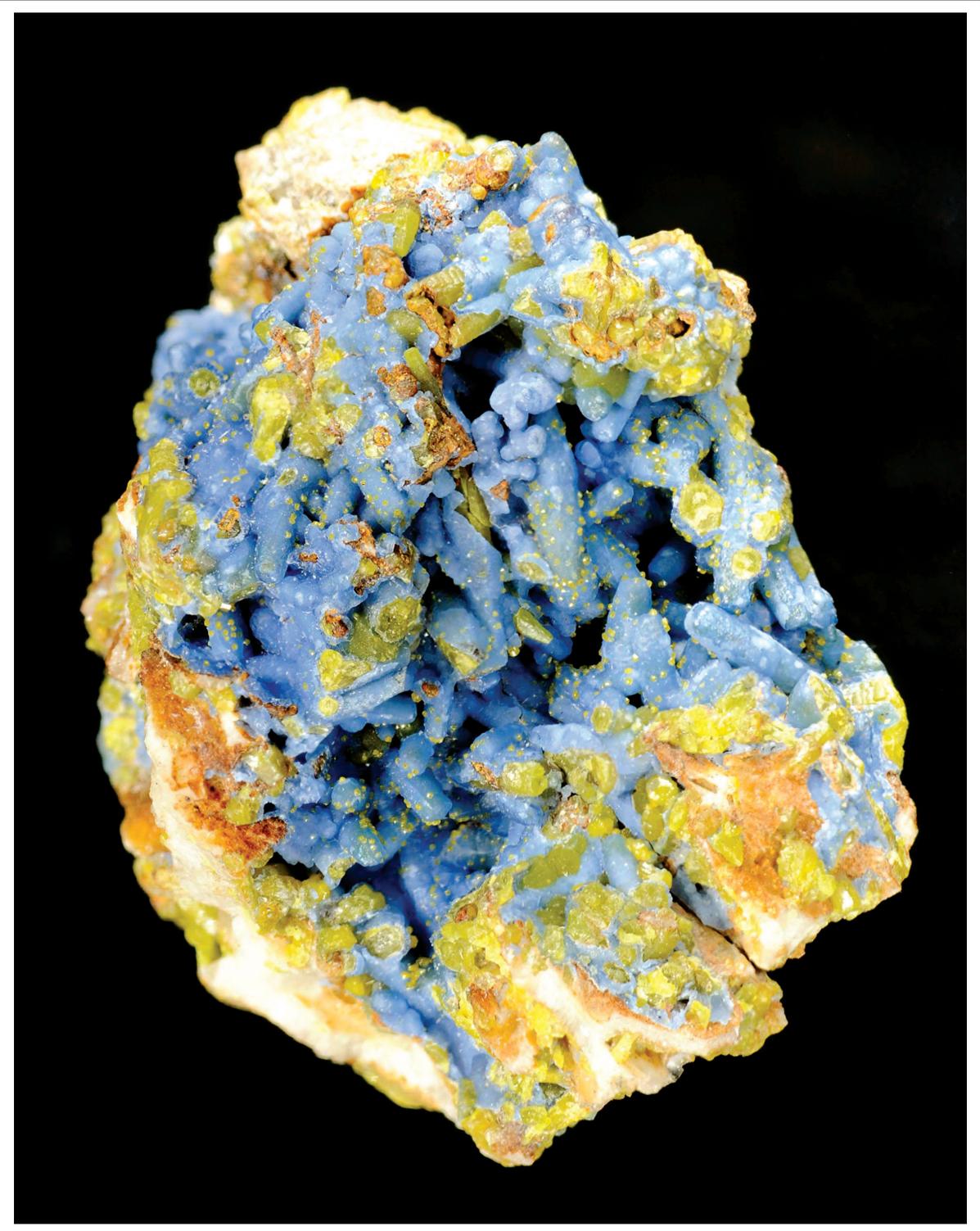


JOURNAL  
OF  
*The Russell Society*

Volume 14, 2011



# JOURNAL OF THE RUSSELL SOCIETY

The journal of British Isles topographical mineralogy

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### FRONT COVER:

Blue plumbogummite with yellow pyromorphite. Roughton Gill Mine, Caldbeck Fells, Cumbria.  
R.J. King Collection (ex. Harwood Collection), National Museum of Wales, Cardiff (NMW 83.41G.M.7821).  
Specimen height 42 mm. David Green photograph.

### BACK COVER:

A white cerussite crystal, 6 mm high, with minor yellow pyromorphite in a cavity lined with green malachite.  
Roughton Gill Mine, Caldbeck Fells, Cumbria. Norman Thomson Collection. David Green photograph.

# Journal of the Russell Society

## CONTENTS

Volume 14, 2011

### GUEST EDITORIAL

- Taking stock after 40 years  
*Roy Starkey* 2

### PAPER

- A review of the mineralisation of the Roughton Gill mines, Caldbeck Fells, Cumbria: Part 3 Roughton Gill Mine  
*Trevor F. Bridges, David Green, Michael S. Rumsey and C. Michael Leppington* 3-23

### NOTE

- Alluvial occurrences of fergusonite and gadolinite in the Mourne Mountains, Northern Ireland  
*Norman R. Moles and Andrew G. Tindle* 23-25

### PAPERS

- Danburite from Meldon Quarry, Okehampton and other UK localities  
*Michael S. Rumsey, George Ryback and Richard Tayler* 26-32

- A review of the mineralogy of the area around Markfield, Leicestershire  
*Francis Ince* 32-44

- A review of the mineralogy of the area around Groby, Leicestershire  
*Francis Ince* 44-62

- A report on Hay Gill Mine, Caldbeck Fells, Cumbria  
*Trevor F. Bridges, Michael S. Rumsey and C. Michael Leppington* 62-68

- Goethite pseudomorphs after marcasite from the Northern Pennine Orefield  
*Brian Young and Trevor F. Bridges* 69-76

## Guest Editorial

### Taking stock after 40 years

In his Editorial for Volume 10, Frank Ince, then General Secretary of the Society, provided a reprise of the history of the Journal of the Russell Society, to mark 25 years of publication.

The Russell Society has come a long way since its inception on 27<sup>th</sup> October 1972, and is now a widely respected organisation within the field of mineralogy, drawing its membership from amateur and professional mineralogists and geologists both in the UK and overseas. One of the main aims of the Society has been to publish original peer-reviewed articles on the topographical mineralogy of the British Isles, although articles on associated topics are welcomed and have always been included. The fact that the Russell Society publishes a Journal owes much to the enthusiasm and dedication of Bob King, who acted as the Editor for the first four issues (numbered as Volume 1, Parts 1-4) published in the period 1982-1986.

The Society wishes to acknowledge a very generous donation made by Bob and Sally King which has funded this issue of the Journal of the Russell Society, and to thank Bob for his tremendous enthusiasm and support for the Society.

We look forward to celebrating forty years of the Russell Society at the Annual Society Meeting in Falmouth in April 2011; however, the Society faces several challenges and Council is committed to addressing these as it prepares for the future. An extensive consultation exercise is being launched and you should have received details of this by the time this issue of the Journal reaches you. Do please take time to get involved and let us have your feedback.

Forty years ago the UK still had an active metalliferous mining industry, predominantly in SW England, and fluorspar mining in the Pennines was flourishing. The latter came to an abrupt end in the 1980s, and in these areas there are no actively producing metal mines remaining. As this Journal goes to press however, the picture is changing:

- The Anglesey Mining annual report for 2011 states that a detailed review of the resources and the development options for Parys Mountain will be undertaken during the remainder of 2011. With revenues now being generated from the company's Labrador Iron Mine, prospects for some real activity at Parys Mountain look better than for many years.
- Scotgold's Cononish gold and silver project was unanimously approved at a recent planning enquiry held on 25<sup>th</sup> October 2011; this is excellent news for the Tyndrum community. The Company also continues to actively conduct more widespread exploration under the banner of the Grampian Gold Project with a significant number of potential targets.
- Further south, Wolf Minerals' core project at the world class Hemerdon tungsten and tin deposit in Devon is forging ahead with the company focused on developing the prospect into a large scale, open pit mining operation.
- The current high price of fluorspar may yet see a resurgence of interest in re-evaluating deposits in the north of England, and it has also been reported recently that the famous Clogau gold mine near Dolgellau may be re-opened.

These are exciting times indeed for the UK minerals industry, let's hope that some of these projects make it through to fruition.

Roy Starkey  
Honorary President

# A REVIEW OF THE MINERALISATION OF THE ROUGHTON GILL MINES, CALDBECK FELLS, CUMBRIA: PART 3 ROUGHTON GILL MINE

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**Roughton Gill Mine worked a number of veins in the north face of Iron Crag, of which the Roughton Gill South Vein was by far the most important. It was one of the biggest mines in the Caldbeck Fells, producing large amounts of lead and copper ores. The main primary minerals were galena, chalcopyrite and sphalerite in a quartz/carbonate gangue.**

**Oxidation of the primary sulphides was extensive, resulting in sufficient malachite, pyromorphite and cerussite for these to be considered ores. In addition to these, about 32 other supergene minerals have definitely been identified from the mine, with several not fully confirmed species. The mine produced world class specimens of pyromorphite, hemimorphite and plumbogummite. The supergene mineralogy of the site is simpler than other mines in the area due to the presence of abundant carbonates. These have served to keep pH and carbonate ion activity ( $a_{\text{CO}_3^{2-}}$ ) relatively high, to the detriment of those species requiring low pH formational conditions, such as anglesite, leadhillite and caledonite, all of which are quite rare at Roughton Gill.**

**The dominance of the mine in the Caldbeck Fells has confused the reported mineralogy of the area, there being good reason to believe that numerous specimens have been ascribed to the site that actually originated elsewhere. These are discussed in the text, with particular reference to Arthur Kingsbury's claims for the site, although at Roughton Gill only gold and parahopeite are definitely considered fraudulent, with azurite probably so.**

## INTRODUCTION

The Roughton Gill mines are situated at the head of the Dale Beck Valley in the Caldbeck Fells of the northern Lake District and include workings in Silver Gill, on Balliway Rigg and the workings in Iron Crag (which terminates the valley). As part of an ongoing survey of the mines of the Caldbeck Fells, we have already published reviews on some of the Roughton Gill workings namely of Silver Gill (Green *et al.*, 2005), which can be considered as Part 1 of the review of the Roughton Gill mines and Part 2 which covers the Roughton Gill South Vein on Balliway Rigg (Green *et al.*, 2008), this latter working also being commonly called Higher Roughton Gill, and in some older literature, Thief Gill. This review considers Roughton Gill Mine itself, i.e. the 30, 60 and 90 fathom levels situated under and on the west side of Iron Crag. Other workings to be considered within the umbrella of the Roughton Gill mines are Mexico Mine, Todd Gill and minor excavations such as 'Barstow's Trench', which will be the subject of a future review.

Roughton Gill is the largest mine in the Dale Beck valley and one of the largest in the whole of the Caldbeck Fells and it has been extensively researched. Cooper and Stanley (1990) list a total of 55 species from the mine, but several of these are old records which are doubtful. Others have only been claimed by Arthur Kingsbury, summarised in good faith by Hartley (1984), some of which are now

considered fraudulent (Ryback *et al.*, 1998; 2001 and Tindle, 2008). Even in modern times collectors have not always clearly differentiated between the various mines, workings and trials at the head of the Dale Beck Valley. The need to address these problems, combined with the fact that new species have been identified since 1990, has prompted this series of reviews. A further problem arises from the dominant nature of Roughton Gill Mine in the area, which means there is good reason to believe that some old material, labelled from the mine, actually originated elsewhere. A classic example of this is the excellent 19<sup>th</sup> century linarite specimens, long thought to originate from the nearby and much smaller Red Gill Mine, a view supported by Bridges *et al.* (2008). This review is based as carefully as possible on material actually from the three levels of Roughton Gill Mine itself, of which the 90 fathom level dumps are by far the most important.

## HISTORY

The history of the mines at the head of the Dale Beck Valley, which includes Roughton Gill Mine, Mexico Mine and the workings in Silver Gill, has been summarised in numerous publications of which the following are considered to be the most useful: Shaw (1970), Cooper and Stanley (1990), Jecock *et al.* (2001) and Tyler (2009). Briefly summarising the history of Roughton Gill Mine itself, the earliest workings are shrouded in mystery, but

Shaw considers the 30 fathom cross cut onto the South Vein was driven in the 18<sup>th</sup> century. This was nearly worked out by 1832 and work then commenced on the 60 fathom level. Between 1832 and 1845 records show 3229 tons of lead and 150 tons of copper ores were raised. The mine was abandoned briefly in 1845 when the leases expired, but in 1849 the Roughtongill Silver Lead and Copper Mining Company took up the lease and by 1852 the 90 fathom level (commenced in 1849) was replacing the higher workings as the main source of ore. The mine changed hands several times in the years that followed and by 1866 workings above the 90 fathom level were running out of ore and Lainton's Shaft was sunk to access ore below the 90 fathom level. However, water ingress and bad management resulted in bankruptcy in 1878 and the mine never worked again. Finally, in 1913 Carlisle Urban District Council bought the mine to pump water from the 90 fathom level into the public water supply.

Mineralogically, Cooper and Stanley (1990) note that the principal ores were galena, chalcopyrite and sphalerite, but that pyromorphite, cerussite and malachite were also important ores. Shaw (1970) notes that a major orebody was found between the 60 and 90 fathom levels which he calls the 'Great Bunch'. The vein in this orebody reached a width of 9 m and extended for 70 fathoms in length and all the way down from the 60 to the 90 fathom levels. The 'Bunch' was composed of gossan, friable quartz and calcite, with pyromorphite and cerussite on the fringes and silver rich galena further into the deposit.

Roughton Gill Mine is renowned world wide for magnificent specimens of blue plumbogummite, pyromorphite and beautiful blue mammillary hemimorphite, all of which were unquestionably from the mine. It is of interest to note the earliest records of these minerals in the collections of the Natural History Museum (NHM).

1837. The earliest reference to a Caldbeck Fells mineral within the main NHM collections. Donated by Sowerby, it is a pyromorphite later assumed to be from Roughton Gill.

1843. The earliest reference to 'Roughten-gill' as a specific locality in the database. It is a suite of 'rocks' purchased from Mr Wright and included - pyromorphite, linarite, anglesite and cerussite. It is possible the last three actually originated from Red Gill. In the same suite is a reference to mimetite, specifically from 'Drygill', and a 'green calamine'. Unfortunately, the locality for the latter is ambiguous and could be Dry Gill or Roughton Gill. Incidentally, this appears to be the first transaction that the NHM had with the famous 19<sup>th</sup> century mineral dealer Mr [Bryce McMurdo] Wright Sr.

1844. The first reference to the mineral now called plumbogummite and again obtained from Wright. The specimen is listed as 'quartz coloured blue like chalcedony' and again the locality is not obvious, but appears to be 'Foss Crag' (Force Crag?), Cumberland. The entry has been updated at various times by various people to read hemimorphite, hitchcockite, plumboresinite and finally plumbogummite. At some point the locality has been assigned to 'Roughten Gill'.

In the same suite of specimens as the above plumbogummite is a not completely convincing record of the classic hemimorphite. It is listed as 'blue carbonate and silicate of zinc' and again the initial locality appears to be 'Foss Crag', Cumberland. However, confusion with 'ditto's' and 'ibids' means it is not clear whether the 'ibid' refers in this case to 'Cumberland' or 'Foss Crag'.

1850. There is a reference to a 'Cumberland' hemimorphite in the Allan Greg Collection, with the locality later assumed to be Roughton Gill.

1851. The earliest reference to a specific 'Roughten-gill' hemimorphite as a 'silicate of zinc'. The specimen was obtained from Wright.

1856. The first reference specifically to 'Roughten Gill' for a specimen of plumbogummite. This was also obtained from Wright labelled as 'blue calamine' later altered to the correct identity.

1897. This appears to be the time when all the 'blue calamines' in the collection were altered to plumboresinite, now plumbogummite.

As with Red Gill (Bridges *et al.*, 2008), the above shows the problems that are experienced when trying to resolve the true history of early collecting. In many cases, true localities were not known and collectors and dealers also often sought to guard their sources.

Excellent specimens of many other species occur at Roughton Gill Mine including rosasite, brochantite and tsumebite. Small specimens of many of these species could be collected from the spoil heaps into the late 1990s when the Lake District National Park Authority (LDNPA) seriously restricted collecting to preserve the remaining archaeology, a restriction that remains in place today. For this reason this review is nearly entirely based on material from collections.

## LOCATION

Figure 1, taken looking south, shows the extensive dumps of the 90 fathom level of the mine on the valley floor below the prominent feature of Iron Crag. The entrance to the level is behind the Carlisle Urban District Council building in the right centre of the photograph. All that is visible of the entrance now is a manhole cover at NY 3025 3439. On a visit in 2008, the dumps were seen to be totally dominated by quartz, with abundant dolomite and small amounts of calcite. Visible supergene minerals included common iron staining, and minor amounts of malachite and pyromorphite.

To the right of the building, Roughton Gill runs steeply uphill with numerous waterfalls and several coffin levels from the early Elizabethan period. The 60 fathom level is situated about half-way up the gill at the height of the line of horizontal dumps on the left hand side of the gill at NY 3021 3423. Much of the material extracted from the level has been washed down the gill, but quartz, ankerite and minor malachite, pyromorphite and the copper-rich silica gel commonly called 'chrysocolla' can be seen on the surface.



