep northern slopes of Coomb Height. According to Shaw (1970) this vein was the most prolific producer. Trials in the Emerson Vein south of Grainsgill were unsuccessful, but Shaw (1970) recorded the finding here of very fine crystals of quartz.

The veins are steeply inclined, with very sharp contacts with their wall-rocks, and vary from 0.1 m to 1.5 m in width (Shepherd *et al.*, 1976). They are typically filled with white quartz, crystals of which up to 0.3 m long have been seen in vugs. Tungsten occurs both as wolframite and scheelite. The former mineral occurs as tabular crystals up to about 10 cm across, commonly forming clusters on or near the vein walls (Figures 2.13 and 2.14). Scheelite is common, in places clearly replacing earlier wolframite; scheelite pseudomorphs after

Figure 2.13 Harding Vein, between gabbro wall-rocks, exposed underground at Carrock Mine–Brandy Gill. Clusters of large wolframite crystals are prominent within massive white quartz. Other conspicuous constituents of the vein include arsenopyrite and a little scheelite. (Photo: T. Bain, BGS No. D3957, reproduced by permission of the British Geological Survey, © NERC. All rights reserved. IPR/116-33CY.)

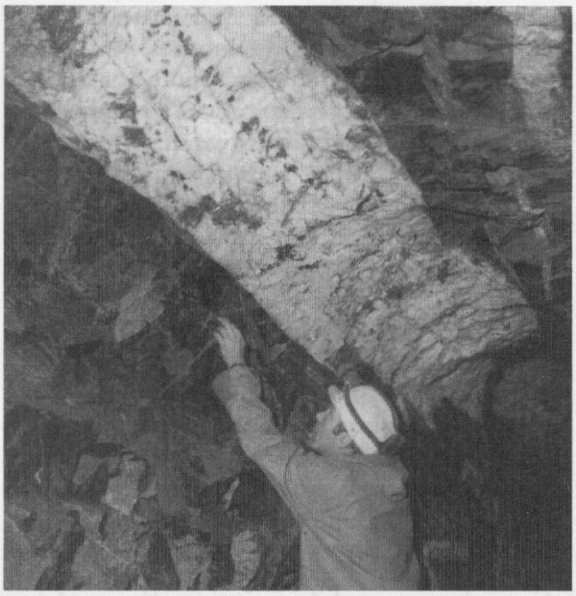

Figure 2.14 Smith Vein, between gabbro wall-rocks at Carrock Mine–Brandy Gill. The vein here is composed mainly of white quartz in which a faint banding may be seen. The dark minerals are wolframite, arsenopyrite and scheelite. (Photo: T. Bain, BGS No. D3945, reproduced by permission of the British Geological Survey, © NERC. All rights reserved. IPR/116-33CY.)

wolframite have been found (Young, 1987a). Well-formed crystals of pale to deep orange-yellow scheelite have long been known from here. Cooper and Stanley (1990) referred to fine specimens collected in the 19th century, including examples figured by Lévy (1837), Greg and Lettsom (1858), and Bauer (1871), and commented on the finding in the 1970s of a very large vug within Smith Vein lined with large scheelite crystals. Shaw (1970) noted that within the Harding Vein much of the tungsten was present as scheelite, whereas in the Emerson Vein wolframite was the main tungsten mineral.

In addition to tungsten ores, the veins contain a great variety of other minerals. Prominent amongst these are arsenopyrite, for which the mine is well known as a source of beautifully crystallized specimens (e.g. Cooper and Stanley, 1990), pyrite, pyrrhotite and sphalerite. This latter mineral typically occurs as the very dark-brown to black iron-rich variety known as 'marmatite'. Other metalliferous minerals recorded in smaller amounts include bismuthinite, chalcopyrite, columbite, cubanite, galena, jamesonite, josëite, molybdenite, native bismuth, powellite, stibnite, tetradymite and uraninite (Young, 1987a). Traces of gold and very rare specimens of cassiterite have also been reported (Shackleton, 1966; Shaw, 1970; Appleton and Wadge, 1976; Hartley, 1984; Young, 1987a; Cooper and Stanley, 1990). Non-metalliferous minerals include apatite, for which the mine has long been a well-known source of fine crystals (e.g. Phillips, 1823; Lévy, 1837; Greg and Lettsom, 1858; Rudler, 1905), barite, dolomite, fluorite, microcline, muscovite, rutile and tourmaline. Carrock Mine–Brandy Gill provided the first British occurrence of several minerals, including aikinite, boulangerite, carpholite, cosalite, josëite-A, and zinkenite (Kingsbury and Hartley, 1956a), and raspite (Neall and Green, 2001b).

The courses of the three principal tungsten-bearing veins are easily followed through old opencuts and collapsed stopes on either side of Brandy Gill and, in the case of the Harding Vein, on the steep slopes of Coomb Height, south of Grainsgill. Portions of quartz veinstone, with small amounts of metalliferous and other minerals, can be seen locally, particularly in the opencast workings along the Emerson Vein. Abundant spoil alongside the opencuts and adjacent to the entrances to levels driven on the veins provides good representative examples of typical veinstone. Whereas the site has long attracted the attention of mineral collectors, examples of even some of the rarer minerals may still be found. Fine sections of the veins, exposed in the underground workings, are no longer safely accesssible.

The tungsten-bearing veins are cut and displaced by at least two E–W-trending lead veins (Figure 2.12). The northernmost lead vein, which crosses Brandy Gill almost 1 km upstream from its confluence with Grainsgill, has been worked on a small scale from levels on both banks of the stream. These workings, known as 'Brandy Gill Lead mine', are well known for a variety of rare supergene minerals collected both from the vein outcrops and from the small spoil-heaps. The site has provided the first British occurrence of arseniosiderite, beaverite, duftite, hedyphane, and stolzite. A small vein exposure which has also yielded fine examples of a variety of rare supergene species including carminite and beudantite, at the head of an un-named eastern tributary stream (Cooper and Stanley, 1990), may be on the same vein. More recently, the iron arsenate symplesite has been reported from the waste tips at Carrock Mine–Brandy Gill (Green *et al.*, 2003).

Young (1987a), and Cooper and Stanley (1990) provide comprehensive lists of the minerals, including many rare supergene species, from the Carrock Fell and Brandy Gill workings.

Ryback *et al.* (2001) have demonstrated that the late A.W.G. Kingsbury falsified the localities of numerous rare mineral species. This deception affects a number of locations in the Lake District, including Carrock Fell Mine and the adjacent lead mines in Brandy Gill. The discredited claims for this site are: lindgenite (Kingsbury and Hartley, 1955), descloizite and vanadinite (Kingsbury and Hartley, 1956b), and carpholite (Kingsbury and Hartley, 1957b). Although this discovery must cast serious doubt on much of Kingsbury's labelling, the reporting of aikinite, cosalite, and other minerals from Carrock Fell Mine (Kingsbury and Hartley, 1956a) may be reliable as exactly similar material has subsequently been collected from this locality.

Interpretation

Useful synopses of the considerable volume of interpretive investigations carried out on the Carrock Fell mineralization are presented by Firman (1978a), and Rice (1993). The following brief summary incorporates the essential features and conclusions of these studies.

Intrusion of the Skiddaw Granite (minimum age 392 ± 4 Ma) was followed by greisenization within the Grainsgill Cupola, and formation of barren quartz, quartz-microcline and quartz-apatite veins (Firman, 1978a). The main tungsten-bearing veins, consisting of early quartz accompanied by a little scheelite, were then emplaced in north–south fractures. Hitchen (1934) suggested that tungsten mineralization passes laterally into manganese-rich mineralization in an outer 'halo' around the Carrock Fell deposits. This was followed shortly afterwards by the introduction of sulphides including arsenopyrite, pyrite, pyrrhotite, iron-rich sphalerite ('marmatite'), chalcopyrite, bismuthinite, molybdenite, bismuth sulphotellurides and native bismuth (Ball *et al.*, 1985). The replacement of substantial amounts of the original wolframite by scheelite probably took place at this time, together with the local formation of columbite, perhaps exsolved from primary wolframite (Beddoe-Stephens and Fortey, 1981). Cosalite and a number of lead antimony sulphosalts, described from Carrock Fell Mine by Kingsbury and Hartley (1956a), and the early quartz Sb-Fe-As minerals in the nearby Wet Swine Gill Vein (see **Wet Swine Gill** GCR site report, this chapter) (Fortey *et al.*, 1984) may also date from this period of sulphide mineralization. Hydrothermal muscovite from the intensely greisenized wall-rock of these veins gives an age of 387 Ma, suggesting a very close link between granite emplacement and mineralization. The main sequence of mineralizing events recorded within the tungsten-bearing veins is assigned a Lower Devonian age by Stanley and Vaughan (1982a). A final episode of pervasive carbonate mineralization, which filled narrow fissures within the tungsten-bearing veins with calcite, dolomite and a little arsenopyrite is undated but may represent the episode of mineralization which emplaced lead and minor copper ores in the E–W-trending veins which cut and displace the tungsten veins. These are likely to be part of the widespread suite of Lake District lead-bearing veins for which a Lower Carboniferous age has been proposed (Stanley and Vaughan, 1982a).

Mineralogical, oxygen-isotope and fluid-inclusion studies support a genetic connection between the formation of the Grainsgill Cupola greisen and the tungsten mineralization (Hitchen, 1934; Ewart, 1962; Shepherd *et al.*, 1976; Ball *et al.*, 1985). From these it appears that the mineralizing fluids responsible for the tungsten mineralization were low salinity (maximium 10 wt% NaCl equivalent), CO_2-rich aqueous fluids which were depleted in ^{18}O relative to magmatic fluids and which therefore appear to have contained a major non-magmatic component. Temperatures of 235°–335°C are indicated for this mineralization. The main sulphide mineralization appears to have been deposited at temperatures between 170°C and 235°C. The final calcite-dolomite mineralization formed at between 110°C and 130°C from high-salinity (in excess of 23 wt% NaCl equivalent) $CaCl_2$-rich aqueous fluids.

Shepherd *et al.* (1976) suggested that greisenization may have been caused by moderately saline non-magmatic fluids in the country rocks being drawn into the Grainsgill Cupola of the Skiddaw Granite during cooling. These fluids were then expelled into the north–south fractures where they mixed with additional non-magmatic fluids and deposited the main mineralization. Fluid convection is likely to have been driven by thermal energy from the cooling pluton (Shepherd and Waters, 1984).

The extensive range of supergene minerals is likely to have developed in comparatively recent geological times when erosion brought the deposits within reach of oxidizing groundwaters. Elements from both tungsten- and lead-bearing veins contributed to the formation of such rare species as wulfenite, stolzite and lindgrenite.

Conclusions

Carrock Mine–Brandy Gill provides opportunities to study comparatively high-temperature mineralization associated with extensive greisenization of the northern Grainsgill Cupola of the Caledonian Skiddaw Granite. Early wolframite-rich tungsten mineralization is followed by a varied assemblage of sulphides accompanied by abundant scheelite. Lead-rich mineralization occurs in later veins which cut the main tungsten-bearing veins. The Carrock Fell deposits include a great variety of primary and supergene minerals, for several of which the site is the first reported British occurrence.

BUCKBARROW BECK, CUMBRIA (SD 137 907)

Description

A narrow quartz vein, exposed in the west bank of Buckbarrow Beck, Corney Fell, carries abundant chalcopyrite and scheelite with smaller amounts of ferberite. A number of rare supergene copper, tungsten and bismuth minerals, including cuprotungstite and russellite, are locally abundant. Traces of scheelite have been seen in a handful of other small veins a short distance upstream. All of these veins cut the Eskdale Granodiorite, the southernmost part of the Eskdale Intrusion.

Small trials, of unknown date, have been made on a small copper-bearing vein roughly parallel to the tungsten-bearing vein, on the opposite bank of Buckbarrow Beck. The tungsten-bearing vein was discovered during the mapping of the Eskdale Intrusion by the British Geological Survey in 1984.

The Eskdale Intrusion, which hosts this small vein, has been the subject of investigations by Dwerryhouse (1909), Simpson (1934), Trotter *et al*. (1937), Firman (1978b), Rundle (1979, 1981), Ansari (1983), O'Brien *et al*. (1985), Firman and Lee (1986), Young (1985a), and Young *et al*. (1988). The mineralogy of the tungsten-bearing vein has been described by Young (1985b), Young *et al*. (1986, 1991), and Neall *et al*. (1993).

Description

The Buckbarrow Beck veins lie within the Eskdale Granodiorite, close to where its south-eastern contact dips beneath hornfelsed andesites of the Borrowdale Volcanic Group. The granodiorite is the southern part of the Eskdale Intrusion, the largest surface expression of the largely concealed Lake District Batholith. There is evidence that the granodiorite is the older part of this intrusion (Young *et al*., 1988).

Buckbarrow Beck is crossed, about 200 m upstream from the bridge on the Ulpha to Bootle road, by a NNE–SSW-trending vein in granodiorite (Figure 2.15). In the west bank of the stream the vein is barren and consists of a

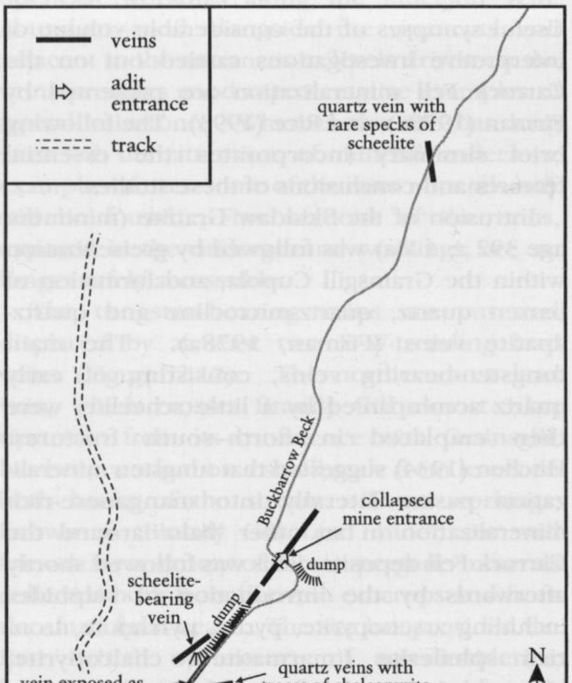

Figure 2.15 Sketch of Buckbarrow Beck showing the distribution of the main mineral veins. After Young (1985b).

1 m-wide belt of soft kaolinized granodiorite, locally showing staining by iron and manganese oxides. This type of argillic alteration is common locally in the Eskdale Granodiorite, although Buckbarrow Beck is one of the few sites at which it is seen to be associated with obvious mineralization (Young, 1985b). On the eastern bank of the stream, a level, the entrance of which is now collapsed, has been driven on the vein. The small dumps show abundant massive quartz in which occur abundant specks of chalcopyrite together with encrustations of malachite, chrysocolla and goethite.

A sub-parallel vein up to 10 cm across, and dipping steeply to the north-west, is exposed on the west bank of the stream about 10 m west of the previously described vein. Massive quartz is the main constituent, with local conspicuous concentrations of chalcopyrite and goethite. Although superficially resembling the veinstone on the dump from the trial level on the opposite bank, this vein is distinguished by containing abundant scheelite, together with small amounts of ferberite. The scheelite occurs as pale-fawn, rather friable masses and more continuous bands up to 3 mm thick on each wall of the vein, or as irregular pockets up to 8 mm wide within the vein, and is in places patchily replaced by ferberite. Ferberite occurs sparingly as groups of crystals up to 4 mm long embedded in quartz on the margins of the vein. Young *et al.* (1986) reported that the composition is considerably more ferroan than the wolframite from the Carrock Fell tungsten deposit in the north of the Lake District (see **Carrock Mine–Brandy Gill** GCR site report, this chapter).

The vein outcrop is deeply weathered and contains abundant crusts of a variety of supergene minerals (Young, 1985b; Young *et al.*, 1986, 1991; Neall *et al.*, 1993). Perhaps most conspicuous because of their colour are crusts of malachite, chrysocolla and goethite. Cuprotungstite, for which Buckbarrow Beck is the first recorded British locality, has been found on a few specimens as vivid grass-green crusts on scheelite. More abundant are bright-yellow, earthy coatings and patches, up to 6 mm across, of bismutoferrite, commonly associated with patches of dark-brown earthy goethite. Russellite is also locally abundant within the vein. It commonly forms thin (< 1 mm), pale-buff to greenish-yellow, discontinuous crusts up to 10 mm across on joint- and fracture-surfaces of quartz. In places, these coalesce to form circular spherulitic masses up to 1 mm across in which a faint radiating crystalline structure and colour banding is apparent. Open joints have yielded specimens which consist of complete hemispherical masses of spherules up to 0.3 mm across (Figure 2.16). Young *et al.* (1986, 1991) compared analyses of the Buckbarrow Beck russellite with that of russellite from the type locality at Castle an Dinas, Cornwall and from Poona, Western Australia. They showed that the Cumbrian mineral exhibits differences in the relative proportions of W, Bi and O, and concluded that this appears to confirm the variability in composition of this mineral suggested by Hey and Bannister (1938). Buckbarrow Beck is only the fourth world locality known for this mineral. Other rare supergene minerals identified from the Buckbarrow Beck Vein include namibite, also reported here

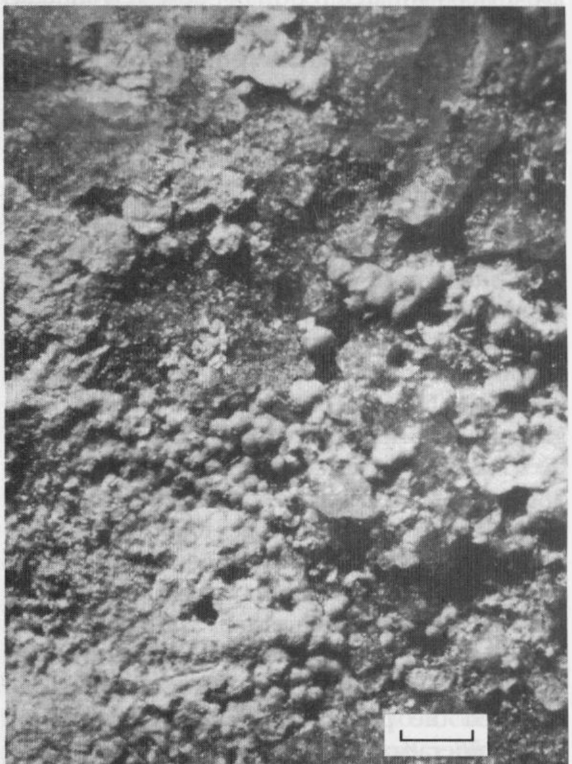

Figure 2.16 Spherules of russellite on quartz from the tungsten vein at Buckbarrow Beck. The scale bar is 1 mm. (Photo. F. McTaggart, BGS No. P244159, reproduced with permission of the British Geological Survey, © NERC. All rights reserved. IPR/116-33CY.)

for the first time from a British locality, eulytite, bismutite and mixite (Neall *et al.*, 1993).

The threat to this rather small and sensitive site from mineral collectors prompted the then Nature Conservancy Council to collaborate with the land owner and the British Geological Survey in arranging the rescue collection of representative samples of veinstone from the outcrop (Nature Conservancy Council, 1987). The material collected is held by the British Geological Survey and is available to *bona fide* research workers.

Interpretation

Tungsten mineralization is well known in the Lake District in the veins at **Carrock Mine–Brandy Gill** (see GCR site report, this chapter). Traces of scheelite have been found in drusy cavities in the Shap Granite (Firman, 1953, 1978a), and there are unsubstantiated reports of tungsten minerals at Scar Crag and Force Crag, near Keswick (Greg and Lettsom, 1858; Kingsbury and Hartley, 1957a). The Buckbarrow Beck Vein is the first record of tungsten mineralization from the granitic rocks of the western Lake District.

Greisens occur around the margins of the Eskdale Granite (Young, 1985a; Young *et al.*, 1988). The topaz-greisen at **Water Crag** (see GCR site report, this chapter) locally contains concentrations of arsenopyrite-bismuthinite-molybdenite-fluorite mineralization (Young, 1985b). In addition, enhanced levels of tin and tungsten have been recorded from these greisens (O'Brien *et al.*, 1985; Ansari, 1993). In their review of Lake District mineralization Stanley and Vaughan (1982a) provided evidence for a Lower Devonian age for the tungsten mineralization at Carrock Fell and the widespread copper mineralization throughout the Lake District, although Millward *et al.* (1999) have suggested that at least some of this mineralization may be significantly older. Young *et al.* (1986) explored the possibility that the Buckbarrow Beck mineralization may be genetically related to the emplacement of the Eskdale Granite. If this were so, a late Ordovician or early Silurian episode of mineralization is implied. However, in view of the evidence that the Eskdale Granite was subjected to hydrothermal alteration during the end-Silurian to early Devonian period, these authors concluded that the Buckbarrow Beck mineralization is more probably of late Silurian to early Devonian age.

Conclusions

The Buckbarrow Beck Vein is the only known occurrence of tungsten mineralization within the granitic rocks of the western Lake District. In addition it affords a unique opportunity to study a wide range of rare supergene minerals. The site is one of only four world locations for russellite and is probably the only known site at which this mineral may today be seen *in situ*. In addition the site offers important scope for research into mineralization associated with the Lake District Batholith.

LONG COMB, CUMBRIA (NY 206 207)

Introduction

A NNE–SSW-trending quartz vein, usually known as 'Scar Crag Vein', crops out on the east side of Long Comb, between Sail and Scar Crags above the head of Coledale. The vein is unusual in the Lake District in carrying abundant apatite and arsenopyrite together with small amounts of cobalt minerals. The presence of cobalt led to several trial workings on it in the 19th century, although none was successful.

According to Adams (1988) the first trial workings, in search of cobalt ore, were made in about 1848. Dressing floors and a smelter were built at Stoneycroft, about 3 km to the east in the Vale of Newlands, to process the ore. The initial optimism was not rewarded and the venture seems to have been a spectacular failure with little, if any, cobalt recovered from the workings (Postlethwaite, 1913; Adams, 1988).

Despite the failure to prove workable cobalt ores the vein has attracted considerable mineralogical interest. Descriptions of the minerals include those by Davidson and Thomson, (1948), Kingsbury and Hartley (1957a), Strens (1962), Stanley (1979), Ixer *et al.* (1979), Stanley and Vaughan (1982a), and Young (1987a, 1988). Aspects of the local geology and its relevance to the origins of mineralization in this part of the Lake District have been the subject of investigations by D.C. Cooper *et al.* (1988).

Description

The Scar Crag Vein occupies a NNE–SSW-trending fault of very small throw which cuts slates assigned to the Kirk Stile Slates of the Ordovician Skiddaw Group. The bleached and locally iron-stained slates, originally described by Eastwood *et al.* (1931) as the 'Blake Fell Mudstone', are within the broad area of hydrothermal alteration known today as the 'Crummock Water thermal aureole' (Cooper, D.C. *et al.*, 1988). The vein forms a small gully which may be traced for approximately 150 m along the foot of the crags above the footpath through Long Comb. According to Postlethwaite (1913) four levels were driven on the vein, although Adams (1988) commented that only three could then be located. The vein is well exposed above the portals of these levels. In these exposures it is up to 1.5 m wide, and composed of several parallel bands, each up to about 0.5 m wide, of massive quartz with abundant chlorite. Within these occur local concentrations of arsenopyrite, much of which has been weathered to cellular masses of pale-green to brown scorodite. Dark-red hematite staining is common along fractures and joints. Abundant spoil from the levels shows conspicuous concentrations of white to pale-cream apatite prisms up to 5 mm in diameter embedded in quartz and chlorite. In addition to the small surface exposures of the vein, good sections may be examined underground in the small stope accessible a few metres inside the upper level of the mine.

In a detailed study of the ore mineralogy, Ixer *et al.* (1979) recorded a suite of cobalt minerals including glaucodot, skutterudite, cobaltite and alloclase, recorded here for the first time from a British locality. All are present as minute grains or as overgrowths on arsenopyrite. Other metalliferous minerals recorded by these authors include small quantities of marcasite, pyrite, native bismuth, bismuthinite and molybdenite. Ixer *et al.* (1979) also noted the presence of tourmaline and rutile as early members of the paragenesis. Much, if not all, of the smaltite reported by Postlethwaite (1913) may be skutterudite. The presence of löllingite, claimed by Strens (1962), and Kingsbury and Hartley (1957a), and scheelite, suggested by Kingsbury and Hartley (1957a), has not been substantiated by the more-recent studies.

Young (1988) described the occurrence of wavellite and variscite in the Scar Crag Vein. These minerals are sparingly present coating joint-surfaces in a quartz rib on the western side of the vein in the small stope in the upper level of the mine. Wavellite occurs here as colourless to white acicular crystals forming flat spherulitic aggregates up to 10 mm across, and very rarely as small hemispherical spherules up to 2 mm across. Variscite typically forms bright turquoise-blue to green crystalline coatings and minute botryoidal aggregates up to 1.5 mm thick on quartz.

Scorodite is the most abundant supergene mineral at the site. Erythrite, reported by Postlethwaite (1913), and Davidson and Thomson (1948), appears to be very rare. Kingsbury and Hartley (1957c) found that much of the pink material which superficially resembles erythrite proved to be either pink scorodite or altered apatite.

Ryback *et al.* (2001) have demonstrated that the late A.W.G. Kingsbury falsified the localities of numerous rare mineral species, including many from the Lake District. Although no conclusive proof has been established of deception relating to specimens from this site, great care should be exercised when considering claims by Kingsbury which have not been substantiated or duplicated by subsequent collectors. Particular caution should be applied to Kingsbury and Hartley's (1957a) claim of childrenite and scheelite from Long Comb, which must now be considered unlikely.

Interpretation

Ixer *et al.* (1979) presented a detailed paragenetic sequence for the component minerals of the Scar Crag Vein. In their discussion of the formation of this mineralization they suggested that arsenopyrite here may be employed as a geothermometer. They concluded that the early sulpharsenide assemblage, including arsenopyrite, glaucodot and alloclase, formed at temperatures within the range 350°–400°C, with later ore minerals such as pyrite deposited at around 300°C.

Ixer *et al.* (1979) suggested that the Scar Crag mineralization could be related to a concealed granitic intrusion beneath the Causey Pike area. Stanley and Vaughan (1982a) assigned a Lower Devonian age to the Scar Crag Vein.