**Figure 1.** Photograph of the site from the north.

In 2008, the 30 fathom level entrance was buried under scree. It is situated a little beyond the point where Roughton Gill can be seen to level out in the top right hand corner of Figure 1. Cooper and Stanley (1990, p. 55) show a photograph of the level taken in 1987. No dumps associated with the level could be seen.

Figure 2 (see p. 6) shows a plan of the site with the main levels and remaining dumps shown. Also included are other minor trials and levels in the vicinity of the mine. Note that Blind Wastel and the 1600 crosscut are early ‘coffin’ levels driven on to the Silver Gill Vein and are not part of the Roughton Gill Mine workings.

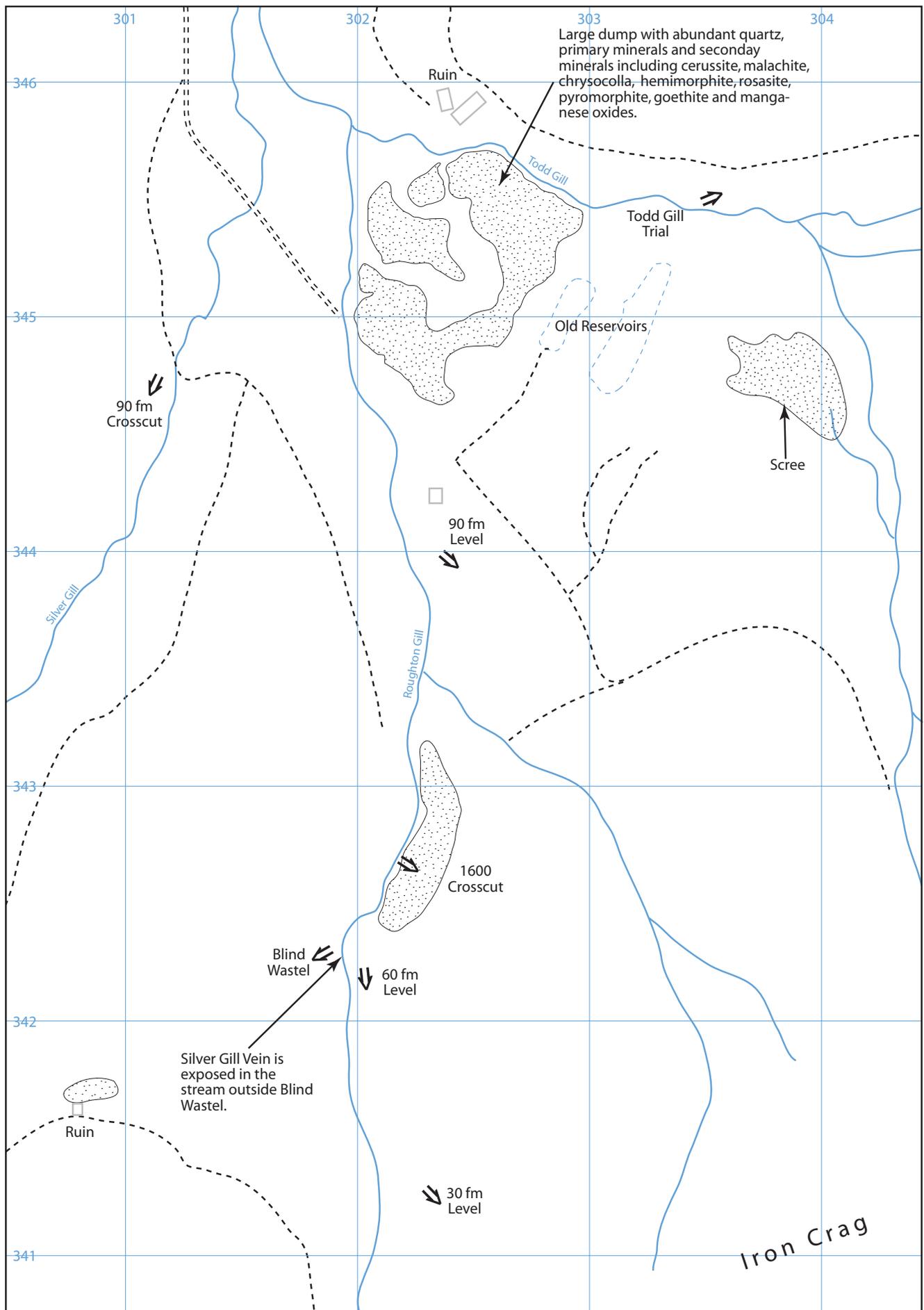
## SUMMARY OF THE GEOLOGY

The Roughton Gill Mines worked the Roughton Gill South Vein, Silver Gill Vein and several smaller veins over a distance of a little more than a kilometre at or near the boundary between extrusive igneous rocks of the Eycott Volcanic Group and intrusive rocks of the Carrock Fell Complex (Eastwood *et al.*, 1968). The most important orebodies were on the Roughton Gill South Vein, a major fracture which can be traced for many kilometres and which is well mineralised between Sandbed Mine, where it lies in the rocks of the Eycott Volcanic Group and Thief Gills where mineralisation dies away in the fine grained sedimentary rocks of the Skiddaw Group (British Geological Survey, 1997).

Rocks of the Eycott Group dominate the geology of the northern part of the Caldbeck Fells and comprise mafic to intermediate lavas which are locally interbedded with

volcaniclastic sandstones and pyroclastic flows (Millward *et al.*, 2000; Millward, 2002). The Carrock Fell Complex, which is immediately to the south, extends along the junction between the Eycott Volcanic Group and the Skiddaw Group, and crops out over an area of approximately 6 km from east to west and 2 km north to south, between Carrock Fell and the headwaters of the Roughton Gill beck (Hunter and Bowden, 1990; Stephenson, 2000). Since the Roughton Gill veins are largely within the Carrock Fell Complex it is worthwhile describing them in more detail.

The Carrock Fell Complex is traditionally divided into two divisions (Hunter and Bowden, 1990; Stephenson, 2000). The oldest rocks, which are collectively described as the Mosedale Gabbros, are layered cumulates that were intruded as a thick subhorizontal sill at the base of the Eycott Volcanics. The Mosedale Gabbros crop out along the southern margin of the Complex, but are not exposed in Roughton Gill which is at its western edge. A composite kilometre-scale intrusion cuts across the Mosedale Gabbros along their northern margin. It comprises micrographic microgranite (which was formerly called the Carrock Granophyre) and microgabbro (formerly called diabase). An apatite-rich ferrodiorite is present on the southern margin of the microgranite. These rocks are collectively described as the Carrock Gabbro-Microgranite Intrusions and are commonly known as the Carrock Division of the Carrock Fell Complex. There is strong evidence that they were intruded as vertical sheet like bodies (Hunter and Bowden, 1990; Piper, 1997). Their cross-cutting relationship shows they are younger than the Mosedale Gabbros, but a reliable radiometric date of  $452.4 \pm 4.1$  Ma (for the microgranite)



**Figure 2.** Plan of the site showing other minor trials in the vicinity and the main dumps.

was not established until relatively recently (Millward and Evans, 2003)

The geology of the western edge of the Carrock Fell Complex, which includes the Roughton Gill mines is complicated by the presence of several minor felsic intrusions that extend along the Roughton Gill and Dry Gill fault systems. These are the Iron Crag and Red Covercloth microgranites and the Harestones Rhyolite. The relationship between these intrusions and the surrounding rocks is unclear. They lie along the faulted contact between the Carrock Fell Complex and the Eycott Volcanic Group. Stevenson *et al.* (2000) consider they post-date and are probably unrelated to the Carrock gabbro-microgranite intrusions.

The granophyric, micrographic, microgranite (Carrock Granophyre) and microgabbro (diabase) which make up the Carrock Gabbro-Microgranite intrusions are present on the south wall of the Roughton Gill South Vein over much of its length. However, the vein lies wholly within the feldsparphyric Iron Crag Microgranite where it crosses Iron Crag. The fault zone that the Roughton Gill South and Silver Gill veins occupy is geologically complex and the wall rocks include an apatite-rich ferrodiorite, which may belong to the the Carrock Gabbro-Microgranite intrusions, the Iron Crag Microgranite and rocks which belong to the Eycott Volcanic Group. Ferrodiorite is present to the south and west of Iron Crag. The Iron Crag Microgranite is common across the face of the crag and in the fault zone to the north and east. Rocks of the Eycott Volcanic Group are present in the northeastern and southwestern extremities of the zone and they make up much of the north wall of the Silver Gill Vein.

Regarding the veins, the Silver Gill Vein can be seen crossing the Roughton Gill beck just below the entrance to the 60 fathom level. It consists of a quartz vein, with a coffin level (Blind Wastel) driven along the vein on the west side. The Roughton Gill South Vein is apparent as a broad fracture zone in the west side of the Roughton Gill beck valley where the latter flattens out above the waterfalls. The South Vein was by far the most important from the point of view of ore production, but other minor veins were worked.

## METHOD

As previously stated, it is often difficult to be certain of the exact provenance of specimen material from the Roughton Gill mines, but every effort has been made to ensure the notes that follow refer to material from the 30, 60 and 90 fathom workings only. Except when clearly stated otherwise, the identifications and descriptions that follow are based on over 300 specimens, mainly in private collections, collected in the last 70 years and of good provenance, but it must be remembered that most of the material collected is supergene in origin since collectors consider this more 'interesting'. Primary material is therefore under-represented. There are numerous references to Roughton Gill Mine in the literature and these are discussed under the relevant minerals. One significant reference is Hartley (1984) who listed minerals claimed to have been collected by Arthur Kingsbury.

All specimens were initially studied using a stereomicroscope for their morphological characteristics and mineralogical associations and in some cases wet chemistry was then used as a simple extra check on minerals such as cerussite and malachite. Many of the minerals had already been identified by X-ray diffractometry (XRD). Where this was lacking, samples were taken for analysis by energy dispersive X-ray spectroscopy (EDS) using a scanning electron microscope (SEM). When the identification was still not fully confirmed, material was then sampled for XRD.

It should be noted that most of the minerals referred to in Cooper and Stanley (1990) were previously reported by Young (1987) in his 'Glossary of the minerals of the Lake District and adjoining areas'. In this review, precedence is given to the Cooper and Stanley reference, since this is considered the definitive work on the Caldbeck Fells and is more descriptive.

## THE MINERALS

Minerals which have not been fully identified, or are of dubious provenance, are shown in lower case in the text that follows. Minerals which it is considered should not be included in the list of Roughton Gill Mine species are shown in lower case and italics.

### *Acanthite, Ag<sub>2</sub>S*

Small black needles occur as an alteration product of silver, but are post-collecting in origin.

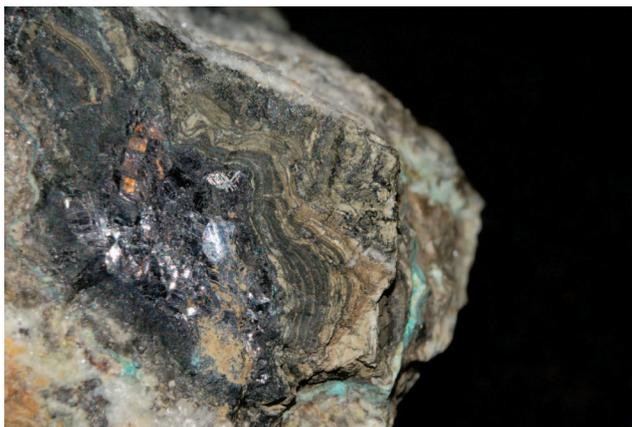
### ANGLESITE, PbSO<sub>4</sub>

Long known from the mine, Goodchild (1885) refers to anglesite from both Roughton Gill and Red Gill. Cooper and Stanley (1990) note that crystals up to 25 mm long were found in the 19<sup>th</sup> century, but that very little has been found since the mine closed. It is possible that the earliest reported large crystals actually originated from Red Gill Mine (Bridges *et al.*, 2008).

Anglesite is rare on the dumps, but has been found in sword-shaped crystals up to 10 mm long, but mostly much less than this, and as aggregates of small diamond shaped tablets and prisms in cavities. Figure 3 shows a



**Figure 3.** Anglesite crystal, 4.5 mm long, in quartz.



**Figure 4.** Banded anglesite, 4 mm thick, on galena, with an outer thin crust of cerussite on the anglesite.

more unusual specimen of an elongated near square prism, 4.5 mm long, with small associated anglesite blades. On a single specimen, anglesite occurs as a banded pale to dark brown alteration crust of galena, 4 mm thick, overcoated by massive crystalline cerussite, which appears to be an alteration product of the anglesite (Fig. 4).

#### Aragonite, $\text{CaCO}_3$

Tapering prisms of aragonite were recorded by Goodchild (1884). However, it has not been found in this study and is considered to be a doubtful species.

#### Atacamite, $\text{Cu}_2\text{Cl}(\text{OH})_3$

A specimen of this mineral in the NHM is labelled from 'Roughtongill'. Kingsbury and Hartley (1956) consider the specimen actually originated from Potts Gill Mine, where Kingsbury claimed to have found further similar specimens. It has not been found in this study and is very unlikely to occur in the geochemical environment of Roughton Gill. It should not be included in a list of Roughton Gill minerals.

#### AURICHALCITE, $(\text{Zn,Cu})_5(\text{CO}_3)_2(\text{OH})_6$

Davidson and Thomson (1951) note that aurichalcite is not rare, a finding confirmed by this study. It is by no means as common as rosasite, but occurs as pale turquoise blue radiating platy crystals up to 3 mm long, often forming hemispherical rosettes. The rosettes occasionally aggregate to cover areas several centimetres across (Fig. 5). Figure 6 shows a spray of aurichalcite on quartz. Hemimorphite and rosasite are commonly in association.

Hartley (1984) notes the presence of aurichalcite on material Kingsbury claimed to have collected from the 90 fathom dumps. The specimen could not be found in Kingsbury's collection, but there does not seem to be any reason why it should not have been genuine.

#### AZURITE, $\text{Cu}_3(\text{CO}_3)_2(\text{OH})_2$

Azurite is surprisingly rare at Roughton Gill considering the abundance of malachite and primary carbonates. There is only one definite specimen, which was collected from the 90 fathom dumps in 1975. It consists of a 2 mm compact rounded crystal cluster in a cavity in iron stained quartz,

with malachite and pyromorphite in other cavities (R.S.W. Braithwaite, *personal communication*).

Figures 7 and 8 show the front and back of a specimen in the Tony Rigby Collection, with an attached label saying 'Azurite, Roughtengill, Caldbeck, E.H. Shackleton'. The matrix is compatible with a Roughton Gill locality, but the specimen seems remarkably good for a mineral which is so rare in the Caldbeck Fells.

Hartley (1984) records the presence of azurite on material claimed to have been collected by Kingsbury from the 30 and 60 fathom levels. In the Kingsbury Collection there is a single small (3 cm) specimen of brown and white brecciated quartz with damaged 4 mm crystals of dark blue azurite, but the specimen does not look typical of the site.



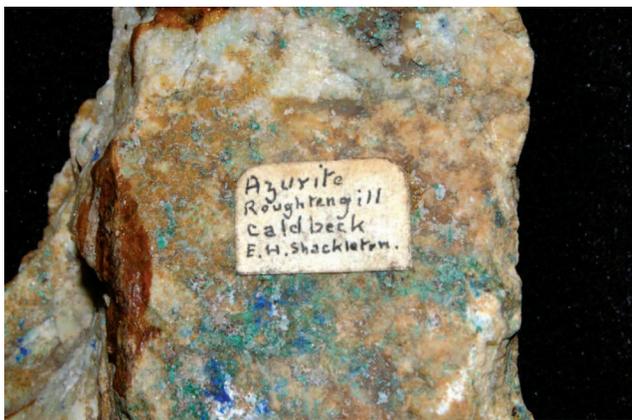
**Figure 5.** Encrustation of aurichalcite crystals on iron stained quartz. Field of view 2 cm.



**Figure 6.** Radiating aurichalcite crystal cluster 7.5 mm high. R.J. King specimen in the National Museum of Wales collections (NMW 83.41G.M.5614).



**Figure 7.** Azurite on quartz, labelled 'Roughtengill Mine'. The scale rod is 5 cm long.



**Figure 8.** Label on the reverse of the specimen shown in Figure 7.

## BARYTE, $\text{BaSO}_4$

In the specimen material examined in this study, primary baryte is quite rare, only occurring as small blades up to 10 mm long in cavities in quartz. A careful inspection of the surface of the 90 fathom dumps failed to reveal any baryte at all. Davidson and Thomson (1951) and Shaw (1970) note that the dumps were reworked for baryte, which could account for its rarity. However, Dunham and Dines (1945) in a wartime pamphlet on baryte note: "Roughton Gill Veins principally produced lead and copper. Some barytes was present, but it is doubtful whether the output of 541 tons recorded from this area during 1887-93 actually came from these Veins". The main dump from the 90 fathom level shows no sign of having been reworked, although smaller dumps on the ground to the west could have been. On balance it seems unlikely that baryte was a significant feature of the workings.

Bridges and Green (2008) note that extremely thin laths of baryte occur encrusting ochres of limonite and wad and that these are clearly supergene in origin. In this study, further examples of supergene baryte have been found as crystals consisting of small diamond shaped plates up to 2 mm across and small glassy flat bladed crystals resembling one form of anglesite which reach 5 mm long, but are less than 1 mm thick. Associated minerals are rosasite and brochantite, clearly indicating the supergene origin.

## Beaverite, $\text{Pb}(\text{Fe,Cu})_3(\text{SO}_4)_2(\text{OH,H}_2\text{O})_6$

Thin earthy to micro-crystalline crusts of yellow-brown material in cavities in quartz, resembling some forms of beaverite, were checked by EDS and found to contain lead, copper and iron. The copper peaks were quite significant, but detailed microprobe (WDS/EPM) analysis would be necessary to be sure the mineral was not plumbojarosite.

## Bornite, $\text{Cu}_5\text{FeS}_4$

Young (1987) notes that there is a specimen of this mineral in the Keswick Museum labelled 'Roughton Gill'. However, the specimen consists of a small dark brown ochrous looking mass with white streaks. No bornite is visible from outside the cabinet and the matrix does not look typical of Roughton Gill Mine. It has not been found in the current study and it is considered that this mineral should not be included in the list of Roughton Gill Mine species.

## BROCHANTITE, $\text{Cu}_4(\text{SO}_4)(\text{OH})_6$

The first record of brochantite from the mine is by Greg and Lettsom (1858) who describe it as small brilliant crystals on quartz and associated with malachite. Davidson and Thomson (1951) note that well-crystallised specimens are in the possession of several museums and that the first named author found a few small specimens in 1949.

Brochantite is by no means uncommon with several specimens having been found by Norman Thomson and other collectors. It occurs as crusts of small emerald green equant and chisel-shaped crystals, up to a maximum of 3 mm long (but usually much less than this), on quartz matrix. Associated minerals include malachite and rarely tsumebite, which Cooper and Stanley (1990) note has been found with 2-3 mm brochantite crystals. Figure 9 shows brochantite in association with tsumebite.



**Figure 9.** Brochantite crystals, 1 mm long, with tsumebite on quartz.

## CALCITE, $\text{CaCO}_3$

Calcite is not as abundant as dolomite, but can be found on the surface of the 90 fathom dumps as lumps up to about 30 cm across. Small nailhead calcite crystals up to 0.5 mm occur on specimen material in collections. Dewey and Eastwood (1925) note that calcite was a major constituent of the 'Great Bunch'. The abundance of calcite has had a significant effect on the supergene mineralogy of the site (see Discussion).

## CALEDONITE, $\text{Pb}_5\text{Cu}_2(\text{CO}_3)(\text{SO}_4)_3(\text{OH})_6$

Davidson and Thomson (1951) note that they found no trace of caledonite at Roughton Gill and, as with linarite, it seems likely that early specimens actually originated from Red Gill Mine or Higher Roughton Gill. In this study it has only been noted on three specimens. In the Richard Bell Collection it occurs as minute turquoise blue blades reaching c.1 mm long in a cavity about 2 mm across and on another specimen in the Mike Leppington Collection it consists of a spray of minute flat needles 0.3 mm long associated with small (0.5 mm) linarite crystals in a small cavity in quartz. Figure 10 shows a 0.7 mm crystal associated with leadhillite and linarite on a specimen from the Norman Thomson Collection.

## CERUSSITE, $\text{PbCO}_3$

Cerussite occurred in sufficient amounts to be considered an ore (Cooper and Stanley, 1990). In this study it remains a very common mineral, occurring mainly as jackstraw crystals which are often up to 7 mm long and as flat bladed crystals up to 10 mm long. Many of the flat crystals show evidence of hexagonal twinning (Fig. 11). Rarely cerussite is a cement in breccias of quartz and rock and has also been observed as black masses replacing galena. Common associated minerals are malachite and pyromorphite (Fig. 12).

Hartley (1984) records cerussite from all three levels on material Kingsbury claimed to have collected. The specimens could not be found in the Kingsbury Collection in the NHM, but it is possible some of Kingsbury's Roughton Gill material was never included in his collection.

## CESÀROLITE, $\text{PbH}_2\text{Mn}_3\text{O}_8$

## CORONADITE, $\text{PbMn}_8\text{O}_{16}$

## Manganosite, $\text{MnO}$

Manganiferous minerals are not common on the dumps of Roughton Gill Mine, which is perhaps surprising since they are common in the outcrops of the South Vein on Iron Crag. They are considered together, since the first two formed part of the research project outlined below.

Six specimens that appeared to be candidates for manganese minerals were analysed by EDS, but all were only encrusted with black-grey deposits in a fairly minor way. Two contained Pb, Mn and Fe and the other specimens the same elements with other elements such as Cu, Si and Zn. The three richest specimens were examined by XRD at the National Museum of Wales. One of the specimens



**Figure 10.** Caledonite crystal, 0.7 mm high, with linarite and leadhillite on quartz.



**Figure 11.** Cerussite crystals, 2 mm long, with linarite and leadhillite.

containing just Pb, Mn and Fe was glossy black with a botryoidal surface and proved to be coronadite. The other, which was closely associated with pyromorphite, was soft with a dark grey-black layered structure and proved to

be dominated by cesàrolite, with the possibility of some coronadite also being present. The third more complex specimen, with minor Cu and Si in addition to the Pb, Mn and Fe in fact seemed to be dominated by goethite and quartz with no obvious manganese mineral present. This study clearly illustrates the complications involved in identifying manganese minerals.

Manganosite was identified on a specimen from 'Roughton Gill' submitted to the NHM in 1986 by a Mr Mings (Ryback and Tandy, 1992). The specimen is not in the NHM collections and since it may have originated from Iron Crag its provenance is not certain.



**Figure 12.** Cerussite crystal, 6 mm high, with minor pyromorphite in a cavity lined with malachite.



**Figure 13.** 'Chrysocolla' in quartz and goethite. The scale rod is 5 cm long.

## CHALCOPYRITE, $\text{CuFeS}_2$

Chalcopyrite was one of the principal ores in the veins and is common on the 90 fathom level dumps, mainly as blebs reaching no more than a few centimetres across in quartz. Oxidation to brown 'limonite' is common and alteration to grey copper(I) sulphides is apparent on a few specimens.

## Chrysocolla, $(\text{Cu,Al})_2\text{H}_2\text{Si}_2\text{O}_5(\text{OH})_4 \cdot n\text{H}_2\text{O}$

Masses of 'chrysocolla' have been noted from Roughton Gill Mine from as long ago as 1858 (Greg and Lettsom, 1858) and on several occasions since. However, there is now considerable doubt about the status of this mineral, a view supported by Farges *et al.* (2006) who analysed specimens from localities from the Americas and the Congo and found all to be mixtures of copper in the form of spertiniite,  $\text{Cu}(\text{OH})_2$ , mixed with hydrous amorphous silica. All specimens examined from this and nearby mines (Green *et al.*, 2008 and Bridges *et al.*, 2008) are copper-rich silica gels. For convenience, in this study this material has been referred to as 'chrysocolla', placed in inverted commas to indicate its doubtful status.

At Roughton Gill it is very common on the 90 fathom dumps and has been noted from the 30 fathom level as quite large lumps. Traces can also be seen on the 60 fathom dumps. It occurs as blue to blue-green masses with a waxy appearance and often showing dessication cracks. Figures 13 and 14 show typical specimens. It commonly overcoats malachite forming botryoidal crusts and other common associated minerals are hemimorphite and pyromorphite. Rarely, it forms tapering epimorphs after pyromorphite.



**Figure 14.** 'Chrysocolla' with pyromorphite. Field of view 9 mm.

## CINNABAR, HgS

Cinnabar is very rare, but has been noted as an earthy brick-red coating on limonite, with hemimorphite and rosasite in the same area and as bright red spots up to 1 mm across on a matrix of quartz and a zinc-rich clay. Confirmation was by EDS.

## COVELLINE, CuS

Iridescent purple coatings on chalcopyrite have been confirmed as covellite by XRD. Similar coatings occur on several specimens of sphalerite and galena.

## CUPRITE, Cu<sub>2</sub>O

Cuprite is rare, but has been found as bright red encrustations, generally of the order of 2 mm across, associated with grey copper(I) sulphides and malachite on a small number of specimens (Fig. 15).

## Dolomite, CaMg(CO<sub>3</sub>)<sub>2</sub>

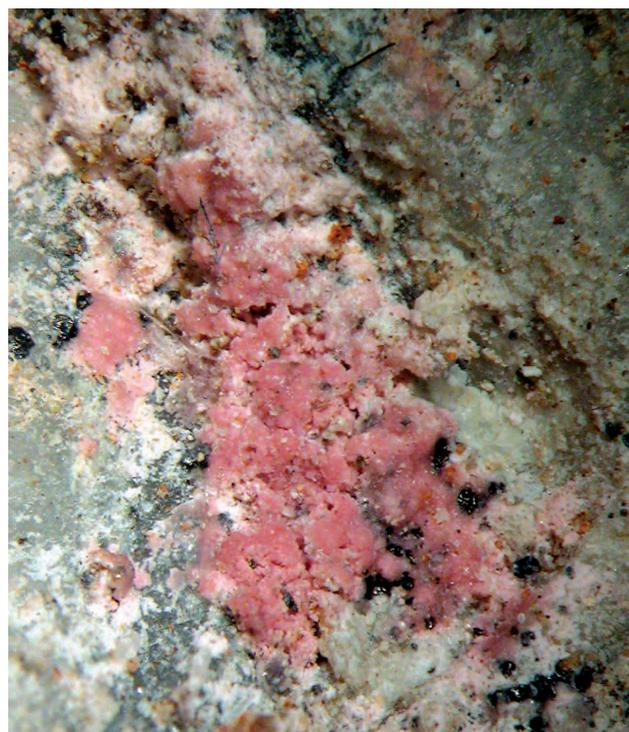
Day (1928) and Davidson and Thomson (1951) reported dolomite from the dumps. Certainly dolomitic material is common on the 90 fathom dumps as quite large blocks, cavity infills in quartz and as veinlets in weathered rocks. The surface is always oxidised to a light brown colour (Fig. 16), indicating the presence of iron, but analysis shows the iron content to be no more than 2 to 3%. The material is therefore dolomite with a minor iron content.



**Figure 15.** Cuprite with goethite on quartz. Field of view 3 mm.



**Figure 16.** Large block of dolomite, 30 cm across, with goethite stained surface. The dolomite is infilling cavities in quartz.



**Figure 17.** Encrustation of erythrite on quartz. Image width 3 mm.

## ERYTHRITE, Co<sub>3</sub>(AsO<sub>4</sub>)<sub>2</sub>·8H<sub>2</sub>O

Cooper and Stanley (1990) and Young (1987) report erythrite as pale pink coatings on quartz and calcite. Small amounts have been found in the course of this study as minute balls up to 0.5 mm diameter, with a radiating structure, and encrusting fractured quartz surfaces (Fig. 17).

## GALENA, PbS

Galena was the main ore from the mine and worked from all the levels. Shaw (1970) notes that it was the main ore in the central part of the 'Great Bunch' opened up from the 60 fathom level, occurring as 'cubical galena'. Good crystalline specimens appear to be rare and Cooper and Stanley (1990, p. 96) are doubtful that an excellent specimen of cubo-octahedral galena in the Russell Collection in the NHM actually originated from the mine.

In this study it is surprisingly uncommon in specimen material, but occurs as cleavage fragments on some specimens, mainly in quartz, and as small cubo-octahedral crystals to 2 mm in cavities in quartz with sphalerite in one case.

## GOETHITE, $\alpha$ -FeO(OH)

Eastwood (1921) notes that the pigment umber was worked at Roughton Gill Mine from the dumps, although there is some doubt about this, since the main dumps seem to be undisturbed. Cooper and Stanley (1990) note the presence of 'limonite'. Brown stains and crusts of limonitic ochres are very abundant on dump material and are probably mostly goethite. Rarely it is found as pseudomorphs of small pyrite crystals and saddle shaped crystals of dolomite up to 0.5 mm long. Less common are very dark brown to black botryoidal crusts which can reach 3 mm in thickness (Fig. 18).

## Gold, Au

The Kingsbury Collection in the NHM contains a single specimen of gold labelled from the 90 fathom level dumps of Roughton Gill Mine and claimed to have been collected in 1960. It consists of a small area of hackly gold in a brown quartz matrix with grey copper sulphide oxidising to malachite. The specimen has obviously been broken into at least two parts, but there is no sign of the remainder of the specimen in the collection. Grey copper sulphides are rare at Roughton Gill, the specimen does not look typical of the site and no other collector has found gold here. This specimen must be considered fraudulent.

## Grey Copper(I) Sulphides

This is used here as a general term for copper(I) sulphides with the general formula  $\text{Cu}_{2-x}\text{S}$ , where 'x' is a small number including zero. It includes minerals such as chalcocite, digenite, djurleite etc. Grey sulphides are not common at Roughton Gill, being mainly restricted to thin alteration rims around chalcopyrite and galena.

Kendall (1884) reported chalcocite from Roughton Gill, but at that time it would not have been possible to differentiate it from related copper sulphides. An attempt to positively identify the sulphides on two samples by XRD was only partially successful. One was clearly a bad sample, but chalcocite seemed to be the dominant component of the other.

## GYPSUM, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$

A single specimen of sphalerite in quartz in the Tim Neall Collection has a small area encrusted in minute 'selenite' crystals of gypsum. It is clearly post-mining in origin.

## Hematite, $\text{Fe}_2\text{O}_3$

Davidson and Thomson (1951) note the presence on the dumps of a 'red massive substance' that they considered to be hematite. In this study it has been noticed that some of the goethite encrustations have dehydrated to give a red colour and streak. However, these seem to be X-ray amorphous and to consist of an iron-rich silica gel and it is safest not to include hematite in the list of minerals for the site.



**Figure 18.** Goethite on quartz. Specimen width 7 cm.

## HEMIMORPHITE, $\text{Zn}_4\text{Si}_2\text{O}_7(\text{OH})_2 \cdot \text{H}_2\text{O}$

Hemimorphite is one of the three minerals for which Roughton Gill Mine is justly famous. Beautiful sky blue botryoidal crusts were found in the 19<sup>th</sup> century, sometimes reaching 3 cm thick. A good description of the occurrence is in Cooper and Stanley (1990, pp. 88-89; with pictures of classic specimens on pages 71 and 98). Specimens are to be found in major museums throughout the world and small specimens have been found on the 90 fathom dumps into the period of this study.

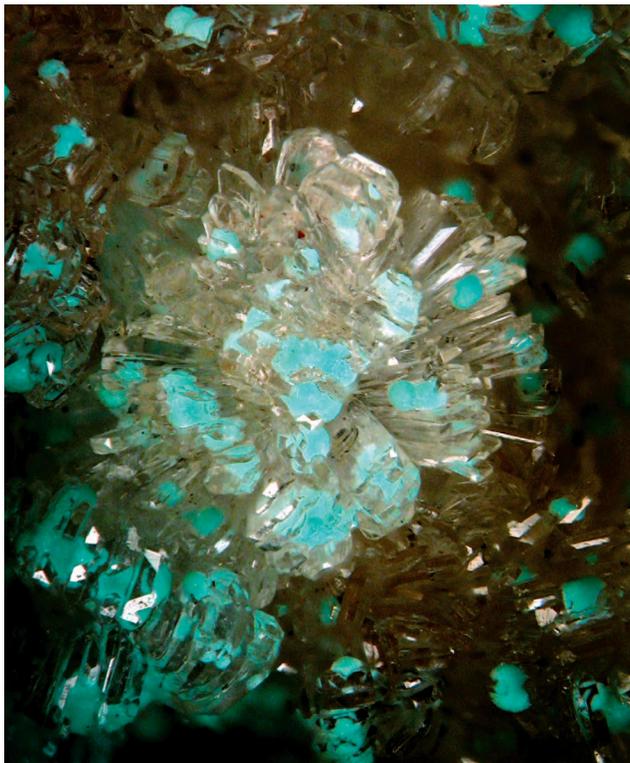
The classic form of the blue botryoidal hemimorphite has a smooth surface (Fig. 19) and similar smooth white botryoidal specimens are common. Sometimes the blue hemimorphite has a drusy surface which again is replicated



**Figure 19.** Hemimorphite, 95 mm wide. R.J.King specimen in the National Museum of Wales collections (NMW 83.41G.M.6138).



**Figure 20.** Cluster of 1 mm hemimorphite crystals.



**Figure 21.** Hemimorphite crystal cluster, 3 mm across, with rosasite.



**Figure 22.** Hydrocerussite crystal groups, 1.6 mm across, on iron stained quartz.

in numerous modern white and colourless specimens. The drusy surface often becomes more open, giving crusts of radiating bladed crystals, which again can be blue, but more commonly are colourless. Also very common are open cellular masses of colourless radiating blades, with individual crystals reaching 5 mm although usually much less than this (Fig. 20; see p. 13). Rosasite is a common associate of these masses (Fig. 21), but as Cooper and Stanley (1990) note, the botryoidal forms are not usually coated with other minerals beyond a little pyromorphite.