The bleaching and spotting of the Skiddaw Group rocks in this area, to which Eastwood *et al.* (1931) applied the term 'Blake Fell Mudstone', are now interpreted as forming part of the Crummock Water thermal aureole, an elongate zone of intense hydrothermal alteration overlying a postulated granitic body

(Cooper, D.C. *et al*., 1988). Within this zone the bleached rocks exhibit significant depletion in several elements including Cl, Ni, S, Zn, Cu, Fe, Li and Mn, together with net additions of such elements as As, B, K, Rb, Ca, F and Si. The zone is veined by numerous tourmaline veins (Fortey and Cooper, 1986). The age of this metasomatism has been dated at 401 ± 3 Ma (Cooper, D.C. *et al*., 1988).

Apatite-chlorite-quartz veins, very similar to that at Scar Crag, although without sulphides, occur in Ennerdale at Brown How (Clark, 1963) and Crag Fell (Young, 1987a). The presence of albite in some of these veins suggests a pegmatitic origin. The relatively high temperatures for deposition of early ore minerals in the Scar Crag Vein may be consistent with such an origin. It is conceivable that this very distinctive style of mineralization may be genetically related to either the late stages of the Ennerdale Intrusion or the metasomatism within the Crummock Water thermal aureole.

The development of supergene minerals within the Scar Crag Vein is almost certainly related to geologically recent weathering.

Conclusions

The quartz-chlorite-apatite-ore mineral assemblage within the Scar Crag Vein appears to be unique in the Lake District, and possibly in Britain. The relative abundance within it of a variety of cobalt sulpharsenides, together with its situation within the Crummock Water thermal aureole offers considerable scope for further research.

RED GILL MINE, CUMBRIA (NY 294 348)

Introduction

Red Gill Mine is one of a number of mainly small mines in the Caldbeck Fells, in the northern part of the Lake District, from which lead and copper ores were worked from veins which cut rocks of the Ordovician Eycott Volcanic Group. The ore minerals were galena and chalcopyrite. However, the main mineralogical interest of the site lies in the abundance and quality of specimens of the large variety of supergene minerals found within the veins, including the recently described species redgillite, for which this is the type locality.

Red Gill Mine is said to have been worked by the Elizabethans and some of the workings may be even older. There are documentary records of working here in the 18th century, but best recorded are the 19th century operations. Production figures are far from complete, although records from the 19th century workings indicate that 47 tons of dressed copper ore were raised between 1863 and 1869: a little under 18 tons of lead ore were produced between 1861 and 1866. Historical descriptions of the mine include those by Shaw (1970), Adams (1988), and Cooper and Stanley (1990).

Descriptions of the geology, with particular reference to the veins worked, have been given by Eastwood (1921), and Dewey and Eastwood (1925). Comprehensive descriptions of the minerals found at Red Gill have been published by Young (1987a), and Cooper and Stanley (1990). Exhaustive lists of references to the site are contained in these two latter publications. Spectacular specimens of many of the minerals for which the site is famous are to be seen in major museum collections throughout the world.

Description

Three veins, all predominantly within andesites of the Eycott Volcanic Group, are known at Red Gill, although most of the workings were within the NNW–SSE-trending Main or South Vein. Eastwood (1921) recorded that where seen in an 8 m-deep shaft near the junction of Red Gill with Swinburn Gill this vein was found to be up to 1.2 m wide and composed of '...quartz-ribs with broken country rock in a matrix of sand and clay stained with 'manganese'...' Several short cross-cut levels have been driven to the vein. In one of these Eastwood (1921) described the vein as being up to 1.5 m wide, although, except for the local presence of traces of malachite, he gave no other description.

The courses of the other veins at Red Gill may be traced from small trial workings. The northernmost vein trends north-west–south-east across the junction of Swinburn Gill and Wet Smale Gill. A NNE–SSW-trending vein occurs on the east side of Swinburn Gill.

More details of the known extent of the underground workings at Red Gill may be found in Eastwood (1921), Shaw (1970), and Adams (1988).

Although mine explorers are known to have gained access to parts of the Red Gill workings, none is permanently accessible today and there are no good *in situ* exposures of the mineralization for which the mine is celebrated. The small dumps, mainly derived from workings on the Main or South Vein, provide small but representative examples of this mineralization despite having been the focus of attention for many generations of mineral collectors. The site lies within the area in which mineral collecting is controlled by a permit system administered by the Lake District National Park Authority.

Although Red Gill has long been famous for fine specimens of a number of colourful supergene species, it is perhaps best known for magnificent crystals of linarite which occur within cavities in quartz-sulphide veinstone (e.g. Greg and Lettsom, 1858; Hessenberg, 1864a,b). Cooper and Stanley (1990) described and figured beautiful examples of thick deep-blue crystals up to 25 mm long, and commented that these were probably the finest examples of the species known when they were collected in the 19th century. Red Gill is also noted for superb specimens of leadhillite and caledonite, commonly found in association with linarite. Cooper and Stanley (1990) described and figured fine examples of these species and, in addition, provided a comprehensive list of the minerals recorded from this mine.

It is interesting to note that despite the long history of mineral collecting from this site, and thus the considerable depletion of the available amount of mineralogically interesting veinstone, significant finds of minerals hitherto unrecorded from this locality continue to be reported. These include macphersonite and mattheddleite (Cooper, M.P. *et al.*, 1988; Wirth, 1989), two species previously known only from Leadhills, Strathclyde Region, and a few very small specimens of native silver, of supergene origin (Wirth, 1989). Red Gill Mine has provided the first British occurrence of the rare lead-zinc sulphate silicate mineral queitite (Braithwaite *et al.*, 1989) and is the type locality for the recently described mineral redgillite ($Cu_6(OH)_{10}(SO_4).H_2O$) (Pluth *et al.*, 2005).

Ryback *et al.* (2001) have demonstrated that the late A.W.G. Kingsbury falsified the localities of numerous rare mineral species, including many from the Lake District, especially in the Caldbeck Fells. Although no conclusive proof has been established of deception relating to specimens from this site, great care should be exercised when considering claims by Kingsbury which have not been substantiated or duplicated by subsequent collectors.

Interpretation

Red Gill Mine worked deposits typical of the lead- and copper-bearing veins of the Caldbeck Fells. The veins at Red Gill exhibit a complex primary mineralogy like those of other Caldbeck Fells mines including Roughtongill (see **Roughtongill Mine** GCR site report, this chapter). The importance of the site, however, lies in the abundance of supergene minerals, principally lead and copper sulphates, carbonates and phosphates, formed within the upper, oxidized zone of these deposits. The date of this supergene alteration is unclear but clearly results from a prolonged circulation of oxygen-rich groundwaters within the veins. Stanley and Vaughan (1982a) have proposed a Jurassic age for at least some of the supergene alteration of the Caldbeck Fells veins. The great wealth of species here no doubt results, in part, from the varied chemistry of the primary mineralogy as well as from the input of elements, perhaps most notably phosphorus, from the leaching of the locally much-altered igneous wall-rocks (Cooper and Stanley, 1990). The supergene assemblage at Red Gill, like that of Roughtongill, has much in common with that known from some of the deposits of the ***Leadhills–Wanlockhead*** GCR site mining area in southern Scotland, where similarly complex primary assemblages have been subjected to intense supergene alteration.

Conclusions

Red Gill Mine has long been known as a rich source of a great variety of lead- and copper-bearing supergene minerals. Many of these have been found as superbly crystallized specimens, and spectacular examples are prominent in many of the world's major mineralogical collections. Whereas no significant mineralization is permanently exposed *in situ* at the site, and although the relatively small dumps have suffered intensive collecting over many years, they still contain small representative examples of supergene veinstone. Interesting and important finds of rare minerals are still, from time to time, reported from the site, which is also important as the type locality for the hydrated copper sulphate, redgillite.

ROUGHTONGILL MINE, CUMBRIA (NY 304 344)

Introduction

Roughtongill Mine is one of the largest abandoned mines in the Caldbeck Fells, in the northern part of the Lake District. Included in the site to be described are the nearby much smaller mines of Silver Gill and Mexico. Together these mines have yielded copper, lead and zinc ores with some barite and 'umber', an ill-defined soft earthy mixture of iron and manganese oxides.

Like most mines on the Caldbeck Fells, those at Roughtongill have enjoyed a long history of exploration and production. The most comprehensive accounts of the history of mining here are those by Shaw (1970), and Cooper and Stanley (1990). Shaw (1970) suggested that working here may date from the 12th century. There are fine examples of ancient hand-cut 'coffin levels' in the higher parts of the mine and traces of old smelting hearths are known (Postlethwaite, 1913). The mines were worked vigorously by the Elizabethans, and according to Cooper and Stanley (1990) Roughtongill may have been the principal Elizabethan working on the Caldbeck Fells. Little more is known of the mines until the beginning of the 18th century when working is recorded in the Silver Gill area. Mining continued intermittently throughout the 18th and 19th centuries, with copper, lead and in later years some zinc ores being raised. Some of the lead ore is reputed to have been notably argentiferous, although reliable figures for silver content are not available. During the latter part of the 19th century the mine raised barite and 'umber'. Complete production figures are not available for the various minerals worked commercially from Roughtongill, although Eastwood quoted figures for 19th century outputs of copper, lead and zinc ores.

The chief interest of Roughtongill lies in the great wealth of supergene minerals found in the veins. Magnificent specimens of many of these, mostly obtained while the mine was working, are prominent in major mineralogical collections. Despite the attentions of mineral collectors for almost a century, the extensive dumps still contain appreciable quantities of most of the species for which the site has long been famous. The site lies within the area in which mineral collecting is controlled by a permit system administered by the Lake District National Park Authority.

Description

The surface geology and pattern of veins is shown in Figure 2.17. Most published descriptions of the Roughtongill mines (e.g. Postlethwaite, 1913; Eastwood, 1921; Dewey and Eastwood, 1925; Cooper and Stanley, 1990) refer to two principal, generally NE–SW-trending, veins. Shaw (1970), and Adams (1988) noted the presence of at least two other veins, and recent detailed mapping by the British Geological Survey has revealed a more complex structure than hitherto supposed, with at least four roughly parallel mineralized veins (Figure 2.17). The veins occupy substantial faults which juxtapose rocks of the Ordovician Eycott Volcanic Group against a variety of intrusive rocks of the Carrock Fell Intrusive Complex and, in the extreme west, rocks of the Skiddaw Group. No good plan is known of the underground workings at Roughtongill. However, from limited contemporary records and observations made whilst parts of the workings were still accessible, Eastwood (1921), and Shaw (1970) commented on the relationship of the wall-rock lithology to the productivity of the veins. The veins were worked from a number of cross-cut adits. Whereas some of these today remain accessible in part, none gives access to any vein sections. Surface exposures of the veins can be seen locally.

Eastwood (1921) reported that the veins at Roughtongill are typically filled with broken country rock together with abundant quartz and chalcedony. Calcite and barite are also locally common. The main sulphide ores are, in order of abundance, galena, chalcopyrite and sphalerite. Supergene minerals are especially abundant, and pyromorphite, cerussite and malachite are thought to have been worked commercially.

The most extensive workings appear to have been in the Roughtongill South Vein. According to Shaw (1970) the best orebody occurred where granophyre, recognized by the most recent British Geological Survey mapping as the 'Iron Crag Microgranite', formed the footwall, with gabbro on the hangingwall. Eastwood (1921) recorded that in places the vein reached up to 9 m in width in an area known as the 'Great Bunch', in which copper and lead ores