Hemimorphite is associated with rosasite on a group of small specimens in the Kingsbury Collection in the NHM. It consists of small typical radiating blades and there is no reason to doubt they are from Roughton Gill.

## HYDROCERUSSITE, $Pb_3(CO_3)_2(OH)_2$

Hartley (1984) notes the presence of hydrocerussite on specimen material collected by Kingsbury from all three levels, but no specimens could be found in Kingsbury's collection in the NHM.

It is very rare, but has been found on a few specimens from the 90 fathom dumps where it occurs as crusts of thin white plates, often with a near semi-circular shape, and with individual crystals up to 1.6 mm across, in cavities in quartz (Fig. 22). One of the specimens of quartz examined contained a mass of white material 5 mm across with the appearance of cerussite, but with a distinct cleavage in places. It is probably a mass of hydrocerussite partly altered to cerussite.

## HYDROZINCITE, $Zn_5(CO_3)_2(OH)_6$

White encrustations of hydrozincite on sphalerite are rare, but do occur. They are probably the result of dump alteration.

## Illite (A group of micaceous minerals)

Young (1987) notes that a member of the illite family has been reported from Roughton Gill Mine spoil heaps. In this study, minute aggregates of buff micaceous crystals, no more than 0.2 mm across, occur in cavities in quartz and may be the same material.

## LANGITE, $Cu_4(SO_4)(OH)_6 \cdot 2H_2O$

Langite is very rare, but has been found as a microcrystalline (<0.1 mm) crust of blue crystals on a matrix of chalcopyrite and quartz and as similar sized blocky crystals on a grey copper sulphide and as similar sized crystals scattered thinly on iron stained quartz.

## LEADHILLITE, $Pb_4(SO_4)(CO_3)_2(OH)_2$

Early specimens of leadhillite, attributed to Roughton Gill Mine, may well have originated from Higher Roughton Gill or Red Gill. In the present study it is very rare, but has been found as thin hexagonal plates reaching 2.5 mm across on quartz with small crystals of linarite and cerussite in association (Fig. 23).

## LEPIDOCROCITE, $\gamma\text{-FeO(OH)}$

On two specimens in the Mike Leppington Collection, mats of radiating dark brown goethite have extremely thin glassy brown near circular plates of lepidocrocite, partly amalgamated into irregular hemispheres, perched on their surface.

## LINARITE, $PbCu(SO_4)(OH)_2$

Some early excellent linarite specimens are attributed to Roughton Gill Mine, but Davidson and Thomson (1951) expressed doubts about the provenance, an opinion supported by Bridges *et al.* (2008) who used mineralogical and geochemical evidence to support the view that these specimens actually originated from Red Gill Mine.



**Figure 23.** Leadhillite crystals, 2.5 mm across on quartz.



**Figure 24.** A 3 mm crystal of linarite with malachite on quartz.

In this study linarite is a fairly rare mineral; most specimens taking the form of a thin blue crust and are clearly a dump alteration product of galena and chalcopyrite. Crystals, when found, take the form of royal blue blades up to a maximum of 3 mm long. Figure 24 shows a 3 mm crystal associated with malachite, but also see Figure 11, where linarite occurs in association with caledonite and leadhillite.

## MALACHITE, $\text{Cu}_2(\text{CO}_3)(\text{OH})_2$

Excellent specimens of malachite have long been known from Roughton Gill Mine (Greg and Lettsom, 1858; Goodchild, 1884). Cooper and Stanley (1990) note that it was an important ore. It remains abundant in specimen material and it is interesting to note that several of the specimens examined appear to be iron stained brecciated quartz and metasomatised rock cemented by malachite, which may be small examples of malachite as an ore.



**Figure 25.** Radiating needles of malachite, 10 mm long on goethite and quartz.



**Figure 26.** Malachite with cerussite. Field of view 30 mm wide. R.J. King specimen in the National Museum of Wales collections (NMW 83.41G.M.4732).

In cavities it is common as mats of fibrous needles a few millimetres high which can cover areas over 10 cm across and botryoidal encrustations of similar size. Aggregates of radiating bright emerald green needles reach 10 mm in length in some cavities and small blocky crystals also occur. By far the commonest associated minerals are cerussite and hemimorphite. Figure 25 (see p. 15) illustrates a radiating crust of needles 10 mm long and Figure 26 (see p. 15) shows a typical association with cerussite.

#### Mattheddleite, $Pb_{20}(SiO_4)_7(SO_4)_4Cl_4$

Mattheddleite is very rare having only been noted on a single 4 cm specimen where it lines four 5 mm cavities as sprays of minute (<0.1 mm) needles. The matrix is iron stained quartz-galena and associated minerals are susannite, cerussite and hydrocerussite. On the reverse of the specimen is yellow pyromorphite. Regrettably, although the specimen was found on the 90 fathom dumps, it is very similar to material from Higher Roughton Gill and the possibility of it having originated there cannot be dismissed. For this reason the provenance is considered doubtful. Figure 27 shows typical sprays of the mattheddleite on the specimen.

#### OXYPLUMBOROMEITE (BINDHEIMITE), $Pb_2Sb_2O_6(O,OH)$

This mineral has recently been re-named as part of the reclassification of the pyrochlore group of minerals (Atencio *et al.*, 2010). It occurs rarely as pale yellow powdery crusts in cavities with cerussite, anglesite and in one case with leadhillite and linarite.

#### Parahopeite, $Zn_3(PO_4)_2 \cdot 4H_2O$

Hartley (1984) noted the presence of parahopeite on a specimen Kingsbury claimed to have collected from the



Figure 27. Needles of mattheddleite lining a cavity in quartz. Image width 1.5 mm.

60 fathom dumps. The specimen could not be found in the NHM and no other collector has found the mineral in the Caldbeck Fells. It has to be considered fraudulent (see Discussion).

#### PLUMBOGUMMITE, $PbAl_3(PO_4)_2(OH)_5 \cdot H_2O$ *Hidalgoite*, $PbAl_3(As,S)O_4(OH,H_2O)_6$ *Hinsdalite*, $PbAl_3[(P,S)O_4]_2(OH,H_2O)_6$

These three minerals are considered together due to analytical work carried out by Förtsch (1964). They are all closely related members of the alunite/jarosite group.

Regarding plumbogummite, Roughton Gill Mine is well known world wide for the magnificent blue specimens that were found in the 19<sup>th</sup> century. Cooper and Stanley (1990, pp. 115-118) give a good summary of the early finds of the mineral and the confusion that reigned over its composition into the 20<sup>th</sup> century. They include several photographs of Roughton Gill specimens and a picture of the mineral is featured on the front cover. The plumbogummite occurs mainly as smooth to drusy crusts on quartz and often overcoats or pseudomorphs pyromorphite (Fig. 28). In turn, the plumbogummite is often encrusted with crystals of pyromorphite and these specimens are generally considered to be the most desirable. Figure 29 shows a specimen originally from the Harwood Collection and then the King Collection, now in the National Museum of Wales, and Figure 30 a very large specimen of plumbogummite with pyromorphite in the NHM collections. Specimens of the mineral have been found on the 90 fathom dumps in the period of this study, but they are very rare and do not compare with the old time specimens.

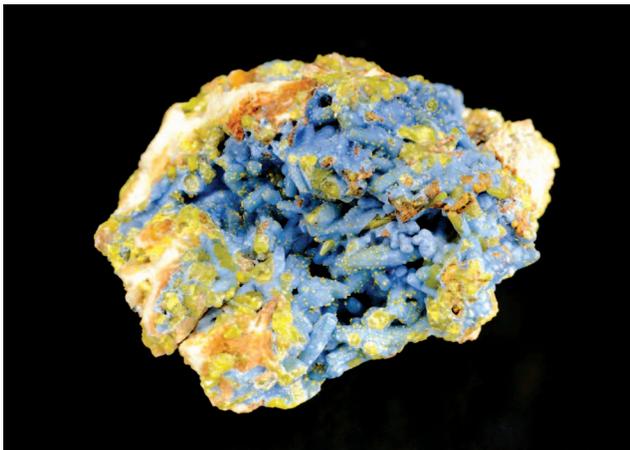
Förtsch (1964) carried out XRD, optical and infrared studies, but no detailed chemical analysis, on a single specimen of plumbogummite from 'Roughton Gill, Cumberland' in the collection of the Mineral Museum, University of Bonn, Germany. He compared theoretical compositions from the above with a chemical analysis of plumbogummite carried out by Hartley (1900). He found evidence for the presence of sulphate, carbonate and probably arsenate and showed the specimen was zoned across an encrustation on a pyromorphite crystal. He concluded the specimen was probably a 'carbonate-bearing mix-crystal of plumbogummite, hinsdalite and hidalgoite'. Since these minerals almost certainly form at least a partial tri-partite system of phosphate, arsenate and sulphate, it is unlikely that the mineral is outside the compositional field of plumbogummite. At this stage, it is considered safest not to include hinsdalite and hidalgoite in the list of species from Roughton Gill, but it would be very interesting to carry out wavelength dispersive spectrometry on several specimens to see if bands of these two minerals are present across crystals. A recent paper by Grey *et al.* (2011) analysed plumbogummite from Dry Gill Mine and found a low percentage of substitution of carbonate for phosphate. It would be interesting to see if the same substitution applies to Roughton Gill material.

## PYRITE, FeS<sub>2</sub>

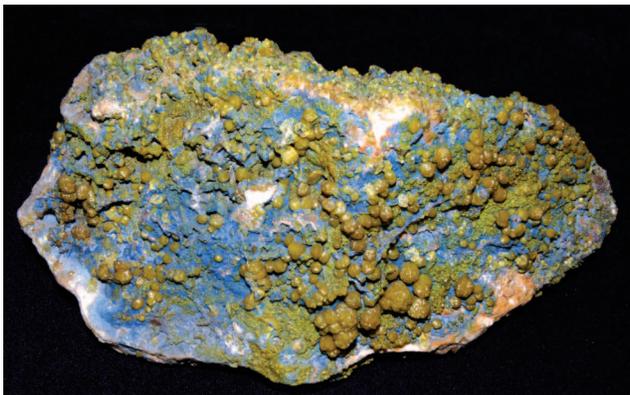
Pyrite is surprisingly rare having only been found on two specimens in this study. On both it occurred as a crust of cubo-octahedral crystals up to 1 mm across covering an area about 20 mm across on dolomite and quartz. It is possible the mineral is more common and has just been neglected by collectors.



**Figure 28.** Plumbogummite encrusting pyromorphite. Field of view 9 mm. R.J. King specimen in the National Museum of Wales collections (NMW 83.41G.M.7825).



**Figure 29.** Plumbogummite and pyromorphite. Specimen width 42 mm. R.J. King specimen in the National Museum of Wales collections (NMW 83.41G.M.7821).



**Figure 30.** Plumbogummite with pyromorphite. Specimen width 22 cm.

## PYROMORPHITE, Pb<sub>5</sub>(PO<sub>4</sub>)<sub>3</sub>Cl MIMETITE, Pb<sub>5</sub>(AsO<sub>4</sub>)<sub>3</sub>Cl

It should be noted that it is difficult to be certain that the pyromorphite examined in this study is not from 'Barstow's Trench' or from the slopes of Iron Crag. It is intended to describe these localities as part of a later paper.

Hartley (1984) reports the presence of pyromorphite on material collected by Kingsbury from all three levels. There is no reason to doubt the presence of the mineral on material from these levels, but the only specimen in the Kingsbury Collection in the NHM and claimed as collected by him is similar in appearance to specimens from the slopes of Iron Crag.

Pyromorphite occurred in hundred tonne quantities and was an important ore (Cooper and Stanley, 1990). In addition, the mine became known in the 19<sup>th</sup> century for producing fabulous specimens which are now found in museum collections world wide, the 60 fathom level in particular being very prolific (Cooper and Stanley, 1990). Perhaps best known of all are the specimens where it occurred in association with plumbogummite. Examples of all of these are figured in Cooper and Stanley (1990, pp. 122-123), but another excellent specimen is shown here in Figure 31. The Kingsbury Collection contains material



**Figure 31.** Pyromorphite from Roughton Gill. Specimen width 8 cm. Natural History Museum specimen and photograph.



**Figure 32.** Pyromorphite from the Thomas Kingsbury Collection. Specimen width 8 cm. Natural History Museum specimen and photograph.

from the Thomas Kingsbury Collection (Arthur Kingsbury's great grandfather), but we know Arthur Kingsbury added specimens to the older Thomas's collection. It includes some excellent specimens of pyromorphite and an unusual one is shown in Figure 32 (see p. 17).

Mimetite has also long been recorded from Roughton Gill Mine. A specimen figured in Cooper and Stanley (1990, p. 70) is noted as having been collected by J.G. Goodchild in 1890 and is now in the King Collection within the National Museum of Wales. However, recent analysis of this specimen shows it to be an arsenate-rich pyromorphite with a phosphorus to arsenic ratio of approximately 2:1 (Tom Cotterell, *personal communication*). There are several other arsenate-rich pyromorphite specimens in the King Collection and also in the collections of the NHM. Several references to mimetite at Roughton Gill are listed by Cooper and Stanley (1990) and Tindle (2008), but without clear analysis to confirm that arsenic is dominant.

Pyromorphite/mimetite has remained an abundant mineral into the period covered by this study. Crystals vary widely in colour usually from pale to bright grass green and shades of pale to golden-yellow and rarely colourless. The commonest form is globular to barrel shaped crystals up to 10 mm on the longest dimension, but hexagonal crystals up to 5 mm occur and minute hexagonal crystals occasionally form crusts. Rarely the hexagonal form is overgrown by globular crystals. Encrustations of pyromorphite on hackly quartz and metasomatised rock are the commonest occurrence, but associations with cerussite, malachite and 'chrysocolla' also occur.

In this study, following the procedure used at other localities in the Dale Beck Valley, 25 crystals were checked for arsenic by EDS. One specimen contained two distinct generations of near end member mimetite, one generation being small pale buff hexagonal tablets and the other small tapering bright green needles. One other specimen contained both near end member pyromorphite and arsenate-rich pyromorphite and a further six specimens contained arsenate-rich pyromorphite. Fourteen specimens were near end member pyromorphite. It is clear that pyromorphite and arsenate-rich pyromorphite are far more common than mimetite at the site, but visually they are all indistinguishable.

#### QUARTZ, $\text{SiO}_2$

Quartz is by far the main gangue mineral remaining on the dumps today. It occurs as large blocks, often partly encrusted with supergene minerals such as goethite, malachite and pyromorphite. Much of the quartz has been brecciated and is cemented by later quartz and other minerals. Small to large blocks often have a hackly appearance, which is often assumed to indicate they are pseudomorphs or epimorphs of baryte. Small pyramidal crystals are common, but rarely reach more than 10 mm across.

Small bands of white chalcedony are also common on many of the specimens examined, the chalcedony grading into crystalline quartz.

#### Ramsbeckite, $(\text{Cu,Zn})_{15}(\text{SO}_4)_4(\text{OH})_{22} \cdot 6\text{H}_2\text{O}$

A scattering of minute (0.25 mm) emerald green boat shaped crystals on pearly schulenbergite are considered to be ramsbeckite on morphological and environmental grounds, but full identification would result in complete destruction of the specimen. The matrix consists of sphalerite and chalcocopyrite in quartz and there is minor linarite on the same specimen. It has clearly formed as a result of post-mining alteration.

#### ROSASITE, $(\text{Cu,Zn})_2(\text{CO}_3)(\text{OH})_2$

Rosasite was first reported in the British Isles by Kingsbury and Hartley (1957), who described several occurrences in the Lake District, mainly in the Caldbeck Fells and including Roughton Gill Mine. Although rosasite is widespread, usually in small amounts in British orefields, it is very common at Roughton Gill and it is surprising the mineral was overlooked for as long as it was. The Kingsbury Collection contains a group of small specimens of rosasite from the 60 fathom dumps. Collected in 1950, the rosasite is associated with hemimorphite; the specimens are typical of the site and there is no reason to doubt the validity of the Kingsbury and Hartley report.

On the 90 fathom dumps, it occurs as small (up to 1 mm) blue green hemispheres perched as individuals on other minerals, particularly hemimorphite, but commonly the hemispheres aggregate to form continuous botryoidal crusts which can cover areas up to 20 cm<sup>2</sup>. Figure 33 shows a typical small but rich specimen of rosasite on hemimorphite.

#### Schulenbergite, $(\text{Cu,Zn})_7(\text{SO}_4)_2(\text{CO}_3)_2(\text{OH})_{10} \cdot 3\text{H}_2\text{O}$

Minute turquoise crystals consisting of thin hexagonal plates reaching 0.25 mm across, scattered on an area 20 mm by 5 mm on a matrix of quartz and sphalerite are almost certainly schulenbergite. There is too little material for testing without totally destroying the specimen.

#### SERPIERITE, $\text{Ca}(\text{Cu,Zn})_4(\text{SO}_4)_2(\text{OH})_6 \cdot 3\text{H}_2\text{O}$

Serpierite is very rare, but has been found as small radiating sprays of turquoise crystals up to 1 mm long, occasionally aggregating to cover areas up to 10 mm across. It has formed in cavities and on fractures in quartz, chalcocopyrite and sphalerite with associated hemimorphite and smithsonite.