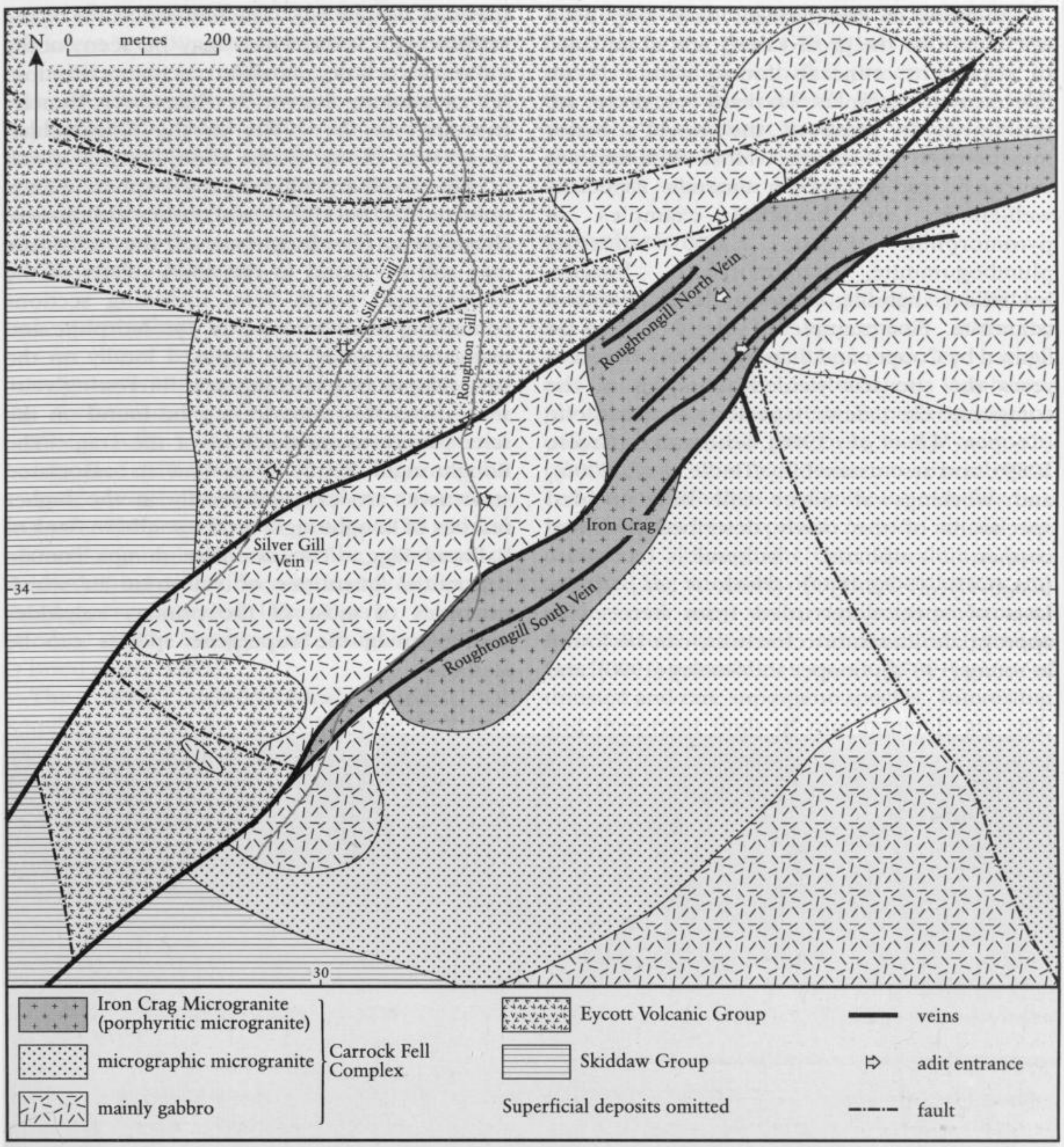

Figure 2.17 Geological sketch map of Roughtongill Mine.

occurred in a predominantly calcite gangue. Eastwood (1921) noted that the galena in this part of the vein had a relatively low (> 10 oz of silver per ton of lead) silver content. Elsewhere in the workings this vein carried large quantities of pyromorphite, malachite and cerussite.

Eastwood (1921) commented that the Roughtongill North Vein resembles the Roughtongill South Vein in its composition, although noted that veinstone on the dumps near the foot of Silver Gill suggests that galena and sphalerite may have been rather more abundant. Previous authors, including Eastwood (1921), and Cooper and Stanley (1990), have regarded Roughtongill North Vein as the eastward continuation of the Silvergill Vein, worked at the head of Silvergill. The Silvergill Vein is known to have carried substantial amounts of argentiferous galena and appears to have been exhausted by about 1700 (Cooper and Stanley, 1990).

The veins at Roughtongill have long been celebrated for the great variety and abundance of supergene minerals found within them. Spectacular examples of many of these are prominent in most of the world's major mineralogical collections. Most abundant are supergene lead and copper minerals. Especially well-known are beautiful examples of pyromorphite (Figure 2.18), mimetite, plumbogummite, hemimorphite, linarite, leadhillite, anglesite, cerussite, brochantite and tsumebite. Fine examples of several of these are figured by Cooper and Stanley (1990). In recent years the site has yielded examples of the comparatively new species matthedleite (Cooper, M.P. *et al.*, 1988), scotlandite (Green, 1989), and arsentsumebite (Tindle *et al.*, 2006), and workings at Silver Gill have yielded specimens of the newly described hydrated copper sulphate mineral redgillite ($Cu_6(OH)_{10}(SO_4).H_2O$) (Pluth *et al.*, 2005). Lists of species recorded from here, with appropriate literature references, can be found in Young (1987a), Cooper and Stanley (1990), and Green *et al.* (2005a). The few exposures of the Roughtongill veins which may be seen locally today carry little metalliferous mineralization. An excavation, known as 'Barstow's Trench', excavated in the 1990s on the Roughtongill South Vein above Mexico Mine, exposed a rich pocket of well-crystallized pyromorphite. This is now mostly backfilled and rather overgrown, although a few fragments of the veinstone may still be found in the spoil. Parts of the Roughtongill South Vein, including sections containing small amounts of pyromorphite and manganese oxides, are exposed locally on the steep slopes of Iron Crag, and interesting veinstone from this outcrop may be found on the scree slopes along the foot of the crag. The Roughtongill South Vein, and its associated structures, are exposed locally in the higher reaches of Roughtongill on the southern flank of Balliway Rigg. The extensive dumps contain substantial quantities of veinstone in which examples of most of the primary sulphides and many of the supergene species can be studied.

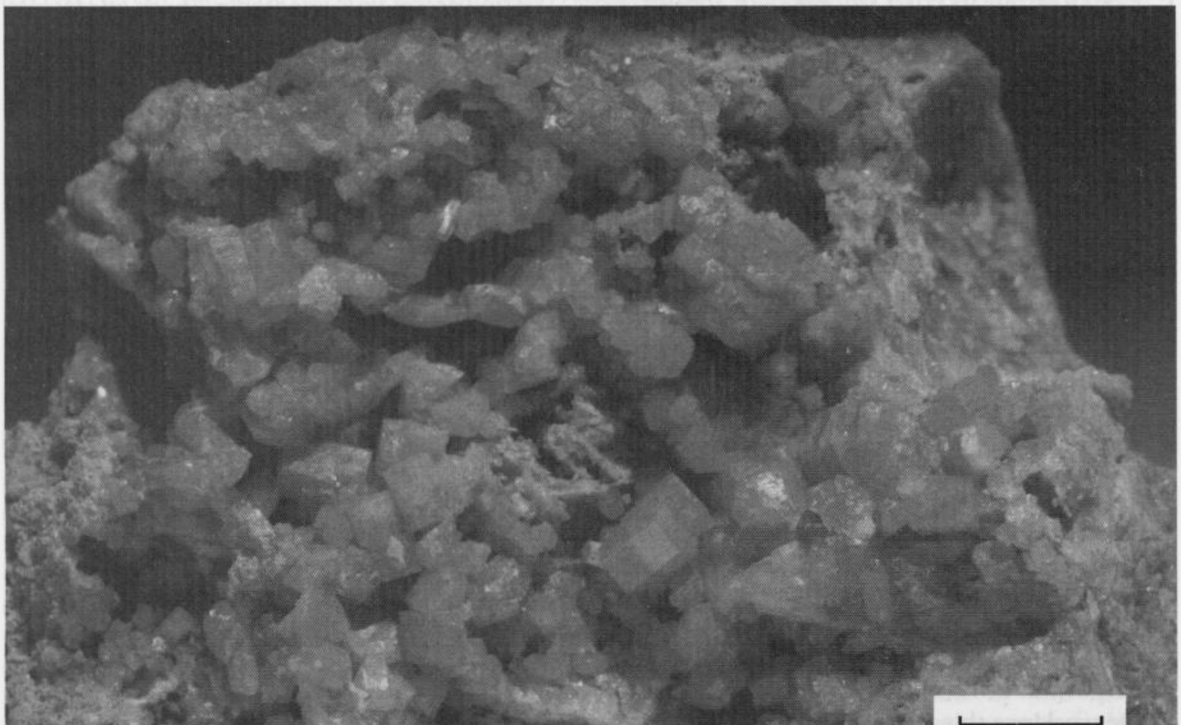

Figure 2.18 Specimen of hexagonal prisms of pyromorphite from 'Barstow's Trench' at Roughtongill Mine. The scale bar is 10 mm. (Photo: T. Bain, BGS No. MNS 4480, reproduced by permission of the British Geological Survey, © NERC. All rights reserved. IPR/116-33CY.)

Ryback *et al.* (2001) have demonstrated that the late A.W.G. Kingsbury falsified the localities of numerous rare mineral species, including many from the Lake District, especially in the Caldbeck Fells. Although no conclusive proof has been established of deception relating to specimens from this site, great care should be exercised when considering claims by Kingsbury which have not been substantiated or duplicated by subsequent collectors.

Interpretation

Roughtongill Mine worked deposits typical of the lead- and copper-bearing veins of the Caldbeck Fells. Like the veins worked at the nearby **Red Gill Mine** GCR site, these exhibit a comparatively complex primary mineralogy and are likely to be the products of several mineralizing episodes, each the products of 'hydrothermal cells' driven by heat flow through the largely concealed Lake District Batholith (Moore, 1982; Stanley and Vaughan, 1982a; O'Brien *et al.*, 1985).

The main mineralogical interest at Roughtongill, like the **Red Gill Mine** GCR site, lies in the great wealth of supergene minerals. Most prominent are carbonates, sulphates and phosphates of lead and copper. Zinc minerals, notably sphalerite and the supergene species smithsonite and hemimorphite, are conspicuous at Roughtongill. The abundance of arsenates in the Roughtongill deposits contrasts markedly with their scarcity at the **Red Gill Mine** GCR site. Their abundance here may be due to the presence of early Devonian mineralization which, elsewhere in the Lake District, is characterized by an abundance of arsenic. The great variety of supergene species no doubt reflects the very varied chemistry of both the primary mineralization and the wall-rocks (Cooper and Stanley, 1990). Whereas supergene alteration at Roughtongill has obviously been intense, the inaccessibility of the vein workings precludes any study of supergene mineralization *in situ*. It is therefore difficult or impossible to suggest the extent or depth of this alteration within the veins. The date of this alteration is unknown, although clearly it reflects a prolonged period of circulation of oxygen-rich ground-waters within the upper parts of the veins. Stanley and Vaughan (1982a) have suggested a Jurassic age for at least some of the supergene alteration of the Caldbeck Fells veins.

The supergene assemblage at Roughtongill, like that at the **Red Gill Mine** GCR site, has much in common with that present in some of the deposits of the *Leadhills–Wanlockhead* GCR site area, in southern Scotland, where similarly complex primary assemblages have been subject to intense supergene alteration.

Conclusions

Roughtongill Mine has long been famous for a great variety of supergene minerals, conspicuous amongst which are lead-, zinc- and copper-bearing carbonates, sulphates, phosphates and arsenates. Superb specimens collected from this site over many years are prominent in most major museum mineralogical collections. Whereas no significant metalliferous mineralization is exposed *in situ* at the site today, and although the extensive dumps have attracted the attention of mineral collectors and dealers over many years, significant amounts of mineralized veinstone remain and provide excellent opportunities to study a variety of unusual and rare supergene species. Interesting and important finds of rare minerals are still, from time to time, reported from the site.

DRY GILL MINE, CUMBRIA (NY 323 346)

Introduction

An E–W-trending vein exposed in the bed and north bank of Dry Gill, a tributary of the Carrock Beck, has been worked opencast and underground at Dry Gill Mine. The mine is of particular mineralogical interest for the abundance of the lead arsenate mineral mimetite, much of which occurs in the distinctive form known as 'campylite' (Figure 2.19).

Unlike many of the mines on the Caldbeck Fells the workings at Dry Gill appear to date only from the middle of the 19th century. Cooper and Stanley (1990) recorded that although the site is known to have been yielding fine specimens of mimetite as early as 1830, the first recorded mining dates from 1846. Subsequently the mine was worked in a small way by a number of operators but was abandoned in 1869. The mine is almost certainly unique in having been worked for mimetite, known by the miners as 'coloured lead ore'. Although several hundred

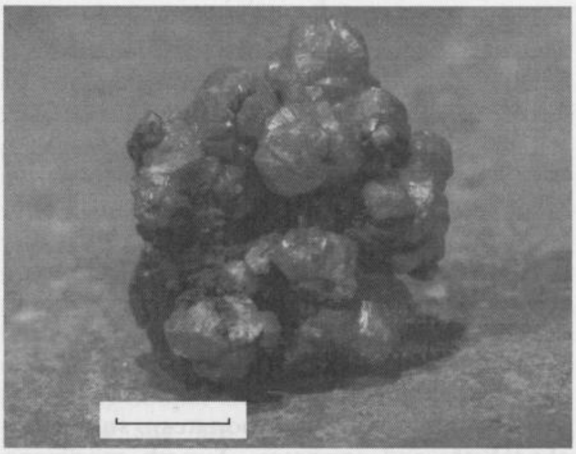

Figure 2.19 Specimen of rounded crystals of 'campylite' at Dry Gill Mine. The scale bar is 10 mm. (Photo: T. Bain, BGS No. MNS 4492, reproduced by permission of the British Geological Survey, © NERC. All rights reserved. IPR/116-33CY.)

tons of this were sold to the glass-making industry (Ellis, 1851) the mine was never a commercial success.

Dry Gill Mine has long attracted geological interest. The site occupies a structurally complex area in which an inlier of Upper Ordovician mudstones, referred to as the 'Drygill Shales', is preserved between outcrops of the Ordovician Eycott Volcanic Group and parts of the Carrock Fell Intrusive Complex (Ward, 1876a,b; Nicholson and Marr, 1877; Marr, 1892, 1900; Elles and Wood, 1895; Green, 1917; Eastwood *et al.*, 1968). Dry Gill Vein is of considerable interest for the abundance within it of mimetite and other supergene minerals. Descriptions of the mine and minerals include those by Eastwood (1921), Eastwood *et al.* (1968), Shaw (1970), Young (1987a), Adams (1988), and Cooper and Stanley (1990).

The site lies within the area in which mineral collecting is controlled by a permit system administered by the Lake District National Park Authority.

Description

The Dry Gill Vein occupies a major E–W-trending fault which separates the Upper Ordovician Drygill Shales on the south from the Ordovician Eycott Volcanic Group to the north. The structure of the Dry Gill area is complex, and the Dry Gill Vein is offset by several N–S-trending faults, at least one of which is a northward continuation from the fault system occupied by the veins of Carrock Fell Mine to the south.

In the vicinity of Dry Gill Mine, the Dry Gill Vein comprises a quartz vein up to 1.5 m wide, hading north at between 10° and 15°, which crops out as a conspicuous ridge along the northern bank of the stream (Figure 2.20). It has been worked both opencast and from short levels driven from the stream banks. These levels are today in a generally dangerous and locally water-logged condition although until recently they were frequently entered by mineral collectors and dealers.

Much of the quartz at Dry Gill is massive, although well-formed pyramidal crystals are present and, in addition, pseudomorphs and epimorphs after tabular or 'cockscomb' barite occur. In places the vein contains concentrations of coarsely crystalline white barite.

The Dry Gill Vein is remarkable and best known for the occurrence of the phosphatian variety of mimetite known as 'campylite' which derives its name from the Greek '*Καμπύλος*', meaning 'curved', in allusion to its distinctive rounded crystals. Much of the lead within the Dry Gill Vein is present in this form, and the deposit has been cited as one of the world's most remarkable deposits of this mineral (Cooper and Stanley, 1990). Galena appears to have been scarce (Shaw, 1970). Eastwood's (1921) comment that galena was the main ore worked is almost certainly incorrect. The mine is known to have been worked last century for mimetite or 'coloured lead ore' as it was then known. The mineral was employed in glass-making, not as an ore of lead.

According to Cooper and Stanley (1990) the description of 'arsenate of lead' by Allan (in Phillips, 1837) may be the earliest published reference to Dry Gill 'campylite', although the occurrence was first figured by Kurr (1858). The occurrence of striking crystals of 'campylite' at Dry Gill has subsequently been quoted in most mineralogical text books. Specimens from here are prominent in most of the world's major mineralogical collections. Several very fine examples are figured by Cooper and Stanley (1990). Although the 'campylite' variety is especially common at Dry Gill, mimetite also occurs here in a number of other morphologies, including tabular and short to long prismatic forms. In all of these forms the mineral is usually a pale to dark orange-brown colour,

Figure 2.20 Dry Gill Mine. View eastwards along Dry Gill Vein which here crops out as a prominent quartz-rib on the north side of Dry Gill. (Photo: B. Young.)

although yellow, greenish-yellow and various shades of green are also common. In many specimens colour-zoning of crystals is conspicuous. Crystals of the mineral are usually up to 10 mm across, although examples over 30 mm across are known. Some arsenic-free pyromorphite is also present at Dry Gill, although this mineral cannot be distinguished visually from the more abundant mimetite. Dry Gill Mine is also noted for excellent specimens of plumbogummite (Cooper and Stanley, 1990).

In most exposures of the vein, and in most specimens of veinstone on the dumps, black manganese oxides are common. Whereas much of this material has been described as pyrolusite (Goodchild, 1885) or 'psilomelane' (e.g. Greg and Lettsom, 1858; Goodchild, 1882; Eastwood, 1921), and at least some of this is now known to be romanèchite (Cooper and Stanley, 1990), a considerable amount of the black manganese oxide here has been shown to be the unusual lead manganese oxide mineral coronadite, for which the site was the first British locality (Hartley, 1959).

Full lists of all minerals recorded from Dry Gill have been given by Young (1987a), and Cooper and Stanley (1990).

Ryback *et al*. (2001) have demonstrated that the late A.W.G. Kingsbury falsified the localities of numerous rare mineral species, including many from the Lake District, especially in the Caldbeck Fells. Although no conclusive proof has been established of deception relating to specimens from this site, great care should be exercised when considering claims by Kingsbury which have not been substantiated or duplicated by subsequent collectors.

Interpretation

Lead mineralization within the Dry Gill Vein is almost exclusively in the form of mimetite with smaller amounts of pyromorphite. Galena, although recorded, is scarce in the levels of the vein exposed within the Dry Gill workings. Mimetite and pyromorphite, the two end members of the mimetite-pyromorphite series, are common minerals found in the supergene zones of many lead veins. Their great abundance here, typically in very large and well-formed crystals, and the great scarcity of galena, suggests either that Dry Gill Vein has undergone intense supergene alteration over a greater vertical interval than usual or, as suggested by

Firman (1978a), the mimetite and pyromorphite may be of primary origin. In their classification of Lake District mineralization Stanley and Vaughan (1982a) suggested a Jurassic age for the supergene alteration of the Caldbeck Fells veins. The arsenic and phosphorus necessary for the formation of these minerals may have been derived both from the wall-rocks and from the alteration of arsenic- and phosphorus-bearing primary minerals within the Dry Gill Vein.

Manganese oxide minerals are very common in many of the veins on Caldbeck Fells, including Dry Gill. The abundance of manganese in these deposits may be an expression of the halo of manganese mineralization which Hitchen (1934) suggested surrounded the Carrock Fell tungsten veins.

The variety of minerals recorded from Dry Gill Mine (Young, 1987a; Cooper and Stanley, 1990) clearly includes many whose supergene origin is clear. Supergene processes have thus been important in producing the mineral assemblage seen today at Dry Gill, as well as at many of the mines on the Caldbeck Fells for which Stanley and Vaughan (1982a) have proposed a Jurassic age, at least in part. Whereas the suggestion of a primary origin for the mimetite is an interesting possibility it cannot be established with certainty.

In addition to the abundance of lead arsenates and phosphates, the Dry Gill Vein carries local concentrations of barite. The presence here of pseudomorphs and epimorphs in quartz after barite suggests that this mineral may formally have been more abundant within the vein. Similar evidence for the greater abundance of barite in many of the lead-bearing veins of the Caldbeck Fells suggests the widespread removal of this mineral and its replacement by quartz, although evidence for the timing of this process is not available.

Conclusions

The remaining exposures of the vein at Dry Gill, combined with an abundance of veinstone within the spoil heaps, provides a unique opportunity to study a vein in which the lead mineralization is mainly in the form of arsenates and phosphates. The abundance of these minerals, normally regarded as typical of supergene alteration, may at least in part here be a result of primary precipitation. The site also contains a variety of other unusual minerals of typical supergene origin. The site has great research and educational value. Despite being the focus of intense collecting activity over more than a century the vein exposures and remaining dumps at Dry Gill Mine remain an important source of specimens of the unique variety of mimetite known as 'campylite'.

EAGLE CRAG, CUMBRIA (NY 357 142)

Introduction

The workings of Eagle Crag lead mine extend over a vertical interval of about 300 m on the steep E-facing cliffs of Eagle Crag, at the head of Grisedale. The vein, which strikes almost due east–west through rocks of the Ordovician Borrowdale Volcanic Group, forms a prominent narrow gully easily traceable across the face of the crags.

According to Shaw (1970) the earliest workings here are probably very ancient. However, the workings seen today almost certainly all date from the 19th century, with the last mining taking place in 1877. No contemporary plans or section are known, although investigations of the workings by mine explorers indicate that the workings are extensive. Descriptions of the workings and the history of the mine are given by Postlethwaite (1913), and Shaw (1970). Adams (1988) made brief reference to workings on the Eagle Crag and nearby veins.

In addition to the comments on the geology and mineralization in the references already noted, Eastwood (1921) provided a short summary of the mine's geology.

Description

Eagle Crag Vein occupies an E–W-trending fault of very small displacement which cuts lapilli tuffs of the Helvellyn Tuff Member of the Ordovician Borrowdale Volcanic Group. The vein hades southwards at a small angle. Shaw (1970) recorded that throughout the workings it was generally narrow, rarely exceeding 0.45 m in width, and composed mainly of broken country rock together with 'open, crumbly quartz'. A little 'cockscomb' barite is locally present

(Young, 1987a). The principal ore mineral, and the only one known to have been worked, is galena. Shaw (1970) commented that this typically occurred as a rib on one of the walls, although gives no indication of which wall. Other minerals within the vein include brown sphalerite, some tetrahedrite and small amounts of chalcopyrite. Tetrahedrite is comparatively conspicuous in the Eagle Crag Vein, and also in some of the nearby associated veins. Whereas Stanley and Vaughan (1981) showed that this mineral, together with bournonite and native antimony, is common in most of the lead-zinc veins of the Lake District, they are usually present as minute, microscopic inclusions within galena. At Eagle Crag tetrahedrite is common as massive or crystalline masses up to 5 mm across. Locally vugs within quartz veinstone contain beautifully developed tetrahedral crystals of this mineral up to 3 mm across. Stanley (1979) noted that the tetrahedrite has a silver content of about 1 wt% Ag. Shaw (1970) recorded that the galena recovered from the mine carried about 16 oz of silver per ton of lead.

The course of the vein across the face of Eagle Crag is conspicuous as an almost continuous line of surface workings in which small sections of quartz-rich veinstone can be seen locally. The vein has also been worked extensively underground from a number of levels driven directly upon it. Some of these have been investigated by mine explorers. Shaw (1970) gives a summary of some of these explorations. Representative samples of veinstone are abundant on the spoil heaps from all of these workings.

Geological mapping reveals that the Eagle Crag Vein is terminated immediately east of Grisedale Beck by a NE–SW-trending fault. Attempts to find an easterly extension of the vein on the lower slopes of St Sunday Crag appear to have been unsuccessful.

Supergene alteration has produced small amounts of hemimorphite, aurichalcite and hydrozincite. Good specimens of the latter mineral, of post-mining origin, were described from parts of the underground workings by Davidson and Thomson (1948).

In Cove Beck, about 250 m north of the main Eagle Crag workings, the spoil from a small trial level driven on an ENE–WSW-trending branch of Eagle Crag Vein shows small quantities of tetrahedrite-bearing veinstone, similar to that from the Eagle Crag workings.

Small workings from a roughly parallel vein about 700 m south of the Eagle Crag workings also contain tetrahedrite-rich veinstone and have, in addition, yielded small specimens of pyromorphite and wulfenite (Young, 1986).

Interpretation

Veins in which lead and zinc minerals are the major metalliferous constituents form an important suite of deposits within the Lake District. Within these veins, galena and sphalerite are typically the most abundant ores, accompanied locally by minor amounts of chalcopyrite. Typical gangue minerals in this suite of veins include quartz and locally barite. The Eagle Crag Vein is an example of this suite of Lake District lead-zinc veins.

Stanley and Vaughan (1982a) noted that the lead-zinc veins occur above the roof region and both the north and south walls of the mainly concealed Lake District Batholith, although with no well-defined relationship to known features of the batholith. K-Ar dating suggests that they may be of Lower Carboniferous age (330–360 Ma) (Ineson and Mitchell, 1974; Stanley and Vaughan, 1982a). Lowry *et al.* (1991) have suggested that these veins formed at temperatures of between 110°C and 130°C from highly saline brines. Metals may have been derived from rocks of the Skiddaw Group, as well as from basement granites, perhaps in part involving convective leaching by Carboniferous seawater.

Similarities between the lead-zinc veins of the Lake District with those of the Northern Pennines have been made by Vaughan and Ixer (1980), and Stanley and Vaughan (1982a), although the latter authors have also highlighted striking similarities in both mineralogy and age with the mineralization in the Carboniferous limestones of central Ireland.

Conclusions

Eagle Crag provides perhaps the finest opportunity to study a vein typical of the Lake District suite of lead-zinc veins. Although examples of mineralization *in situ* are limited to a very small number of surface outcrops and sections accessible underground, the site contains abundant spoil representative of this important group of deposits.

FLORENCE MINE, CUMBRIA (NY 018 102)

Introduction

The underground workings of Florence Mine, the last surviving working hematite mine in Cumbria, provided a unique opportunity to study hematite mineralization *in situ* in a large replacement orebody within Lower Carboniferous (Dinantian) limestones. At the time of editing this description (March 2007) it is understood that pumping of mine water will very soon be stopped. The underground workings are then expected to flood rapidly and become permanently inaccessible. The following section is retained here as a historical description and interpretation of this important site.

The earliest records of hematite iron ore mining in west Cumbria date from the 12th century, and mining is known to have been active here in the 17th and 18th centuries. However, it was the 19th century that was to witness the large-scale mining of these deposits. The abundance of high-grade hematite ore, together with the availability of local coal, provided the basis for the west Cumbrian iron and steel industry, which was to flourish well into the 20th century. Historical reviews of the industry include those by Daysh and Watson (1951), Hewer and McFadzean (1992), and Kelly (1994).

Sinking of the Florence Mine began in 1914 and production started in the early 1920s. In order to secure further ore reserves, the present, No. 2 Shaft (Figure 2.21) was sunk in the 1940s, a short distance north of the original, No. 1 Shaft. Later connections were made with the neighbouring Ullcoats and Beckermet mines. During this time Florence Mine made a significant contribution to the estimated output of around 250 million tons of hematite from the combined west and south Cumbrian iron ore-fields. In the late 1970s the deep workings in the enormous Florence–Ullcoats orebody were abandoned. Until early in 2007 very small-scale production of hematite was maintained from a shallow orebody accessed from the Florence No. 2 Shaft. Hematite from the most recent workings of the mine was employed in specialized steel-making as well as in the pigment industry.