#### SILVER, Ag

Native silver is extremely rare. Only one specimen is known, which is in the Mike Leppington Collection. It consists of silver plates, tarnishing with acanthite, reaching no more than 0.3 mm across in cavities in a quartz-calcite matrix.

#### SMITHSONITE, $\text{ZnCO}_3$

This mineral is surprisingly rare considering how common other supergene carbonates are on the site and the abundance of hemimorphite. It has been found as typical crusts of rounded buff coloured crystals, individual crystals



**Figure 33.** Rosasite on cellular hemimorphite. Specimen width 6 cm.



**Figure 34.** A group of 0.4 mm crystals of smithsonite.

being less than 1 mm diameter. It is usually associated with hemimorphite and sphalerite (Fig. 34).

### SPHALERITE, (Zn,Fe)S

Hartley (1984) lists sphalerite as occurring on material from the 60 fathom level, claimed to have been collected by Kingsbury, but the specimen could not be found in the NHM.

In this study, sphalerite is uncommon, but has been found mainly as brown cleavage fragments, a few millimetres across, in the matrix of specimens of supergene minerals such as hemimorphite and smithsonite. One specimen in the Tim Neall Collection consists of a layer 10 mm thick, with a crystalline surface, on wallrock and partly coated with 2 to 3 mm nailhead calcite crystals. Minor oxidation to hemimorphite is evident on this specimen.

### SULPHUR, S

Minute very pale yellow crystals of sulphur (0.1 mm), amalgamating to form small crusts, have been noted on oxidised galena, but are very rare.

### Susannite, $Pb_4(SO_4)(CO_3)_2(OH)_2$

Cooper and Stanley (1990; Fig. 107, p. 129) report susannite with caledonite from Roughton Gill on a specimen in the Ludlam Collection in the NHM, but the specimen has



**Figure 35.** Blue susannite crystals in a cavity lined with mattheddleite. Field of view 1.5 mm.

the appearance of material from the Roughton South Vein on Balliway Rigg. In this study, it has only been found on one specimen, where it is associated with mattheddleite in one cavity (Fig. 35) with several minute crystals in another cavity. However the provenance is considered doubtful for the reasons outlined previously under ‘mattheddleite’.

### Tenorite, CuO

Greg and Letsom (1858) and Day (1928) note the presence of this mineral at Roughton Gill, but Davidson and Thomson (1951) comment that they were unable to find it. This mineral can only be identified reliably by XRD and as it has not been identified in this study it is considered that it should not be included in the list of Roughton Gill minerals.

### TSUMEBITE, $Pb_2Cu(PO_4)(SO_4)(OH)$

### ARSENTSUMEBITE, $Pb_2Cu(AsO_4)(SO_4)(OH)$

Small (c. 0.25 mm) apple green drusy crystals of ‘tsumebite’ in association with brochantite were noted by Cooper and Stanley (1990). It remains an uncommon mineral, but has been found in the current study as crusts of similar sized crystals, again associated with brochantite (Fig. 36; see p. 20).

Tindle *et al.* (2006) analysed four ‘tsumebite aggregates’ and showed the presence of arsenic in all of them. The arsenic becomes richer towards the outside of the crystals and in one case, at the outer edge of the  $AsO_4/PO_4$  site, is 53 mol%  $AsO_4$  and just falls within the arsentsumebite field.



**Figure 36.** Aggregate of 0.25 mm tsumebite crystals with brochantite.

### WOOLDRIDGEITE, $\text{Na}_2\text{CaCu}_2(\text{P}_2\text{O}_7)_2 \cdot 10\text{H}_2\text{O}$

A copper calcium sodium pyro-phosphate hydrate occurring as ‘sprays of tapering bladed aquamarine crystals’ was described as an unknown species from the dumps of Roughton Gill Mine by Cooper and Stanley (1990, pp. 132-133). An identical mineral was characterised on specimens collected in 1989 at Judkins Quarry, Nuneaton, Warwickshire (Hawthorne *et al.*, 1999). These localities remain the only places in Britain where wooldridgeite has been identified.

Wooldridgeite was identified on a few small specimens collected by the late Peter Braithwaite and the late John Dickinson on the 90 fathom level dumps at Roughton Gill Mine. It occurs as pale ice-blue tapering prismatic crystals, which exceptionally reach 1.8 mm in length, but are usually much smaller than this. The crystals are commonly associated with ‘chrysocolla’ in porous quartz. They are very late in the paragenetic sequence. A few overgrow recent fractures in the quartz matrix which indicate a post mining origin. It has not been found in this study.

### WULFENITE, $\text{PbMoO}_4$

A single small specimen of pyromorphite on a cellular quartz matrix in the Tim Neall Collection has a scattering of minute thin yellow plates of wulfenite which reach a maximum size of 0.5 mm on edge. The size of the crystals is so small that they are easily overlooked and the mineral may be more common than this single specimen implies.

## DISCUSSION

The Discussion is divided into two parts. The first considers the mineralogy of Roughton Gill Mine itself, based on the minerals it is considered safe to include in a list of species. The second part discusses the problems of provenance with minerals in collections which purport to originate from the mine, but about which there has to be some doubt.

### The mineralogy of Roughton Gill Mine

The primary mineralisation of Roughton Gill Mine consists of galena, chalcopyrite and sphalerite in a gangue dominated by quartz, but with significant amounts of dolomite and calcite. All of these minerals are present on specimen material and most could be found on the dumps into the 1990s. This mineralisation is typical for most of the mines in the Caldbeck Fells, which worked E-W or near E-W orientated veins, apart from the large amount of carbonate present, which is unusual for the ore deposits in the Dale Beck valley.

The supergene alteration of the deposit is exceptional in two important respects:

1. The scale and depth of the alteration far surpasses any other deposit in northern England and is really only matched by those of SW England and the Leadhills/Wanlockhead deposits.
2. The vast amounts of pyromorphite (with some mimetite) are unique in the British Isles.

Discussing these in turn, most of the supergene deposits in the area are relatively small and it is not unreasonable to believe that most formed by weathering processes (oxidation) in the period since the last glaciation. The large linarite specimens from Red Gill Mine may have required longer to form, but probably no more than the previous inter-glacial. The Roughton Gill Mine supergene mineral deposit was so large that it is difficult to believe it could have formed since the last glaciation. Cooper and Stanley (1990) suggest the supergene mineralisation may be related to sericitic alteration of the host rocks in Jurassic times, which would certainly give plenty of time for the deposit to form. However, on the whole, the mineralogy is typical of oxidation by air and rain water rather than a hydrothermal process. It is possible the magnitude of the alteration is related to the width of the vein and the fact that the South Vein is very close to the face of Iron Crag, which could have kept the entire vein above the water table. Even so, the vein contained significant amounts of carbonate and galena is very slow to oxidise under such conditions, as evidenced by deposits in the Pennines where sphalerite and pyrite have often virtually completely oxidised, but galena is affected to a much smaller degree. Although it is impossible to be sure, it does seem likely that the Roughton Gill Mine supergene assemblage is at least partly older than the last glaciation.

Pyromorphite, a very stable and insoluble mineral, normally forms when galena oxidises in an environment where phosphate is being released into the groundwater by the weathering of phosphatic rocks, particularly

shales. In the case of the Roughton South Vein, the source of the phosphate is probably weathering of the apatite-rich ferrodiorite which occurs over a wide range of the surrounding area. Galena, oxidising in an apatite-rich environment, readily forms pyromorphite. The large amount of hemimorphite and 'chrysocolla' in the deposit also testifies to extensive wall rock weathering in order to provide the necessary silica.

The source of the arsenic required by mimetite, the arsenate-rich pyromorphite and the arsenic-rich tsumebite/arsentsumebite is a matter for speculation. The arsenopyrite bearing veins of the Carrock Fell area extend northwards in the Caldbeck Fells and account for the common arsenic bearing supergene assemblages in the area to the east of the Dale Beck Valley. The N-S veins of the area are older than the E-W veins and once emplaced, it is difficult to believe that arsenopyrite could be re-mobilised by the lower temperature hydrothermal activity of the E-W veins. It is possible the later copper/lead mineralisation carried small amounts of arsenopyrite into the deposits and in this respect the large size of the Roughton South Vein may have facilitated this. It is also possible that very minor fractures associated with the earlier N-S mineralisation deposited small amounts of arsenopyrite in the Dale Beck Valley, but this mineral has never been identified here. On balance, minor amounts of arsenic in the later mineralisation seems the most likely.

The rest of the supergene mineralisation is dominated by carbonates such as malachite and cerussite and is typical of oxidation of ore deposits with abundant primary carbonates, which keep pH, carbonate ion activity ( $a_{\text{CO}_3^{2-}}$ ) and partial pressure of carbon dioxide ( $p_{\text{CO}_2}$ ) relatively high. Thus, minerals which require low levels of these parameters, such as anglesite, leadhillite and caledonite, are comparatively rare when compared with other mines in the Caldbeck Fells. The supergene mineralisation at Roughton Gill Mine is in some respects more similar to that of the Pennines than it is to most of the remainder of the Caldbeck Fells. However, in this type of environment, azurite might be expected to be more common than it is. Possibly the deposit contained too little pyrite to generate the amount of sulphuric acid required to generate the really high  $p_{\text{CO}_2}$  required for azurite formation. Certainly pyrite proved to be very rare in this study.

### **The problems of provenance with minerals in collections which purport to originate from Roughton Gill Mine**

Regarding the provenance of specimens, Roughton Gill Mine was the dominant metalliferous mine in the area and early in its working became well known for magnificent specimens of pyromorphite, hemimorphite and other minerals. The result is a tendency for specimens of unknown provenance to be attributed to this mine. It can be seen in the History section that early specimens with unspecific locations have later been labelled from Roughton Gill, probably quite accurately in most cases. Even in fairly recent times there is reason to think that specimens from 'Barstow's Trench', Mexico Mine, the slopes of Iron Crag

and Higher Roughton Gill have been given a Roughton Gill Mine label. In addition, Bridges *et al.* (2008) provide mineralogical and geochemical evidence to support a long held view that the splendid specimens of linarite, leadhillite and caledonite attributed to Roughton Gill Mine actually came from Red Gill Mine and it is worth noting that the current study fully supports those conclusions.

Two of the minerals described above, namely mattheddleite and susannite which occurred on the same specimen, gave cause for concern, since superficially the specimen looked similar to material from the nearby Red Gill Mine. However, detailed inspection showed the presence of yellow pyromorphite which would be very unusual for Red Gill. However, the specimen is typical of material from Higher Roughton Gill and could possibly have come from there and been dropped on the 90 fathom dumps.

Hartley (1984) and Kingsbury and Hartley (1957) report numerous minerals from the mine, most of which cannot be found in the Kingsbury collection. Nearly all have been independently identified in this study and, with a few exceptions, there is no reason to doubt the original reports. This is particularly important in the case of rosasite, which was a first report of the mineral in the British Isles. The two clearly fraudulent claims are gold and parahopeite and the azurite is very doubtful. The parahopeite (zinc phosphate) is interesting in that it shows how clever Kingsbury was when making fraudulent claims. Since zinc minerals are common at Roughton Gill and phosphates abundant, there is, on the face of it, no reason why a zinc phosphate mineral should not occur. This parallels the claim of lindgrenite (copper molybdate) at Brandy Gill Mine, shown to be fraudulent by Ryback *et al.* (2001).

Specimen material supporting this study has been placed in the collections of the Natural History Museum, London, the Oxford University Museum of Natural History and the Great North Museum (Hancock), Newcastle.

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## ALLUVIAL OCCURRENCES OF FERGUSONITE AND GADOLINITE IN THE MOURNE MOUNTAINS, NORTHERN IRELAND

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Mineral grains of the rare-earth-element-bearing minerals fergusonite-(Y) and gadolinite-(Y) are reported within alluvial sediment derived from the granitic Mourne Mountains (the Mournes) in northeast Ireland. Fergusonite (ideally  $\text{YNbO}_4$ ) has not previously been described from Ireland (Tindle, 2008). A single crystal of gadolinite (ideally  $\text{Y}_2\text{Fe}^{2+}\text{Be}_2\text{Si}_2\text{O}_{10}$ ) from the Mournes was described by Lacroix (1888) and subsequently Burke *et al.* (1964) mentioned occurrences of gadolinite at two localities, Blue Lough and Diamond Rocks, in the eastern-central Mournes, but to our knowledge no specimens are preserved.

Hyslop *et al.* (1998) describe fergusonite and gadolinite occurring in drusy granite in northern Arran (Strathclyde, Scotland). This was the first in situ occurrence of these mineral species in the British Isles to be confirmed by X-ray analysis. Fergusonite is also recorded from alluvial sediment at several localities in Scotland including Glen Lui, Grampian (Haynes, 1974, cited in Hyslop *et al.*, 1998). Occurrences of gadolinite in the granites of the Red Cuillin, Isle of Skye, Scotland, are mentioned by Green and Todd (2001).

The newly discovered occurrences are in samples of heavy mineral concentrate collected by panning as part of a wider study of alluvial gold and cassiterite within the western Mournes (Warner *et al.*, 2010). Fergusonite and gadolinite were identified by EMPA in resin-mounted mineral concentrate samples comprising thousands of grains 50-300  $\mu\text{m}$  in diameter that are broken and abraded due to alluvial transport. Optical properties such as colour were not observed as the mineral grains are in coated polished blocks. Of the six samples examined, fergusonite was found in three and gadolinite in one. The fergusonite-bearing samples are from the Rivers Bann and Leitrim near Hilltown [Irish Grid J 219 291, J 229 287 and J 213 254], and the gadolinite is in a sample from the White Water, south of Pigeon Rock Mountain [J 271 221]. Whereas only

a few grains of gadolinite were found, the abundance of fergusonite ranges up to approximately 5% by volume of the mineral concentrates.

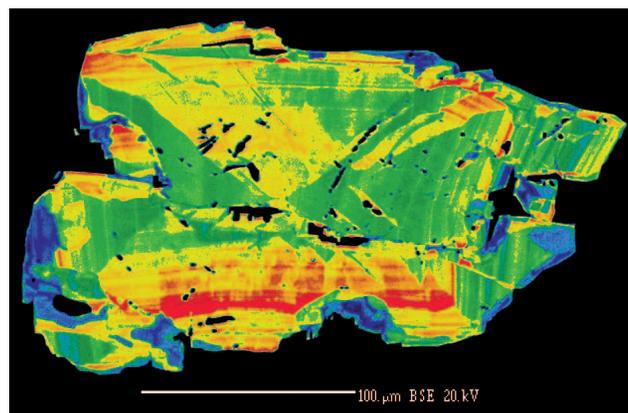
There is no reason to believe that fergusonite and gadolinite are restricted to these localities, indeed considering the enrichment of the granite in rare earth elements (REEs) (Meighan *et al.*, 1984) it is likely that these mineral species are quite widespread in alluvial sediment in the Mournes. This assertion is supported by XRF analyses of the heavy mineral concentrates that show Nb concentrations typically in the range 100-1000 ppm, suggesting the presence of fergusonite and/or other Nb-bearing species in alluvium throughout the western Mournes.

The REE-bearing grains were analysed by EMPA at The Open University using a Cameca SX100 electron microprobe operating at 20 kV and 20 nA (focussed beam) with a Bruker energy dispersive spectrometer, following the procedure described in Tindle (1982). REE-doped glasses obtained from Edinburgh University were used as standards for the REEs. Table 1 (see p.24) shows the compositional range from eight analyses of Mournes fergusonite and a typical composition. Due to substitution, some elements show a considerable range. An analysis of Arran fergusonite by Hyslop *et al.* (1998) is provided for comparison. Fergusonite is a heavy REE enriched species and there is clear similarity between Mournes and Arran fergusonite analyses. Mournes fergusonite has relatively higher Ca, Ce, Tb and possibly U, whereas the Arran fergusonite has higher Ti and Th. We note that EMPA cannot distinguish between fergusonite-(Y) and the monoclinic dimorph  $\beta$ -fergusonite-(Y): another analytical method (e.g. XRD, TEM or Raman spectroscopy) is required to distinguish between these. We found no evidence of metamict alteration of either fergusonite or gadolinite.

Back-scattered electron (BSE) imaging of Mournes fergusonite grains showed that internal features such as

zonation was absent. However, BSE imaging and X-ray mapping of gadolinite grains in the sample from White Water showed internal compositional heterogeneity with oscillatory and sector zonation (Fig. 1). Six EMPA analyses obtained from three gadolinite grains also showed compositional variation with one analysis markedly different to the others in having lower Ca, Y and heavy REEs (Dy, Ho, Er, Tm, Yb and Lu) and a higher proportion of light REEs (Ce). In comparison with the Mournes analyses, Arran gadolinite has much higher Fe and lower light REEs particularly La and Ce.

Also shown in Table 1 is a representative EMPA of monazite-(Ce) from the Mournes samples (this from the River Bann near Hilltown). Monazite-(Ce) is enriched in light REE and depleted in heavy REEs compared to fergusonite and gadolinite from the Mournes. The monazite-(Ce) incorporates relatively large amounts of thorium (7-10 wt% ThO<sub>2</sub>) but less uranium (<1 wt% UO<sub>2</sub>).



**Figure 1.** Sector- and oscillatory-zoned crystal of gadolinite-(Y) in a heavy mineral concentrate of alluvial sediment from White Water near Attical in the Mourne Mountains. False colour backscattered electron image: red to yellow indicate a relatively high atomic weight (Y and REE rich) whereas greens and blues indicate relatively low atomic weight (Si and Ca rich).

	Fergusonite-(Y)				Gadolinite-(Y)		Monazite-(Ce)
	Mournes (this study)		Typical	Arran	Mournes (this study)	Arran	R. Bann, Mournes
	Minimum	Maximum		Hyslop <i>et al.</i>	Typical	Hyslop <i>et al.</i>	Typical
SiO <sub>2</sub>					27.46	23.53	2.23
P <sub>2</sub> O <sub>5</sub>							27.58
CaO	<i>0.59</i>	<i>0.86</i>	0.82	0.48	1.67	0.60	0.14
FeO					7.75	12.41	
TiO <sub>2</sub>	<i>0.54</i>	<i>1.03</i>	0.97	1.31			
Y <sub>2</sub> O <sub>3</sub>	<i>20.38</i>	<i>30.64</i>	27.49	25.51	23.98	24.20	0.00
Nb <sub>2</sub> O <sub>5</sub>	<i>40.88</i>	<i>46.57</i>	44.42	44.93			
La <sub>2</sub> O <sub>3</sub>	<i>0.00</i>	<i>0.19</i>	0.11	0.05	0.90	0.18	16.48
Ce <sub>2</sub> O <sub>3</sub>	<i>0.75</i>	<i>1.68</i>	0.94	0.57	5.17	1.44	31.14
Pr <sub>2</sub> O <sub>3</sub>	<i>0.06</i>	<i>0.37</i>	0.15	0.24	1.27	0.45	3.25
Nd <sub>2</sub> O <sub>3</sub>	<i>1.43</i>	<i>3.07</i>	1.82	1.45	6.90	3.87	8.88
Sm <sub>2</sub> O <sub>3</sub>	<i>0.92</i>	<i>1.52</i>	1.17	1.07	2.96	3.51	0.74
Eu <sub>2</sub> O <sub>3</sub>	<i>0.00</i>	<i>0.12</i>	0.03		0.27	0.01	0.36
Gd <sub>2</sub> O <sub>3</sub>	<i>1.83</i>	<i>2.49</i>	2.21	2.00	3.62	5.92	0.65
Tb <sub>2</sub> O <sub>3</sub>	<i>0.44</i>	<i>0.65</i>	0.55	0.30	0.97	0.56	0.22
Dy <sub>2</sub> O <sub>3</sub>	<i>3.96</i>	<i>5.73</i>	4.59	3.89	4.48	5.73	0.40
Ho <sub>2</sub> O <sub>3</sub>	<i>0.84</i>	<i>1.32</i>	1.02	0.83	0.82	0.98	0.09
Er <sub>2</sub> O <sub>3</sub>	<i>3.00</i>	<i>5.02</i>	3.21	2.99	2.18	2.66	0.00
Tm <sub>2</sub> O <sub>3</sub>	<i>0.29</i>	<i>2.19</i>	0.59	0.65	0.10	0.47	0.01
Yb <sub>2</sub> O <sub>3</sub>	<i>2.62</i>	<i>5.57</i>	3.53	2.88	1.97	1.67	0.00
Lu <sub>2</sub> O <sub>3</sub>	<i>0.00</i>	<i>0.35</i>	0.10	0.66	0.08	0.51	0.00
ThO <sub>2</sub>	<i>1.17</i>	<i>4.06</i>	4.06	6.03		0.49	7.44
UO <sub>2</sub>	<i>1.86</i>	<i>4.19</i>	2.39			0.11	0.70
Total			100.18	95.84	92.54	89.30	100.31

**Table 1.** Analyses of fergusonite-(Y), gadolinite-(Y) and monazite-(Ce) from the Mournes (this study) and from Arran (Hyslop *et al.*, 1998). Values (in italics) in the fergusonite columns headed minimum and maximum are the lowest and highest values for each oxide amongst 8 analyses. The Arran fergusonite-(Y) also contains 2.19% Ta<sub>2</sub>O<sub>5</sub>; U<sub>2</sub>O<sub>5</sub> was not determined: In Mournes fergusonite, tantalum concentrations are below the detection limit of ca. 0.5% Ta<sub>2</sub>O<sub>5</sub>. Low totals in the gadolinite-(Y) analyses are mainly due to Be which cannot be analysed by ED microprobe techniques; data collected by other techniques indicate BeO contents of ~9 wt% are to be expected in this species.

This is consistent with previous research on U- and Th-bearing minerals in the Mourne (Moles *et al.*, 1995) which showed that monazite contains relatively low U and high Th, whereas zircon contains relatively high U and low Th.

Careful searching should eventually lead to discoveries of gadolinite and fergusonite *in situ* within granite in the Mourne Mountains. The gadolinite and fergusonite occurrences in Arran described by Hyslop *et al.* (1998) occur in drusy granite which was intruded in the Palaeocene, at about the same time as the Mourne granites. Both intrusions share other similarities, including relatively high silica and uranium contents, and distinct Sr, Nd and O isotope geochemistry, which make them distinct from the Palaeocene granites of Skye, Rum and Mull (Meighan *et al.*, 1992). These features support a hypothesis of prolonged cooling with less intensive meteoric water-rock interaction resulting in extreme magmatic fractionation and trace element enrichment in the southern sector granites of Arran and the Mourne (Hyslop *et al.*, 1998). Gadolinite and fergusonite crystallised from the last residue of evolved granite melt-fluid phase and may be granite-derived hydrothermal in origin.

## ACKNOWLEDGMENTS

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# DANBURITE FROM MELDON QUARRY, OKEHAMPTON AND OTHER UK LOCALITIES

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**Studies at the Natural History Museum, London (NHM) by the late George Ryback during 1999 and 2000 revealed the presence of danburite  $\text{CaB}_2\text{Si}_2\text{O}_8$  in grossularite-datolite skarn from Meldon Quarry in Devon. Published reports indicate that at least four, and possibly five localities of danburite already exist within the British Isles, but all except one at Red-A-Ven Brook Mine were reported by Arthur Kingsbury and are thus worthy of further investigation. Unpublished data of Ryback indicates that all four of the Kingsbury localities are likely to be invalid and thus the new occurrence at Meldon Quarry now represents the only clearly valid occurrence of danburite in the UK. This paper addresses the details of five previously published localities and presents a brief description of the confirmed occurrence at Meldon Quarry.**

## GEOLOGY

The extensive Meldon Quarry (also known as the British Rail Quarry, centred on National Grid Reference SX 572 924) lies within the contact aureole on the north-west margin of the Dartmoor granite and produces ballast and chippings for the railway network. Carboniferous shales, limestones, siliceous and calcareous mudstones have been metamorphosed by the granite into a variety of rock types, and boron metasomatism has led to the formation of borosilicates such as axinite and datolite at some localities in the region (Dearman, 1967; Edmonds *et al.*, 1968). The datolite bearing veins in metasomatised cherts in Meldon Quarry are described in detail by El Sharkawi and Dearman (1967) to which the reader is referred for further geological background pertaining to the role of boron in the region.

## RECENT STUDIES ON NEW MATERIAL

Recent short-wave UV light (SW-UV) examination of grossularite-datolite skarn specimens, initially using material in the collection of late George Ryback (as specimen GR 99-2) but collected by Richard Tayler in the early 1970's, revealed irregularly shaped fluorescent greenish-yellow patches with a combined surface expression of several  $\text{cm}^2$  in extent. These patches were noted as being significant within what appeared to be an otherwise nondescript, massive, greenish-whitish-brown hand specimen with few redeeming mineralogical features visible to the eye.

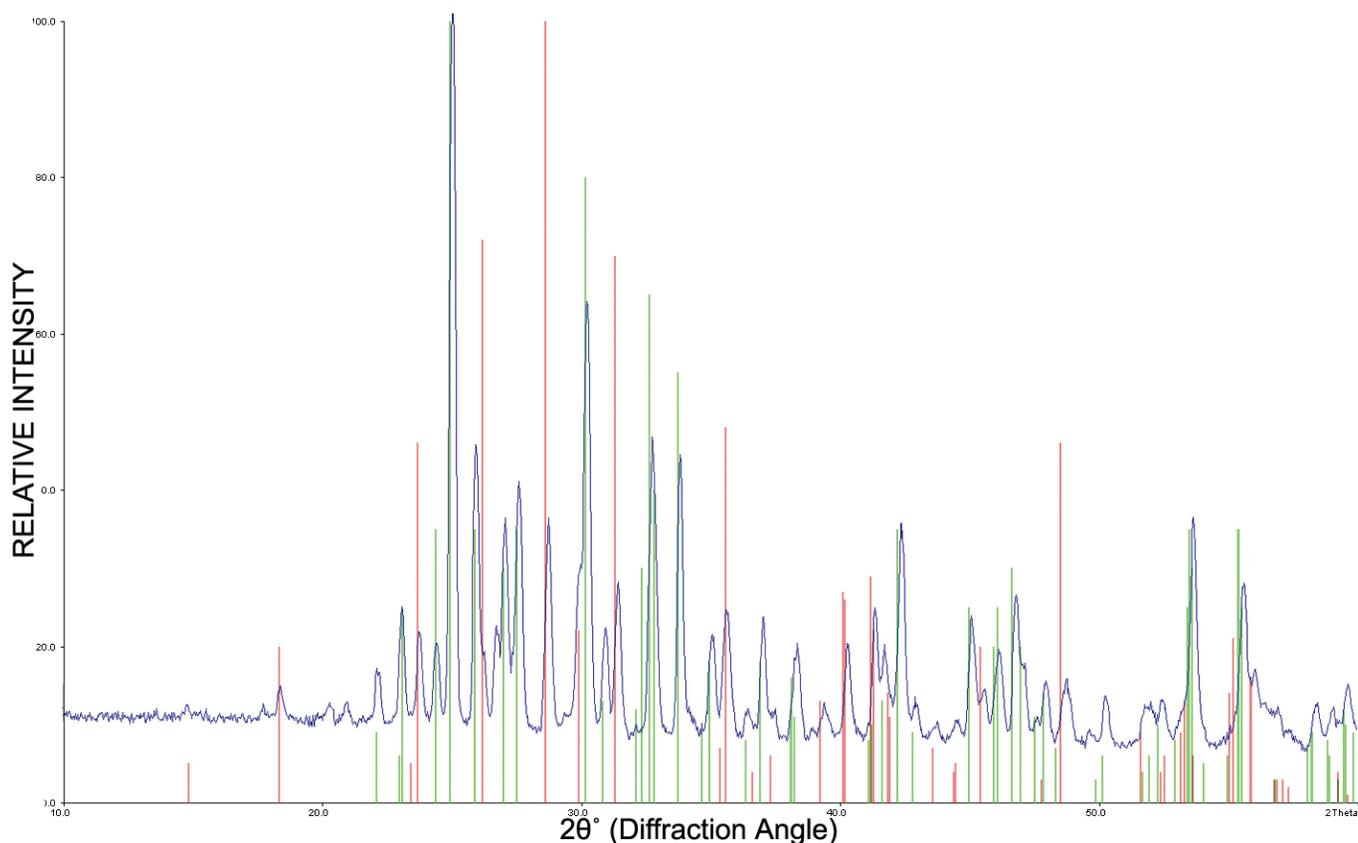
The fluorescent patches were first sampled by GR and studied using IR methods, which seemed to indicate that the fluorescent material was danburite ( $\text{CaB}_2\text{Si}_2\text{O}_8$ ) (IR ref. J954). Further IR analysis confirmed the presence of grossular garnet (IR ref. H248) and datolite ( $\text{CaBSiO}_4(\text{OH})$ ) (IR ref. H109). Further material was removed at the NHM and analysed using a powder X-ray diffraction technique using an Enraf-Nonius PDS120 utilising Cu radiation in conjunction with an INEL curved position sensitive detector  
† Deceased 2003

and the Diffgrab software packages. A small amount of material (circa  $2 \text{ mm}^3$ ) was removed from the specimen, ground to a powder using an agate pestle and mortar and placed on an  $\text{Al}_2\text{O}_3$  substrate for analysis. Silicon powder SRM640 and silver behenate were used as external calibration standards. Data was collected in reflection geometry until a suitable pattern was obtained (about 3 hours) and interpretation of the results was undertaken using both the WinXpow software package in conjunction with the JCPDS powder diffraction database.

The resulting pattern (PSD-G4009) (Fig. 1) clearly indicates the removed material is a mixture of reference pattern JCPDS-29-304 for danburite and JCPDS-36-429 for datolite confirming the original IR analysis performed by GR. A very small amount of quartz impurity was also identified during the XRD analysis.

Danburite is isostructural with the minerals maleevite ( $\text{BaB}_2\text{Si}_2\text{O}_8$ ) and pekovite ( $\text{SrB}_2\text{Si}_2\text{O}_8$ ) and although each mineral has a distinct X-ray pattern, all three are closely related and could be misinterpreted for each other. This is especially significant if the sample being studied is not of an end member composition, or the JCPDS reference patterns were not performed on end-member material. In order to remove any ambiguity, a further small fragment ( $<1 \text{ mm}^3$ ) of the fluorescent material was removed from the main specimen and placed upon a sticky carbon stub, and analysed uncoated, using a Zeiss EVO SEM coupled to an Oxford Instruments energy dispersive X-ray spectrometer fitted with the Inca software package for data interpretation. High vacuum mode was utilised along with appropriate internal calibration standards.

This method of EDX analysis is unable to detect elements lighter than carbon, which includes boron and as such the technique cannot determine the exact chemical signature of the phase. However, as the difference between maleevite, pekovite and danburite pertains only to the large cation present, this method is able to determine the dominant



**Figure 1.** XRD pattern (blue) obtained from datolite/danburite mixture on specimen BM 2005,66, showing reference lines for datolite (red) and danburite (green). Note subtle shift of danburite peaks to the left of the acquired pattern at higher angles. This is a calibration artefact resulting from the reference pattern being produced on a different type of diffractometer.

element present besides silicon. In this case analysis clearly determined that Ca was the dominant cation, thus confirming that the material identified by the XRD and IR patterns is indeed danburite. This technique and method of sample preparation is inappropriate to determine exact stoichiometric values of Ba, Ca and Sr within danburite and should only be used to indicate strong dominance of one cation over another, in this case Ca was seemingly the only cation present apart from Si and thus the level of confidence regarding the interpretation of results is extremely high.

The SEM imaging process required in order to obtain EDX results, showed the material sampled was actually a mixture of three distinct phases, a main constituent and two other materials that were composed of much smaller mineral grains within the main phase. One of the smaller grains was composed of small ( $20\ \mu\text{m} \times 5\ \mu\text{m}$ ) elongated lozenge shaped crystals rich in Ca, Si, Sn, Ti and O, it is seemingly too small a component to have been detected by the XRD or IR analyses, but fortunately its form and chemical constituents strongly suggest that it is part of the malayaite-titanite series and as Sn appeared to be greater than Ti on the EDX analysis it is likely to be the rare tin silicate malayaite. The other grain, which was smaller ( $10\ \mu\text{m} \times 10\ \mu\text{m}$ ), more equant, but much more abundant was of similar composition to the main constituent, being composed largely of Ca and Si, but with a small Mg component. It seems likely that this phase and the main constituent represent danburite and

datolite, however determining which is which on the basis of EDX analysis alone is difficult as the ratio of Ca to Si is the same in each, and boron is undetectable via this method. The slight trace of Mg within the equant grains could be a suggestion that these are datolite and the main mass is danburite, as datolite-gadolinite group minerals have an obvious place in their structure that can contain appreciable  $\text{Mg}^{2+}$  e.g. homilite (Demartin *et al.*, 2001, Anthony *et al.*, 1995) while danburite does not. However, for completeness, it is of note that there are some publications that list trace Mg in danburite, but levels are very low and often considered insignificant and not explained (Sugiyama and Takeuchi, 1985).

## DANBURITE SPECIMEN

The danburite specimen (GR 99-2) (Fig. 2; see p.28) was kindly donated by George Ryback to the NHM, where it was split into two pieces and registered with the NHM numbering system as BM 2005,66 and BM 2005,67. The specimen is an uninspiring, massive skarn containing pale greenish to white massive datolite-danburite, whitish-grey quartz, pale brownish massive grossular garnet, tiny specks of silvery-grey Ni-rich lollingite and the newly identified tiny grains of malayaite. It is of note that it is visually very difficult, if not impossible to determine the exact distinctions between many of the species in hand specimen as the rock is largely recrystallised and the minerals are intergrown with each other in indistinct patches.



Figure 2. Danburite specimen (GR 99-2) now re-registered as BM 2005,66 within the collections at the NHM. Note the pencil lines delineate areas that were found to be fluorescent under UV light.