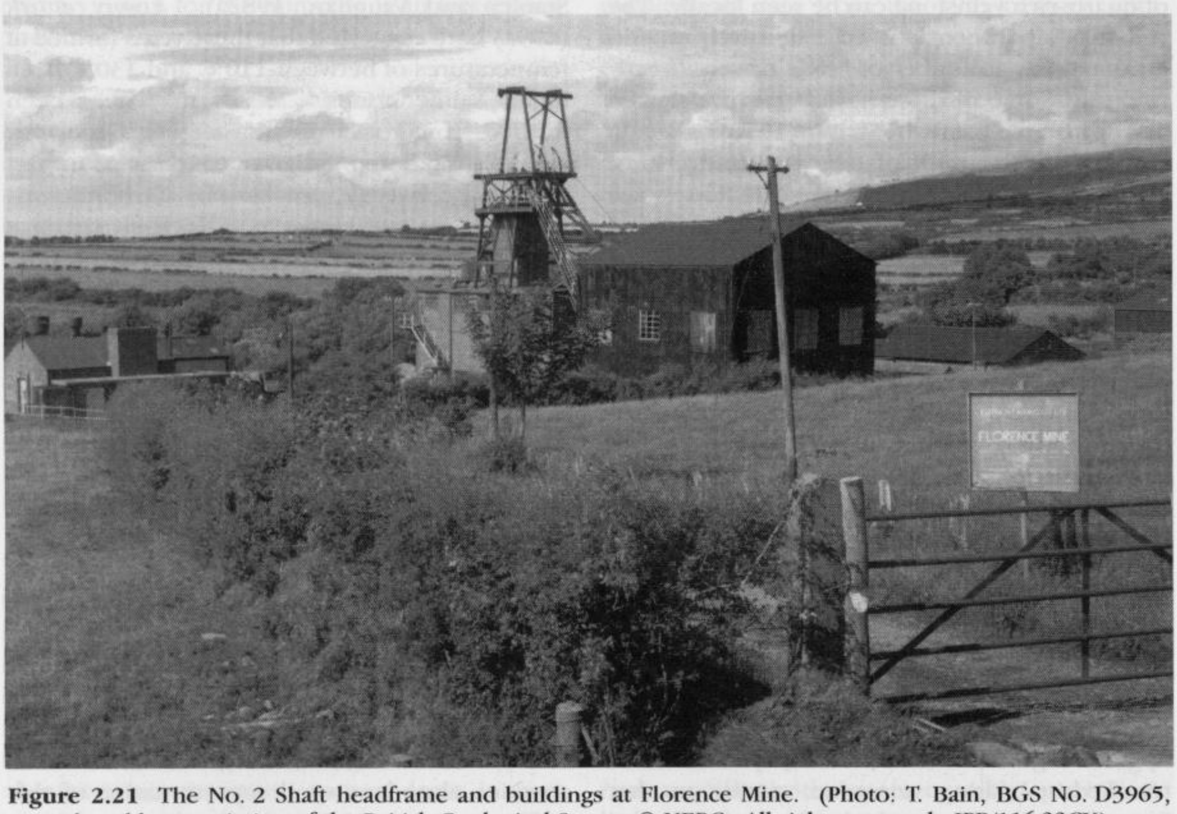

Figure 2.21 The No. 2 Shaft headframe and buildings at Florence Mine. (Photo: T. Bain, BGS No. D3965, reproduced by permission of the British Geological Survey, © NERC. All rights reserved. IPR/116-33CY.)

Description

The west Cumbrian hematite orefield may be considered in two parts. Limestones of the Lower Carboniferous Chief Limestone Group, which crop out in a narrow belt for about 10 km north-east of Egremont, contain numerous large orebodies, many of which reach rockhead. From Egremont south towards Calder Bridge the limestones and their contained orebodies are concealed beneath Permo–Triassic rocks. The most recent workings, including those at Florence Mine, lie within this concealed southern portion of the orefield.

Florence Mine was one of a number of mines in the Egremont area which worked the Florence–Ullcoats orebody. This extensive replacement body of hematite occurs within the lower part of the Lower Carboniferous Limestone (Dinantian) sequence within a graben between the roughly WNW–ESE-trending Ullcoats and Florence faults. The stratigraphical position of the limestone here is uncertain but appears to lie mainly within the Sixth and Seventh limestones (Smith, 1924). The limestones rest unconformably upon mudstones of the Ordovician Skiddaw Group. The limestones, and in places the hematite orebodies, are in faulted contact with Skiddaw Group rocks. Within the neighbourhood of the mine the limestones are everywhere concealed beneath Permo–Triassic rocks. These comprise a group of breccias, known locally as 'Brockram', around 70 m thick and overlain by red sandstones belonging to the St Bees Sandstone Formation, the local representative of the Triassic Sherwood Sandstone Group.

Workings in the main part of the Florence–Ullcoats orebody, and in other associated large orebodies, are now largely worked out and inaccessible in flooded deep sections of the mine. The currently accessible Florence Mine workings are within a higher portion of the orebody, known as the 'Lonely Hearts Orebody', which lies near the Ullcoats Fault between the original Florence workings and those of Ullcoats Mine to the east. Most of the important features which characterize west Cumbrian replacement hematite orebodies may be seen within the present workings. Young (2007) has compiled a detailed description of the geological and mineralogical features exposed in the accessible underground workings immediately prior to the mine's closure.

The deposits are typically wholesale replacements of limestone, commonly closely associated with, or adjacent to, faults. Original features of the limestone, including some fossils, bedding planes and locally stylolitic contacts, are commonly preserved in hematite. Thin mudstone partings within the original limestone may in places be traced through the ore. Hematite is present in a variety of forms. Compact massive hematite is most common. Within this, cavities or vugs, known by the miners as 'lough holes', are very common. Whereas the great majority of these are less than 5 cm in diameter, larger examples are sometimes encountered. They are typically lined with small tabular crystals of specular hematite, usually accompanied by bipyramidal crystals of quartz. Much of the quartz is colourless but striking specimens of deep-brown 'smoky quartz' were formerly common. More rarely quartz crystals of a distinctive deep-red colour due to included finely divided hematite, and known to miners as 'eisenkiesel' or 'tomato quartz', have been found. In many vugs a thin layer of the distinctive fibrous crystalline mammillated variety of hematite, well-known locally as 'kidney ore', separates the massive ore from the lining of specular crystals. More commonly 'kidney ore' occurs as bands and pockets within the orebody (Figure 2.22). West Cumbria has

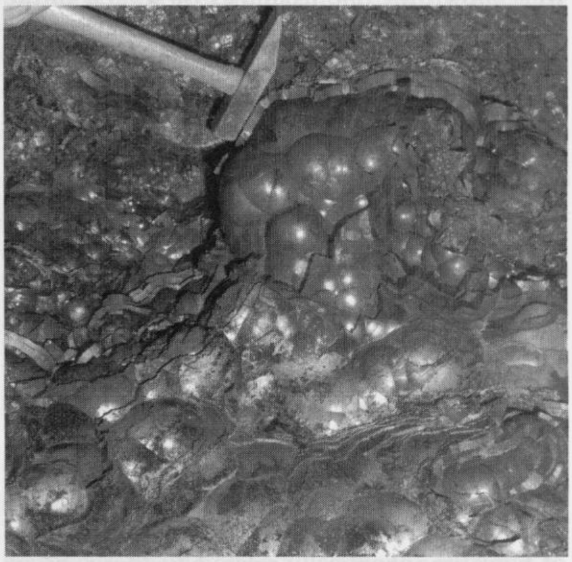

Figure 2.22 Large mass of 'kidney ore' exposed *in situ* in the underground workings at Florence Mine. (Photo: T. Bain, BGS No. D3974, reproduced by permission of the British Geological Survey, © NERC. All rights reserved. IPR/116-33CY.)

long been celebrated as a source of specimens of this form of the mineral, spectacular examples of which are to be found in most of the world's major mineralogical collections. Florence Mine was one of the more famous sources of such specimens, and good examples were common in parts of the most recent workings. 'Kidney ore' typically breaks into roughly conical fragments parallel to the fibrous crystals. These fragments are known locally as 'pencil ore'. When of sufficiently fine grain they can be employed in making hematite jewellery. Other minerals commonly found in vugs in the Florence orebody include fluorite as colourless or pale-blue cubes. Although good small examples of this mineral were fairly common within the recent workings they did not compare with the beautiful sky-blue cubes, sometimes up to several centimetres across, formerly recovered from the deeper workings of the Florence and Ullcoats mines. Fine examples are prominent in many important mineralogical collections. Curved rhombic crystals of creamish-white dolomite, calcite in a variety of habits, and locally a little aragonite also occur in vugs, but these minerals, together with white to pale-pink platy barite crystals are more common in veins and vugs towards the margins of the orebody close to the host limestone.

Whereas Florence Mine, along with a number of now-abandoned Cumbrian hematite mines, is well known for fine examples of several of the gangue minerals, it should be noted that they form only a very small proportion of the orebodies, the overwhelming proportion of which is composed of hematite. Rare traces of a number of sulphides, including pyrite, chalcopyrite, marcasite and galena, together with manganese oxides including manganite and hausmannite, have been found in many of these deposits, although they appear to be rare or absent from the most recent Florence Mine workings.

Interpretation

The hematite deposits of Cumbria occur as large irregular replacements of Lower Carboniferous limestones on the western and southern fringes of the Lake District. Much smaller fissure-veins of hematite, genetically related to these, occur within the Lower Palaeozoic rocks of the Lake District. The Nab Gill deposits within the Eskdale Granite are an example (see **Nab Gill Mine** GCR site report, this chapter).

The origin of the Cumbrian hematite deposits has long been the subject of much speculation and controversy. The most comprehensive description of the deposits is that by Smith (1924). Rose and Dunham (1977), and Shepherd and Goldring (1993) have presented a review of the deposits and their likely origin. The brief summary presented here applies to the formation of both the replacement deposits within the Lower Carboniferous limestones and the vein deposits in the Lower Palaeozoic rocks such as those at the **Nab Gill Mine** (see GCR site report, this chapter).

Early views centred on two different sources of iron-rich fluids. Kendall (1873–1875) suggested a deep-seated magmatic or hydrothermal source, whereas Goodchild (1889–1890) advocated the leaching of iron by meteoric groundwaters from overlying iron-rich rocks such as the St Bees Sandstone Formation. More recently, Shepherd and Goldring (1993) suggested that brines expelled from overpressurized sediments in the East Irish Sea Basin were driven towards the Lake District Batholith. There they leached iron from the granites before being driven upwards through fractures along the western margin of the Lake District. Rose and Dunham (1977) proposed a model whereby iron, leached by warm hypersaline fluids from the Permo–Triassic sediments of the East Irish sea Basin, were forced up-dip towards the margins of the Lake District.

Both models are consistent with the iron-rich mineralizing fluids gaining access to the limestones and Lower Palaeozoic rocks of the Lake District through fractures as well as through permeable formations within the Permo–Triassic sequence. The role of the permeable Permo–Triassic rocks is of crucial importance in this mineralizing process. In west Cumbria, where these rocks rest directly on Dinantian limestone, orebodies are commonly present; but where thick impermeable shales of Namurian, Westphalian or Upper Permian age intervene between the permeable Permo–Triassic rocks and the limestones, no orebodies are found. Young (in Jones *et al.*, 1990) has speculated that certain Coal Measures sandstones, the interstices of which contain concentrations of specular hematite, may have acted as mineralizing aquifers in suitable structural settings. Over much, if not all, of the Lake District the Permo–Triassic sequence is likely to have begun with a variable thickness of breccias or 'brockrams', which were succeeded by sandstone of the Sherwood Sandstone Group. A permeable route for mineralizing fluids is thus likely to have been present over much of the area.

Shepherd and Goldring (1993) concluded that the hematite mineralization is the result of the mixing of sulphatic groundwaters with warm, iron-rich, relatively oxidizing sulphur-poor, hypersaline brines. They advocate a downward flow of mineralizing fluids to account for the distribution of orebodies within the limestones of west and south Cumbria. However, the occurrence of hematite veins within the Lower Palaeozoic rocks of the Lake District, and the distribution patterns for arsenic, barium and fluorine within these deposits, suggests some upward flow of mineralizing fluids. They favour a sedimentary source for the iron. Fluid-inclusion data for quartz, fluorite and calcite within the replacement deposits in the limestones indicate formation temperatures of up to 120°C.

The age of the hematite mineralization has also been disputed for many years. Shepherd (1973) favoured a middle or late Triassic age, whereas Dunham (1984) argued that the structural and stratigraphical relationships require a post-Triassic age. Using palaeomagnetic results a number of authors have proposed a Permian or early Triassic age (DuBois, 1962; Evans and El-Nikhely, 1982; Evans, 1986). In a recent palaeomagnetic study Rowe *et al*. (1998) suggested that hematite mineralization was emplaced during late Carboniferous and early Permian times, although this is difficult to reconcile with the stratigraphical and structural evidence.

Conclusions

The underground workings of Florence Mine provided a unique opportunity to study a replacement orebody of hematite in the Lower Carboniferous limestone within its mineralogical, structural and stratigraphical context.

NAB GILL MINE, CUMBRIA (NY 173 014)

Introduction

Nab Gill Mine, near the village of Boot in Eskdale, provides the finest exposures of hematite veins within the Lower Palaeozoic rocks of the Lake District. The veins at Nab Gill lie within the Eskdale Granite.

Nab Gill Mine is the largest of a number of mines which worked hematite from vein deposits within the Eskdale Granite. Whereas small-scale workings for hematite from these deposits probably took place several centuries ago, the first known workings at Nab Gill were those made in the early 19th century. Although early trials were unsuccessful and were soon abandoned, the increasing demand for domestic supplies of iron ore brought about by the Franco–Prussian war renewed commercial interest in the mines in 1871. Over the next few years substantial quantities of ore were extracted, although mining came to an end in 1882. Although some attempts were subsequently made to resume production, none was successful and all mining and exploration finally ended at Nab Gill in 1917. The hematite deposits of Nab Gill Mine, and the prospects of further deposits in the Boot area, led to the construction of the original Ravenglass and Eskdale Railway, to carry ore from the mines to the main railway at Ravenglass. The history of mining at Nab Gill has been outlined by Davies (1968), and Young (1984).

Description

The main Nab Gill Vein occupies a NNW–SSE-trending fault which cuts and displaces outcrops of granite and microgranite on the steep hillside north of Boot village (Figure 2.23). The fault downthrows to the east and hades in this direction at up to 25°. The stream known as 'Nab Gill' has been eroded along the course of the vein, but this is now largely obscured by subsequent mining activities. Near the hill-top several branches diverge from the main vein which continues to the NNW across White Moss towards Mitredale.

At Nab Gill Mine the vein filling consists of brecciated granite wall-rock and hematite. Payable ore appears to have been concentrated in two orebodies separated by an interval of barren ground (Hibbert *et al*., 1940). Brecciated and hematite-stained granite, presumably representing this barren section of the vein, can be seen in the old opencut above the entrance to the No. 1 Level at NY 1731 0142. Contemporary reports suggest that the vein attained its maximum width near the hill-top where it was up to 6.1 m wide, although this included up to

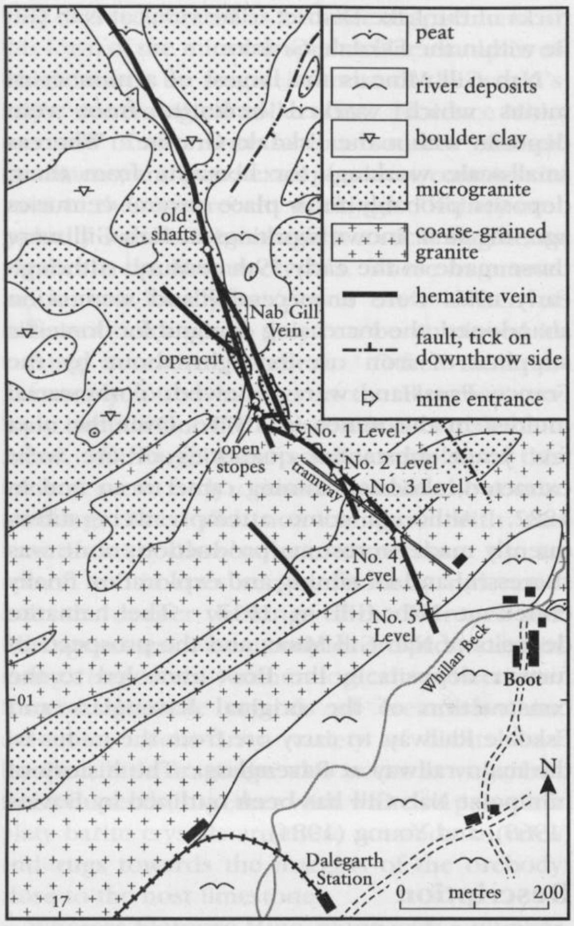

Figure 2.23 Geological sketch map of Nab Gill Mine. After Young (1985b).

3.4 m of granite wall-rock, referred to by the miners as 'horse' or 'rider'. According to Smith (1924) the average width was between 0.76 m and 1.06 m. This is understood to have thinned to as little as 0.15 m in the deepest levels cut immediately prior to the mine's final closure.

Much of the hematite within the vein consisted of 'kidney ore'. A characteristic feature of the Nab Gill ore is its brecciated texture. The most intensely brecciated ore consists of disorientated fragments of 'kidney ore' or 'pencil ore' in a matrix of crushed, rather earthy hematite. Inclusions of unaltered granite are common. Good examples of this type of ore are common on the dumps, especially those from the lowest levels of the mine near the derelict Boot Station. Similar ore may be seen *in situ* locally. 'Kidney ore', forming bands parallel to the vein walls, with the mammillated surfaces facing the centre of the vein, may be seen in the old open stopes near the hill-top.

Massive hematite occurs in small amounts, and Smith (1924) has noted the presence of the uncommon stalactitic variety of hematite known as 'ring ore'.

Other minerals present in minor amounts are quartz, which occurs both massive and as vuggy crystallized masses with turbid white pyramidal crystals up to 5 mm long, and dolomite, present as pale-yellowish coarsely crystalline masses. A little romanèchite occurs locally. Smith (1924) suggested that hematite locally replaces granite, although Young (1985b) found no evidence to support this. Indeed the granite wall-rocks throughout the accessible parts of the workings show little obvious alteration other than some shattering and hematite staining.

Interpretation

The hematite veins found within the Lower Palaeozoic rocks of the Lake District are regarded as part of the much larger province of hematite mineralization emplaced within the Carboniferous rocks of the adjoining areas of west and south Cumbria, of which the **Florence Mine** GCR site, near Egremont, is a fine example (see GCR site report, this chapter). These formerly important iron ore deposits have long been the subject of research. References to this large literature will be found in Smith (1924), Shepherd (1973), Rose and Dunham (1977), Dunham (1984), Young (1985b), and Shepherd and Goldring (1993).

The hematite veins at Nab Gill Mine, like those elsewhere in the Lower Palaeozoic rocks of the Lake District, are distinguished by their almost monomineralic composition. Gangue minerals, including quartz, dolomite and calcite, are typically present in only very minor amounts. The hematite is usually the mammillated fibrous crystalline variety known as 'kidney ore'. The characteristic form of the hematite and the almost monomineralic nature of the veins serves to link them genetically with the very large replacement bodies of hematite in the Dinantian limestones of west and south Cumbria. The origin of these and the related deposits, of which the Nab Gill Vein is an example, are described in the **Florence Mine** GCR site report (this chapter).

Conclusions

The hematite veins at Nab Gill Mine form part of the suite of deposits which include the huge replacement orebodies within the Carboniferous limestones of south and west Cumbria. Nab Gill Mine offers the best exposures of such vein deposits in the area today. The site has very considerable educational and research value.

SEATHWAITE COPPER MINES, CUMBRIA (SD 266 977)

Introduction

This small group of old copper workings is remotely situated in the valley of the Tarn Head Beck, approximately 0.5 km east of the head of Seathwaite Tarn. The workings should not be confused with the old graphite workings in Borrowdale, described in this volume under the **Seathwaite Graphite Mine** GCR site report.

Mineralization at Seathwaite Tarn, which may be regarded as a western extension of the copper mineralization formerly worked at the Bonser and Paddy End mines of the Coniston area, is distinguished by the presence of copper mainly as 'grey sulphide' ores, accompanied by small amounts of wittichenite and rare gold.

Little is know of the history of working, although Adams (1988) noted that the mine lease was forfeited in 1860. No production records survive, although output is likely to have been modest.

Description

According to Dewey and Eastwood (1925), the Borrowdale Volcanic Group rocks in the valley of Tarn Head Beck, east of Seathwaite Tarn, are cut by four roughly E–W-trending copper-bearing veins. More-recent mapping by the British Geological Survey (1998) has revealed that these volcanic rocks here comprise andesitic tuffs belonging to the Whorneyside Formation, and rhyolitic welded tuffs of the Oxendale Tuff at the base of the overlying Airy's Bridge Formation. The Seathwaite Tarn veins occupy part of a series of faults which can be traced eastwards to the Levers Water area where they also locally carry copper mineralization. There are no surface exposures of these mineralized veins. However, several levels (e.g. at SD 2662 9976 and SD 2653 9941) have been driven into them and, although none remains safely accessible, the comparatively small spoil-heaps contain representative samples of veinstone. These reveal that the main vein-filling consists of brecciated wall-rock in which ribs and lenses of massive white quartz carry abundant chlorite and scattered concentrations of copper sulphides. Most abundant are 'grey copper sulphides' with only subordinate quantities of chalcopyrite. Stanley and Criddle (1979) recorded that these grey sulphides include both digenite and djurleite. They also noted the presence in this ore of arsenopyrite, cobaltite, covellite, crystalline hematite and pyrite. Bornite is a conspicuous ore mineral in many samples. In material from the uppermost dump, these authors identified small amounts of the rare copper bismuth sulphide mineral wittichenite (Cu_3BiS_3), the first recorded British occurrence of this mineral, together with a single grain of gold (Stanley and Criddle, 1979).

A level (SD 2611 9933) driven north through andesite of the Birker Fell Formation appears to have been an unsuccessful trial, although Dewey and Eastwood (1925) reported that a vein up to 0.9 m wide was cut. No mineralization is present on the dump from this level.

Interpretation

The Seathwaite veins exhibit many similarities with the widespread suite of copper-rich Lake District veins which includes those at the **Coniston Copper Mines**, **Birk Fell Hawse Mine** and **Dale Head North and South Veins** GCR sites, described elsewhere in this volume. Typically these veins carry abundant quartz accompanied by chlorite, arsenopyrite and copper sulphides. Whereas in most instances, the most abundant copper sulphide is chalcopyrite, in a few locations, notably here at Seathwaite Tarn, 'grey copper sulphides', are dominant. In their classification of Lake District mineralization, Stanley and Vaughan (1982a) commented on the origins of this copper mineralization and proposed a Lower Devonian age of emplacement.

However, more recently, Millward *et al.* (1999) demonstrated a pre-Acadian age for copper mineralization at the **Coniston Copper Mines** GCR site and elsewhere in the Lake

District. Whereas these authors did not specifically investigate the Seathwaite deposits, their mineralogical characteristics and structural setting clearly link them genetically with these other Lake District copper veins.

In the interpretation of the **Birk Fell Hawse Mine** and **Dale Head North and South Veins** GCR sites (see GCR site reports, this chapter), it has been suggested that the abundance of bornite in the higher levels of the veins may be evidence of supergene enrichment. Although nothing is known of the composition of the Seathwaite veins in depth, the sulphide mineralogy here may also reflect such enrichment.

Conclusions

The copper veins at Seathwaite mines are an important expression of pre-Acadian Lake District copper mineralization in which 'grey copper sulphides', rather than chalcopyrite, are the dominant ore minerals. The veins have yielded the first British specimens of witichenite, and may also give evidence of supergene enrichment.

FORCE CRAG MINE, CUMBRIA (NY 200 216)

Introduction

Force Crag Mine, at the head of Coledale, approximately 3 km WSW of the village of Braithwaite, Cumbria, formerly worked the roughly east–west Force Crag Vein. The mine was accessed from a number of adit-levels driven into the vein along a strike length of almost 1 km and over a vertical interval of at least 350 m. The vein appears to be a member of the widespread suite of Lake District lead-zinc veins for which a Carboniferous age of mineralization has been proposed (Stanley and Vaughan, 1982a). There are excellent exposures of mineralization in underground workings, and abundant surface spoil-heaps contain good representative examples of veinstone.

Although there is evidence that lead mineralization at the head of Coledale was known as early as 1578 (Adams, 1988), reliable documentary records of mining at Force Crag appear to date from as recently as 1848. Since that time, and under a variety of owners, lead, zinc and some manganese ores, together with substantial tonnages of barite, have been mined intermittently. The last attempts at mining at Force Crag ended in the early 1990s.

Descriptions of the mine's geology and mineralization have been given by Eastwood (1921, 1959), and by Young and Cooper (1988). Young (1987a) provided a comprehensive list of all minerals then recorded from the site. Details of the mine's history include those by Shaw (1970), Adams (1988), and Tyler (1990). The building that housed the main ore-treatment plant, together with some machinery, are today preserved as a heritage feature.

Description

The Force Crag Vein occupies a roughly E–W-trending fault that cuts cleaved mudstones, siltstones and greywacke sandstones of the Kirkstile Formation, part of the Skiddaw Group of Ordovician age, at the head of Coledale, approximately 3 km WSW of Braithwaite (Figure 2.24). The vein runs parallel to, and a short distance to the north of, the gradational northern boundary of the Crummock Water thermal aureole. This elongate metasomatic aureole within Skiddaw Group rocks corresponds with a Bouguer anomaly, interpreted as being due to an elongate granitic body emplaced along the northern margin of the Lake District Batholith. The metasomatism has been dated at 401 ± 3 Ma (Cooper, D.C. *et al.*, 1988).

The vein generally hades to the north at about 75°, but in places it is vertical. The amount of throw cannot be reliably established (Young and Cooper, 1988). Throughout the worked portions of the vein, between Force Crag and the floor of the Coledale Valley, the vein is said to have averaged 1.5 m in width, although widths of up to 6.1 m have been recorded locally. In the lower levels of the mine, the vein divided into two parallel fractures separated by up to 4.6 m of unmineralized ground. Several small strings diverge from the vein locally, but these were found to be mineralized only near their junction with the main vein. Young and Cooper (1988) suggested that the vein could be identified in Gasgale Gill (NY 1834 2146), approximately 3 km to the west, although subsequent mapping by the British Geological Survey has not confirmed this connection.