A thick-section slice (P10983) some 3 cm x 2 cm was removed from the specimen and studied using a Zeiss Axioplan petrological microscope. The texture of the fluorescent region was dominated by minute grains of individual mineral species, matching data from the SEM images. This clearly indicates re-crystallisation and likely an inability to reach equilibrium during metamorphism. It becomes clear only by looking at the material in section that the fluorescent yellow regions correspond not to those that are rich in danburite as was initially suspected, but instead to those areas that contain the small malayaite-titanite component identified by the EDX analysis. Further XRD analysis was performed to test this hypothesis by sub-sampling a region on the specimen that was visually and texturally similar to the previously sampled region, but lacked the distinctive yellow SW-UV fluorescence. As suspected, this test strongly indicated the presence of danburite as a major component and shows that although a clearly quite rich constituent in the yellow fluorescent areas, it was not the phase that was giving the specimen its colour under illumination in SW-UV light. This second area sampled does however have its own exceedingly weak blue-violet SW-UV fluorescence, barely visible against the specimen and the yellow SW-UV fluorescence of the

malayaite. It is possible that this could be used to suggest regions rich in danburite without malayaite.

It is interesting at this point to note, that the identification of danburite from the locality was purely fortuitous, coming from an investigation of the yellow fluorescence caused by the presence of malayaite-titanite, a mineral series whose occurrence is already well known within Meldon Quarry and its vicinity. It is of note here that this interpretation now fits the published observations on mineral fluorescence much better. The yellow colour of the specimen's SW-UV fluorescence is far more in line with that of the malayaite-titanite series than that of danburite which tends to fluoresce light blue to light blue-green, rather than yellow to yellow-green.

## FORMATION OF DANBURITE

Danburite is found in a wide variety of geological environments, indicating that it is formed throughout a range of physical and chemical conditions (Birch, 1996). Geochemical experiments designed to determine the exact nature of formation have highlighted that for optimum danburite and datolite mineralisation, conditions require high activities of  $H_3BO_3$ , low levels of  $CO_2$  and relatively

high temperatures (Semenov *et al.*, 1988). Consequently danburite is a rock forming mineral in many skarn deposits and is particularly prevalent in those with a calc-silicate and boron rich signature, much like those in the vicinity of Meldon. A number of these skarns from various globally distributed localities were studied by Aleksandrov and Troneva (2007) who also showed that they were commonly a repository for malayaite and titanite, as we have shown in this specimen.

At Meldon, both danburite and datolite are found on the same specimen and it has been shown here that they are intergrown on a microgranular scale. Considering the two mineral species are adjacent to each other on geochemical stability diagrams (Semenov *et al.*, 1988) this association is not unlikely. It does however imply non-equilibrium conditions during the formation of the skarn deposit. The proximity of the two minerals means both underwent the same physical conditions during their formation. Thus the controlling factors determining their crystallisation are dominantly chemical and could either be derived from the metasomatic reaction of the boron rich hydrothermal fluids with different mineral grains of the original rock and their subsequent inability to reach equilibrium, or from partial alteration of one species into the other in order to reach a new equilibrium, due to a change in the composition of the hydrothermal fluid during the event.

Datolite is generally more common than danburite, yet, danburite will form preferentially to datolite if the activities of  $H_3BO_3$  and  $SiO_2$  are both high. Low pH, lower temperature and a reduced activity of  $Ca^{2+}$  can also help to crystallise danburite rather than datolite. Furthermore,  $CO_2$  may be another contributing factor, even at low  $CO_2$  concentrations, the stability field of calcite overlaps that of datolite and impedes its crystallisation. Thus datolite only forms in environments where  $CO_2$  concentration is very low or absent, yet danburite can form when  $CO_2$  levels are relatively high.

The exact reason for the occurrence of danburite at Meldon is as yet undetermined, but as no carbonates exist on the hand specimen, as Ca seems fairly ubiquitous and there is no obvious reason to assume a variation in the  $H_3BO_3$ , pH or temperature in such a small area, it may be that the crystallisation of danburite on this specimen is due to a particularly high activity of  $SiO_2$ , possibly due to an unusually quartz rich area of precursor material before the metamorphism. If this is the case it would seem plausible that some of the metasomatised cherts containing datolite described by El Sharkawi and Dearman (1967) may also contain danburite, that went unnoticed in their original investigation. Further investigation of boron containing, metamorphosed rocks in the area might shed more light on this problem as the extent of danburite formation becomes better documented. It on this problem as the extent of danburite formation becomes better documented.

## DANBURITE IN THE BRITISH ISLES

This occurrence from Meldon appears to be the first reliable published record of danburite in the British Isles.



**Figure 3.** Danburite specimen BM 1965,96. The scale bar is in mm.

A.W.G Kingsbury claimed to have collected danburite from four localities in SW England between 1950 and 1965. However, even though these localities have all been frequented by collectors for decades, we know of no other danburite finds. In view of the uncertainties attached to many of Kingsbury's discoveries (Ryback *et al.*, 2001; Green *et al.*, 2006; Green *et al.*, 2009; etc.), all the relevant material within the Kingsbury Collection and main collections at the NHM has been re-examined. The details of the examinations are outlined below and conclude that all four alleged occurrences must be regarded as suspect until independently confirmed.

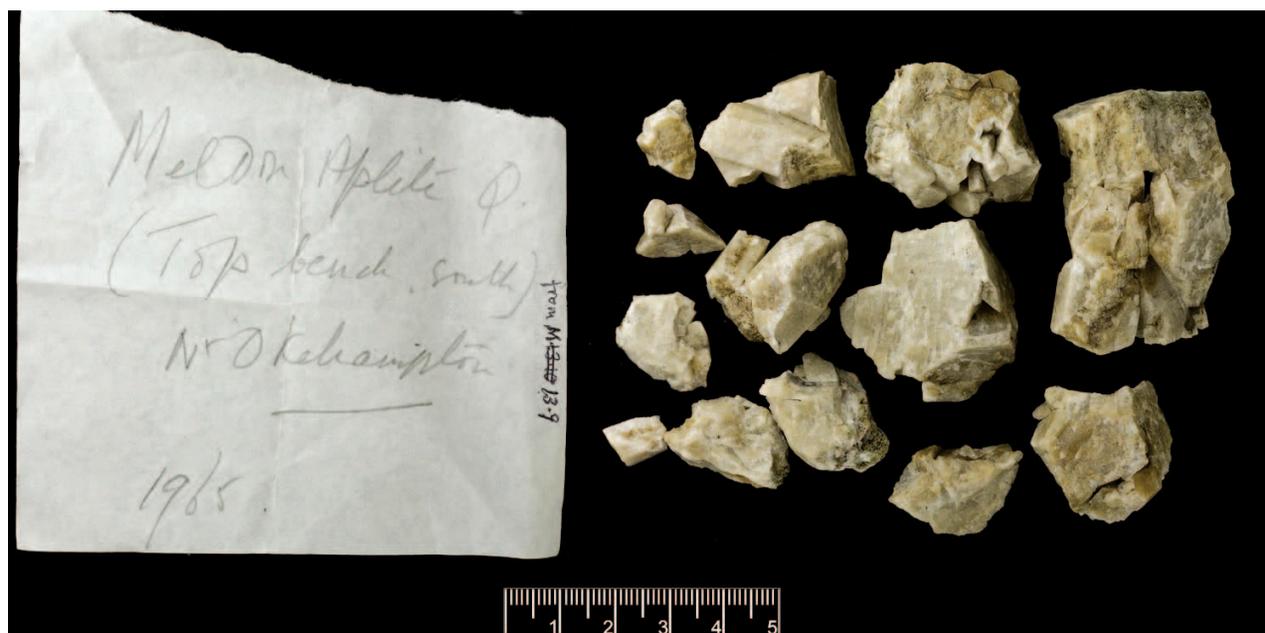
### Danburite from Meldon Old Aplite Quarry, near Okehampton, Devon

Specimen BM 1965,96 (Fig. 3) consists of five detached, colourless, transparent, singly terminated prisms (up to 10 x 4 mm in size) and two 15 mm fragments of larger, corroded crystals collected in 1960. The mode of occurrence is not recorded, and no further specimens of danburite on matrix have been found among the large amount of material from this locality in Kingsbury's private collection (now in the NHM). While it is difficult to prove that these individual crystals were not found at Meldon, the lack of subsequent finds in the last 40 years, the absence of matrix and the reputation of Arthur Kingsbury would suggest that the material is from elsewhere.

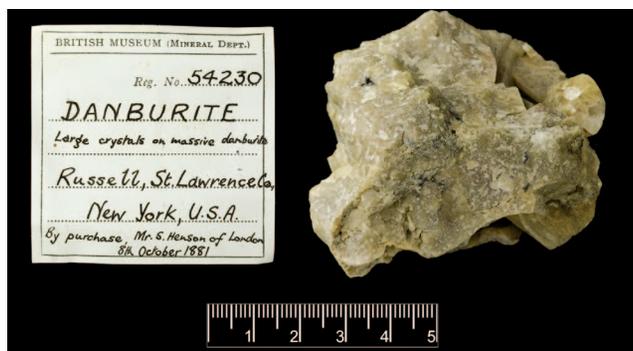
A number of localities are known that produce crystals of this ilk, but it is beyond the scope of this study to try and assess exactly where these separated crystals may have come from. Two obvious possibilities from which Kingsbury could have easily obtained similar material to BM 1965,96 at this time include San Luis Potosi in Mexico and Scöpi Mountain in the Medel Valley, Switzerland.

### Danburite from Meldon New Aplite Quarry, near Okehampton, Devon

Specimen 'K/Mel/65/5' (Fig. 4; see p. 30) is housed within material in the unregistered portion of the Kingsbury Collection and supposedly collected in 1965, consists of several matrix-free pieces up to 45 mm across of confused masses of pale brownish opaque intergrown danburite



**Figure 4.** Danburite specimen ‘K/Mel/65/5’ from the Kingsbury collection, reportedly from Meldon Aplite Quarry. Notice the similarity with Figure 5, a specimen known to be from St. Lawrence County, New York, USA. Scale bar is in cm.



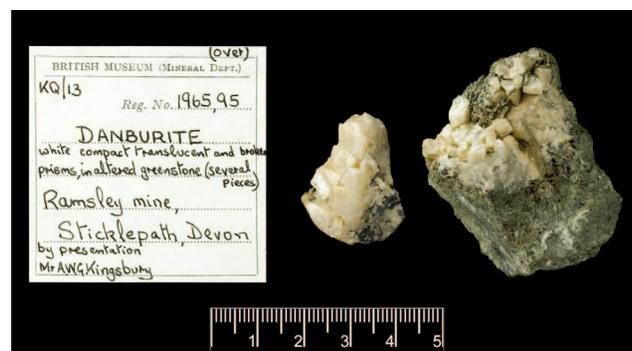
**Figure 5.** Danburite specimen BM 54230, obtained by the NHM in 1881 from Russell, St. Lawrence County, New York, USA. Notice the similarity with Figure 4, a specimen purported to be from Meldon Aplite Quarry. Scale bar is in cm.

prisms, most with a 1-2 mm wide glassy white outer rim. These pieces closely resemble the classic and characteristic material from Russell, St. Lawrence County, New York, USA, (Fig. 5) and very probably represent a specimen from an old collection, broken up and relabelled by Kingsbury.

### Danburite from Ramsley Mine, South Tawton, Devon

Specimen BM 1965,95 (Fig. 6) was supposedly collected in 1958 and consists of two pieces (50 and 25 mm across) plus fragments of white translucent danburite masses and broken prisms, on matrix labelled as altered greenstone. This material also closely resembles other pieces within the NHM collections from Russell, St. Lawrence County, New York, USA, and similarly may represent a specimen from an old collection, broken up and relabelled by Kingsbury.

Some credence is apparently given to this find in the literature as datolite (a mineral often associated with danburite) is recorded from Ramsley Mine by Symes (1977) based on a specimen in the NHM. However investigation of this occurrence indicates that these referenced datolite

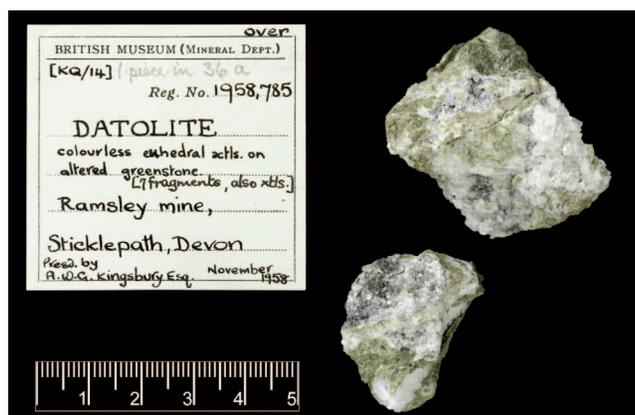


**Figure 6.** Danburite specimen BM 1965,95, purportedly from Ramsley Mine, Devon. Scale bar is in cm.

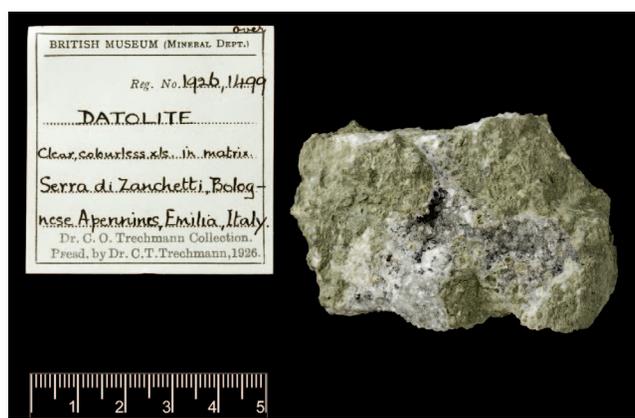
specimens (BM 1958,785 (Fig. 7) and BM 1958,784) also originated from Arthur Kingsbury as part of his specimen “KQ/14”. Visual analysis of datolite specimen BM 1958,785 indicates that the material is visually identical to datolite from Serra dei Zanchetti near Bologna, Italy (Fig. 8).

### Danburite from Cheesewring Quarry, Linkinhorne, Cornwall

Specimens ‘K149’ and ‘K150b’ in the Kingsbury Collection comprise a number of small detached crystals which were supposedly collected in 1951-1952 from two distinct sites in the quarry. The same remarks apply to these matrix-free crystals as to those from Meldon Old Aplite Quarry, above. This occurrence must also be regarded as suspect, as no other specimens have been reported from the locality despite collecting. Specimens from Cheesewring Quarry, like many of the other finds of Kingsbury were donated to the BM(NH) (now NHM) and Sir Arthur Russell, (specimens BM 1958,79 and BM 1964R,9829 respectively) and were reported by Embrey (1978) in the fourth supplementary list of British Minerals.



**Figure 7.** Datolite specimen BM 1958,785, purportedly from Ramsley Mine, Devon. Notice the similarity to Figure 8, a specimen known to be from Serra di Zanchetti, Italy. Scale bar is in cm.



**Figure 8.** Datolite specimen BM 1926,1499, obtained by the NHM in 1926 from Serra di Zanchetti, Italy. Notice the similarity with Figure 7, a specimen purported to be from Ramsley Mine, Devon. Scale bar is in cm.

### Red-A-Ven Mine, Near Okehampton, Devon

The only apparently non-Kingsbury related reference to danburite in the British Isles is a brief mention by El Sharkawi and Dearman (1966) whereby danburite is listed in a table as a mineral characteristic of tin-bearing skarns in calcareous environments. Unfortunately, there is no reference to a specific specimen, a prior reference or any mention of danburite within the bulk of the main text. Furthermore, it is not clear if the table is clearly referencing that these minerals are found specifically at Red-a-Ven Mine or that they are merely those one would expect in an environment similar to that at Red-a-Ven, of which there are many globally (Aleksandrov and Troneva, 2007).

As El Sharkawi and Dearman reference an earlier Kingsbury paper it is clear that they were familiar with his work and therefore it is also conceivable, that if the danburite in the list is not Red-a-Ven specific, the details may have come from one of Kingsbury's four localities outlined above. However El Sharkawi and Dearman appear to have referenced other minerals in the list to specific papers, where applicable, so it seems that this link to Kingsbury is only an outside possibility.

With this in mind, it seems sensible at this stage to await confirmation of danburite as a known species from the Red-

a-Ven Mine. Its occurrence here is entirely plausible, and a search for this material would be of considerable value to clear up the confused literary record. It is suggested here that should such a search be successful a representative sample deposited in a national museum would be of considerable importance in order to ensure that more unusual mineralogical studies can be verified, a rule that should be more generally applied across the science of mineralogy.

### CONCLUSIONS

The identification of more suspicious Arthur Kingsbury occurrences at localities within the British Isles is disappointing as it helps to outline the scale and severity of the task ahead to try and correct these misleading reports. It is of some recompense in this case that no later works known to the authors are based upon these reports of danburite and apart from the topographic mineral lists, in both print and now online, there is no other reference to Kingsbury's danburite localities.

However, it is particularly interesting in this case to note that within the localities that Kingsbury chose to suggest that danburite came from, one did include the locality that has now been shown to contain danburite and the others are closely related deposits. This indicates that Kingsbury was fully aware of the local geology and mineralogy of each site and was able to predict potential minerals that would not be out of place within the assemblage already present. This exemplifies Kingsbury's talent as a mineralogist but also why his fraudulent activities went unnoticed for many years.