Force Crag Vein is rather unusual amongst Lake District veins in exhibiting a marked vertical variation, or zonation, of its constituent minerals.

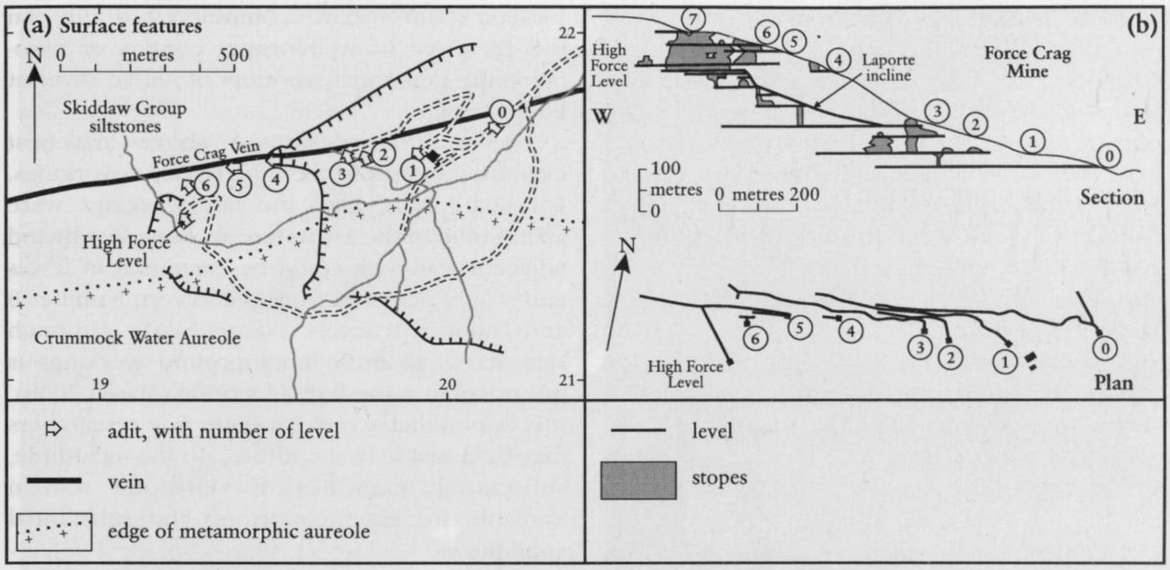

Figure 2.24 (a) Surface features and (b) simplified plan and section of workings at Force Crag Mine. After Young and Cooper (1988).

At the western end of the workings, above the High Force Level, barite is the main vein-filling. This is typically coarsely crystalline with individual crystals commonly up to 15 cm across. Much of it is white, although locally pale-pink shades are present. Large tabular barite crystals have been found in vugs. Much of the mine's commercial output of barite was obtained from these upper workings. Although the underground workings at this level are no longer safely accessible, representative examples of veinstone, abundantly present on the dumps, reveal that barite is accompanied here by a little quartz and abundant manganese and iron oxides. Hard dark-grey manganese oxides, generally referred to as 'psilomelane', are common as massive, reniform or stalactitic masses. 'Psilomelane' also occurs here as reniform nodules within siltstone and mudstone wall-rocks. Softer, black manganese oxides, referred to as 'wad' in some accounts, are locally abundant. Young and Cooper (1988) report that at least some of this material has been identified as todorokite $(Mn^{+2}.Ca,Mg)Mn_3{}^{+4}O_7.H_2O)$. Goethite $(\alpha\text{-}Fe^{+3}O(OH))$ is also abundant in dark-brown massive form and locally as reniform masses with an internal radiating fibrous crystalline structure. Galena and sphalerite are almost absent from this level of the vein.

Below the High Force Level, the vein becomes barren of almost all except massive white quartz which is exposed intermittently at the surface in the gully on the north side of Force Crag. Underground exploration failed to find economic mineralization of any sort at this level.

As the vein is traced down the hillside below Force Crag, economic mineralization re-appears at the Number 3 Level. Here, and in the lower levels, sphalerite and galena are the main economic minerals, with barite usually present in only subordinate amounts. Sphalerite appears to be the most abundant sulphide. It typically occurs as dark-brown to almost black coarsely crystalline bands, although numerous large vugs are lined with well-formed large lustrous black crystals up to 2 cm across. These are commonly partially encrusted with pale-brown curved rhombic crystals of siderite. Striking specimens of black sphalerite crystals accompanied by pale-brown siderite from Force Crag Mine are to be seen in many museum collections (Figure 2.25).

Galena, which is less abundant than sphalerite, occurs as coarsely crystalline masses; freely grown crystals are rare. Eastwood (1921) reported around 30 oz of silver per ton of lead in samples of Force Crag galena. Microscopic inclusions of bournonite $(CuPbSbS_3)$ and native antimony (Sb) have been described from Force Crag galena by Stanley and Vaughan (1981). Chalcopyrite and pyrite are minor constituents of the vein at these lower levels.

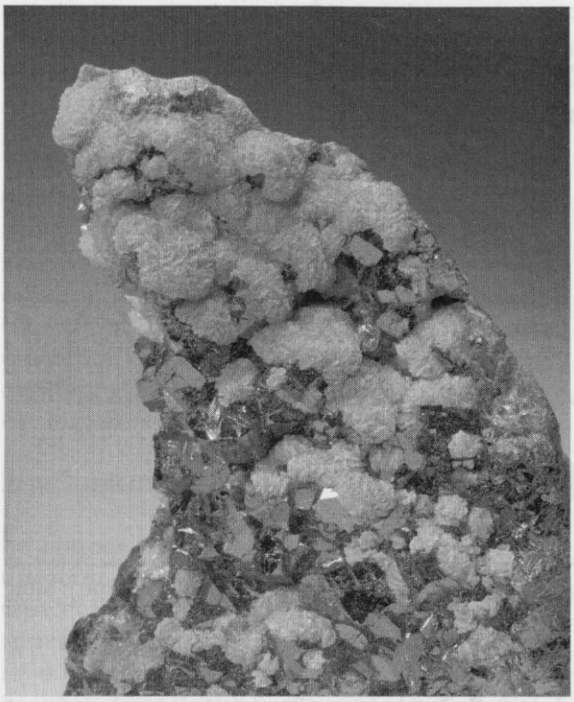

Figure 2.25 Group of large black sphalerite crystals up to 1 cm across partially encrusted with pale brownish-yellow siderite, from Force Crag Mine. (Photo: BGS No. MNS 4491, reproduced by permission of the British Geological Survey, © NERC. All rights reserved. IPR/105-15CX.)

Within the lowest levels of the mine, fluorite was found sparingly as pale-yellow cubes up to 5 mm across, coating siderite crystals within vugs in mudstone breccia cemented by siderite, or as bands a few millimetres thick on the margins of the vein adjacent to the wall-rock.

A number of supergene species have been reported from the Force Crag workings. Included with these are almost certainly the manganese oxides, abundantly present in the upper levels of the mine. Greg and Lettsom (1858) reported the first British occurrence of stolzite ($PbWO_4$) from Force Crag, a record that has been repeated by several subsequent authors cited by Young (1987a). However, in view of the mineralogy and chemistry of the Force Crag deposit, the occurrence of this species here seems improbable. Young (1987a), and Young and Cooper (1988) provided persuasive arguments for regarding this record as erroneous. More recently, Green and Briscoe (2002) have commented briefly on the presence of well-formed crystals of pyromorphite and small amounts of native silver at Force Crag.

The features described above are best examined *in situ* in the underground workings. For some time after the last workings were abandoned in the 1990s fine sections of vein and adjacent wall-rock could be examined in levels and stopes accessed from the lowest, Number 0 and Number 1, levels (Figure 2.26). Although safe access to these underground workings is not possible at the time of writing (March 2008), it is hoped that access for *bona fide* researchers may be possible in the future. In the meantime, substantial quantities of veinstone remain available for examination on the substantial spoil-heaps.

Interpretation

Force Crag Vein is one of a number of Lake District veins characterized by the abundance of lead and zinc mineralization within a gangue of barite, quartz and, at this location, siderite and minor fluorite. In their genetic classification of Lake District mineralization, Stanley and Vaughan (1982a) assigned an early Carboniferous age to these deposits, though the admittedly rather tenuous grounds for this age invite revision. Certainly these lead-zinc-barite veins do appear to comprise a recognizable suite of deposits that clearly post-date the early copper-rich mineralization that is so widespread in the Lake District and for which Millward *et al.* (1999) have demonstrated a pre-Acadian date of emplacement. However, these Lake District lead-zinc veins bear a number of similarities to the lead-zinc-barite-fluorite mineralization of the Northern Pennines, a similarity that is arguably re-inforced by the local presence within them of small quantities of fluorite. It may be significant that the Force Crag Vein exhibits a downward passage from barite-dominated mineralization to a lower zone characterized by the abundance of sulphides and the incoming of fluorite, albeit in comparatively modest amount. A similar zonal transition from barite to fluorite mineralization is characteristic of the veins of the Northern Pennines (see Chapter 3). Further support for this comparison might be adduced from the suggestion of Crowley *et al.* (1997) that $\delta^{34}S$ in

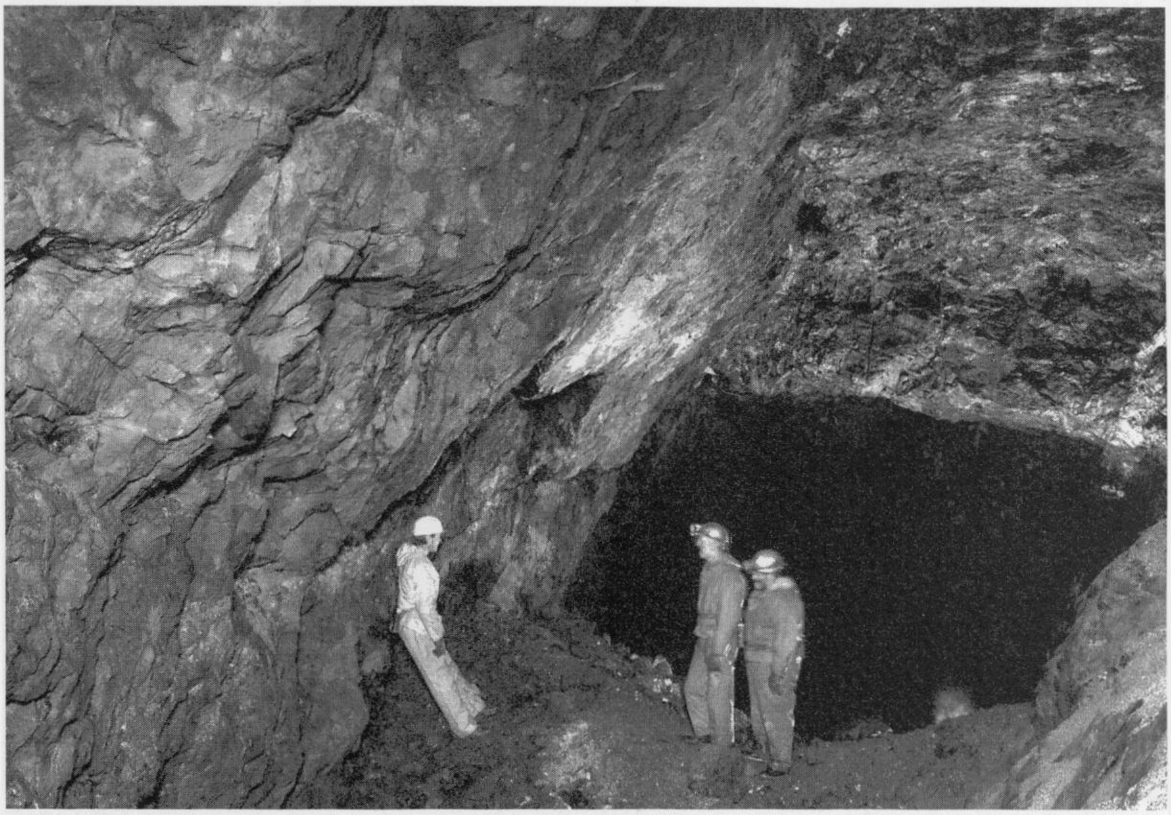

Figure 2.26 Number 1 Level, Force Crag Mine. The vein here is unusually wide and contains an abundance of sphalerite with a conspicuous band of white barite near the right of the picture. (Photo: BGS No. D4794, reproduced by permission of the British Geological Survey, © NERC. All rights reserved. IPR/105-15CX.)

barite from both the northern Lake District and northern margins of the Northern Pennine Orefield appears to have been derived from Lower Carboniferous evaporites from the Solway Basin. If, as seems reasonable, a case may be advanced for regarding these Lake District veins as sharing a similar age and origin to those of the Northern Pennines, a late Carboniferous or early Permian age would be implied.

Conclusions

Force Crag Vein offers the finest opportunity within the Lake District to examine a lead-zinc-barite vein which exhibits vertical zonation of its constituent minerals. In addition, the vein gives some evidence in support of a genetic link between Lake District lead-zinc-barium veins and those of the Northern Pennines.