### ACKNOWLEDGEMENTS

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## A REVIEW OF THE MINERALOGY OF THE AREA AROUND MARKFIELD, LEICESTERSHIRE

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**The Precambrian and Triassic rocks exposed in the area around Markfield, Leicestershire are the hosts for both hypogene (hydrothermal) and supergene minerals. Hypogene minerals are present in a number of quartz- and carbonate-containing veins and shear zones in the Precambrian rocks. Supergene minerals are present in the Precambrian rocks and the Triassic sediments adjacent to the Precambrian-Triassic unconformity. This article describes the history of the quarrying activity, geology and mineralogy of the area around Markfield and makes some observations on the processes responsible for the formation of the hypogene and supergene minerals.**

### INTRODUCTION

The area around Markfield, Leicestershire contains several limited exposures of the South Charnwood Diorites (Worssam and Old, 1988; Ambrose *et al.*, 2007) some of which have been quarried for use in the construction industries (McGrath, 2007). These exposures comprise the north-western part of a late Precambrian intrusion in the earlier Precambrian volcanoclastic rocks of the Bradgate Formation of the Maplewell Group of the Charnian Supergroup (Moseley and Ford, 1985). In the Markfield area the quarries listed below provide exposures of the South Charnwood Diorites and, as quarrying has progressed, a number of quartz- and carbonate-rich veins and shear zones have been exposed in the Precambrian rocks. A combination of the effects of these structures, the presence of a marked Precambrian-Triassic unconformity and the nature of the overlying Triassic sediments has resulted in suites of hypogene and supergene minerals. The mineralogy of the area around Groby, Leicestershire (to the southeast of the Markfield area) is described in the following article (Ince, 2011).

### LOCATIONS

The volcanoclastic rocks of the Bradgate Formation are exposed in the small disused quarries on the southwest side of Billa Barra Hill [SK 466 104], 2.5 km to the northwest of the village of Markfield (Fig. 1) (McGrath, 2004). They are also exposed on the northeast face of Old Cliffe Hill Quarry and in the northwest corner of New Cliffe Hill Quarry (see below).

The South Charnwood Diorites are exposed in three quarries to the west-northwest of the village of Markfield, Leicestershire (McGrath, 2004; McGrath, 2007) (Fig. 1):

1. Hill Hole Quarry [SK 485 103] (Fig. 2; see p. 34) is on the top of the hill on the outskirts of Markfield. In the past this has been referred to as Village Quarry or Markfield Quarry (the latter name appears on the 1:25,000 OS map). In this article its original name, Hill Hole Quarry (the name used by the current owners: Hinckley and Bosworth District Council), will be used.
2. Old Cliffe Hill Quarry [SK 474 106] (Fig. 3; see p. 34), the large quarry ~1 km to the west-northwest of Markfield, was known as Cliffe Hill Quarry during the

earlier phases of its productive life. In this article it will be referred to as Old Cliffe Hill Quarry so that it can be clearly distinguished from its more recent neighbour, New Cliffe Hill Quarry.

3. New Cliffe Hill Quarry [SK 459 108], the extensive quarry ~3 km to the west-northwest of Markfield, is a relatively new addition to the Leicestershire landscape. In 2003 it was linked to Old Cliffe Hill Quarry by the Joskin Tunnel.

## HISTORY OF QUARRYING

The small disused quarries on the southwest side of Billa Barra Hill exploited the volcanoclastic rocks of the Bradgate Formation for building material (e.g. local dry stone walls) and they now form part of a nature reserve (McGrath, 2004).

Hill Hole Quarry may have been a site of building stone extraction in the Roman period and, as its name suggests, the quarry took the form of an excavation on the top of the hill (formerly known as Knoll Hill) on the outskirts of Markfield. Quarrying was in progress in 1830 and the quarry was bought by Josh Ellis and Breedon Everard in 1852 (McGrath, 2007). Eskrigge (1868) noted that “At Markfield the syenite comes up in a broad elliptical boss, and is extensively worked for road setts”; this description probably refers to Hill Hole Quarry as Old Cliffe Hill Quarry does not appear to have been active before the

1870s. Problems with haulage out of the quarry and water ingress meant that extraction had ceased by the time of the First World War. Ownership eventually passed to Midland Quarry Products who subsequently sold it to the Tarmac Group. Hinckley and Bosworth District Council purchased the quarry with grant aid from the National Forest Company (McGrath, 2004; McGrath, 2007) and it is now a nature reserve with the partly water-filled lower levels enclosed within a substantial security fence (Fig. 2).

Old Cliffe Hill Quarry produced setts for a short period in the 1870s and, following its purchase in 1891 by Mr J.R. Fitzmaurice, the Cliffe Hill Granite Company Limited was formed in 1894. The quarry was acquired by the Tarmac Group in 1965 and became part of Midlands Quarry Products in 1996. The northeastern half of Old Cliffe Hill Quarry (far right in Figure 3) is an SSSI for its geology (Natural England, 1990).

New Cliffe Hill Quarry was established in the late 1980s and was linked to Old Cliffe Hill Quarry in 2003 by the 725 m Joskin Tunnel; the tunnel portal (9 m high x 6 m wide) in Old Cliffe Hill Quarry is behind the conveyer belt to the right of the crusher in Figure 3. The combined output of the Cliffe Hill quarries was ~4.5 million tons of aggregate per year (McGrath, 2007). New Cliffe Hill Quarry is currently (2010) being back-filled with Triassic overburden from Old Cliffe Hill Quarry.

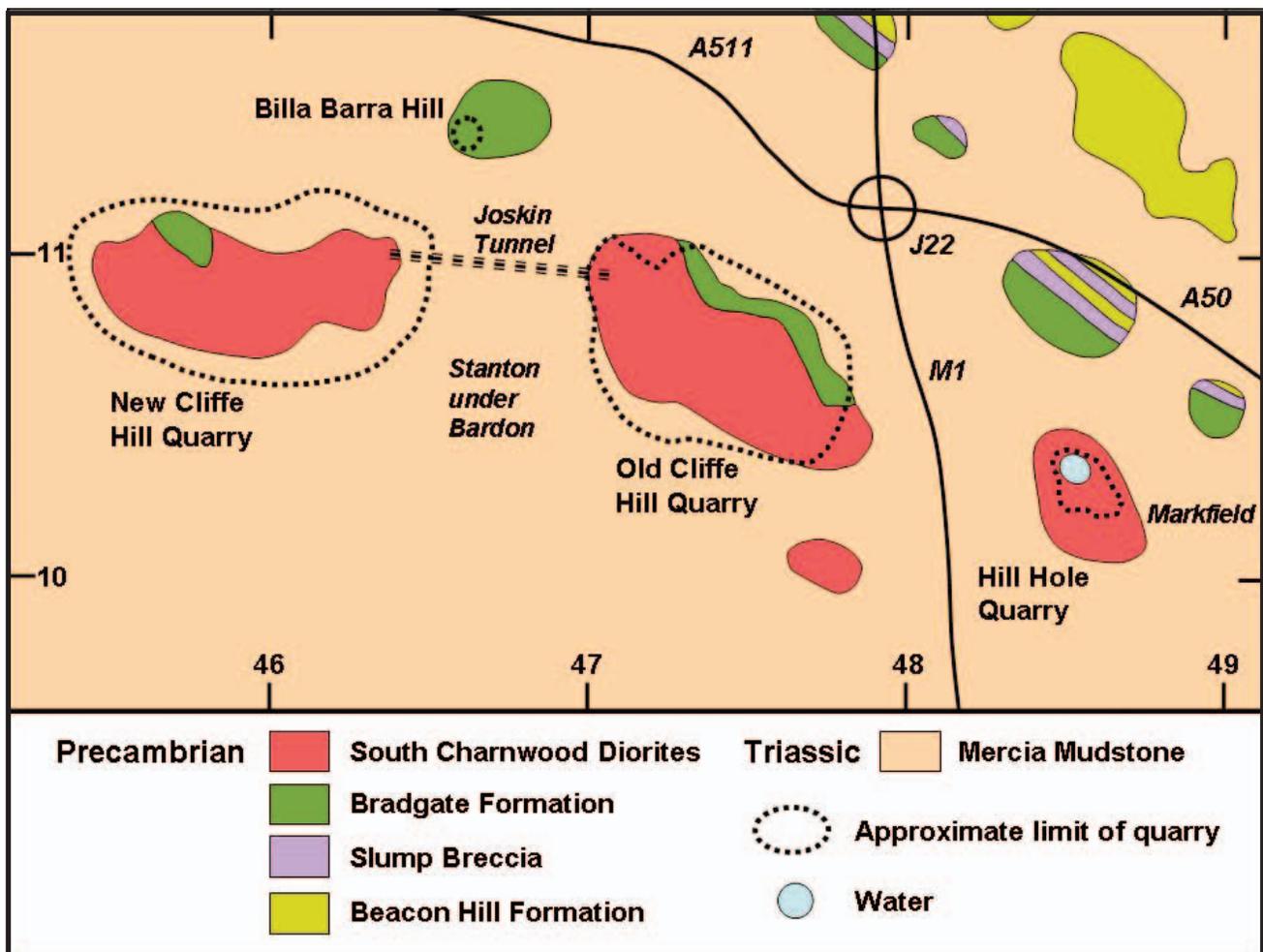


Figure 1. Geological map of the area west-northwest of Markfield; modified from Ambrose *et al.*, 2007.



**Figure 2.** Hill Hole Quarry looking northwest towards Bardon Hill.



**Figure 3.** Old Cliffe Hill Quarry looking northwest.

## GEOLOGY

Limited exposures of late Precambrian volcanic rocks of the Charnian Supergroup are exposed in the Charnwood Forest area of Leicestershire and the geology of the area has been described (Moseley and Ford, 1985; Worssam and Old, 1988; Carney *et al.*, 2000; Ambrose *et al.*, 2007). The Charnian rocks have been assigned to the Ediacaran period of the Neoproterozoic era with a minimum age range of 550-600 Ma. Apart from their significance as some of the oldest rocks in England, the Precambrian rocks of the Charnian Supergroup are particularly important given that Ediacaran fossils occur in some members of the sequence (Ford, 2000). The Charnian rocks are overlain unconformably by Cambrian, Carboniferous or Triassic rocks and the entire sequence is partly covered by Pleistocene glacial deposits.

The rocks of the Charnian Supergroup that are exposed in the Markfield area, the Bradgate Formation of the

Maplewell Group and the South Charnwood Diorites (Fig. 1), have been described in more detail, in particular those exposed in Old Cliffe Hill Quarry (Carney and Pharaoh, 2000). The Bradgate Formation (exposed on the northeast face of Old Cliffe Hill Quarry, in the northwest corner of New Cliffe Hill Quarry and at Billa Barra Hill) comprises a series of mainly grey-green volcanoclastic mudstones, siltstones and sandstones with the material probably originating from volcanic centres to the north to northwest in the areas around Bardon Hill and Whitwick (Carney, 2000). A coarse tuff from Bardon Hill Quarry has been examined using zircon-derived U-Pb isotope methods and afforded an interpreted deposition age of  $566.1 \pm 3.1$  Ma (Compston *et al.*, 2002). Old Cliffe Hill Quarry is an internationally important paleontological site as Ediacaran fossils occur in the volcanoclastic rocks of the Bradgate Formation and the type specimen of *Cyclomedusa cliffi* was recovered from this quarry (Boynton and Ford, 1995; Ford, 2000).

Following post-depositional flexure of the Charnian volcanoclastic rocks, the South Charnwood Diorites were intruded into the rocks of the Bradgate Formation (Carney and Pharaoh, 2000). The intrusion appears to be a faulted sheet with a northwest-southeast trend and extends from northwest of Stanton-under-Bardon to Groby and Bradgate Park. The South Charnwood Diorites are granophyric diorites (Carney *et al.*, 2000) that are usually greenish to pink igneous rocks that have also been variously described as diorites (Worssam and Old, 1988), porphyritic microdiorites (Hatch *et al.*, 1961) or syenites (Eskrigge, 1868; Powell, 1868; Watts, 1947). Hill Hole Quarry is the type locality for 'markfieldite' (Worssam and Old, 1988), as described by Hatch *et al.* (1961), and the name 'markfieldite' is still used locally. The South Charnwood Diorites are petrologically and geochemically similar to the diorites exposed in the Nuneaton area (Carney and Pharaoh, 2000) and the latter intrusion has been assigned a date of  $603 \pm 2$  Ma using U-Pb isotope methods (Tucker and Pharaoh, 1991). If the South Charnwood Diorites are coeval with the diorite from the Nuneaton area ( $603 \pm 2$  Ma), the intrusion of the South Charnwood Diorites appears to pre-date the deposition of the volcanoclastic rocks of the Bradgate Formation ( $566.1 \pm 3.1$  Ma) into which they were intruded; it is evident that more work will be required to resolve this age relationship.

Folding of the Precambrian and Cambrian rocks, particularly during the late-Silurian (Carney *et al.*, 2008), resulted in an anticline plunging to the southeast; consequently, the rocks of the Maplewell Group dip steeply (up to  $80^\circ$ ) to the southwest to west-southwest in the Markfield area (Carney and Pharaoh, 2000). The rocks of the Charnian Supergroup have also been affected by faulting and some these faults and shear zones appear to have controlled aspects of the mineralisation.

The geology of the Triassic sediments has been extensively studied (Bosworth, 1912; Watts, 1947; Worssam and Old, 1988; Carney *et al.*, 2000; Ambrose *et al.*, 2007). Features associated with sub-aerial erosion in the Triassic era are common in many of the Leicestershire quarries; the quarries in the Markfield area are no exception and wadis in the eroded Precambrian rocks, subsequently filled with Triassic sediments, are well-exposed in both Old Cliffe Hill Quarry (Fig. 3) and New Cliffe Hill Quarry. The Precambrian-Triassic unconformity is covered by a basal breccia (containing Charnian clasts) that grades into the buff to red-brown (with occasional greenish bands) sandstones, siltstones and mudstones of the almost horizontally bedded Mercia Mudstone Group. Finally, the entire sequence is partly covered by Pleistocene glacial deposits (Worssam and Old, 1988; Carney *et al.*, 2000; Ambrose *et al.*, 2007).

## THE MINERALS

Whilst New Cliffe Hill Quarry is in the geographical area considered by this article, its mineralogy has been the subject of a number of recent articles (Hubbard *et al.*, 2005; Ixer *et al.*, 2005; Bridges, 2007); consequently, other than previously unrecorded occurrences (epidote, pyrolusite and ramsdellite), the details of the remarkable mineral

assemblage that occurs at New Cliffe Hill Quarry will not be repeated here.

During the preparation of this article a number of collections of specimens from the Markfield area were studied: the King Collection (now at the National Museum of Wales, Cardiff), the collections of the Department of Geology at the University of Leicester, Neil Hubbard and John Jones. A number of specimens from these collections are described below; those from the King Collection are identified as Kxxxx (NMW 83.41G.Myyyy) and those from the Department of Geology at the University of Leicester identified as LUzzzzz.

A variety of techniques, including wet chemistry, optical and X-ray (XRD) methods, have provided data that support the identification of the individual minerals described below (a table of analytical data will be provided on request). The minerals noted in lower case are those where further work is required to confirm their occurrence. The materials in lower case and italics are those that are no longer well-defined mineral species (Back and Mandarino, 2008) or have an ill-defined chemical composition.

### AZURITE, $\text{Cu}_3(\text{CO}_3)_2(\text{OH})_2$

A specimen from Old Cliffe Hill Quarry (LU 20393) has minute amounts of azurite and some malachite on dolomite. In 2007 very small amounts of deep blue masses of azurite were found on joints in diorite boulders and in the Triassic breccia close to the Precambrian-Triassic unconformity on the west side of the Old Cliffe Hill Quarry where it was associated with 'chrysocolla', malachite, native copper and cuprite.

### BARYTE, $\text{BaSO}_4$

Baryte occurred at Old Cliffe Hill Quarry as aggregates of small (up to 1 mm) cream to pink leaflets associated with calcite on a quartz-chlorite-hematite matrix (Neil Hubbard, *personal communication*).

### BORNITE, $\text{Cu}_5\text{FeS}_4$

The remnant of a bornite-containing quartz-carbonate vein system with a strike of  $\sim 312^\circ$  was exposed on the top level of the northwest face of Old Cliffe Hill Quarry in 1959. The vein was 94 mm wide with the bornite occurring as small irregular masses (up to 2 mm) associated with 'chrysocolla', malachite, goethite, calcite and quartz. Where the bornite was embedded in calcite it was heavily oxidised and 'chrysocolla' had formed; however, where the bornite was embedded in quartz, little or no alteration had taken place (King, 1973).

### CALCITE, $\text{CaCO}_3$

Eskrigge (1868) reported the occurrence of calcite in the Markfield area: "Through the Markfield boss there runs a broad vein, varying from 6 inches to 2 or 3 feet, of well crystallised compact carbonate of lime, generally reddish or flesh colour, the same as the feldspar in the syenite". Powell (1868) probably described the same calcite vein: "In the extensive syenite quarry at Markfield,

a vein composed of compact calcite occurs of considerable extent; it has a red or pink tinge, and possess throughout the well-defined rhombic cleavage. It has been proposed to use this for economic purposes, owing to the extent of the vein and its pure character". These descriptions of calcite from Markfield probably refer to occurrences at Hill Hole Quarry; this quarry was active in the 1860s and a calcite vein is still exposed in the quarry (see below). Calcite does occur in Old Cliffe Hill Quarry (see below); however, the quarry does not appear to have been active before the 1870s.

The occurrence of calcite has been reported at Hill Hole Quarry in two distinct environments:

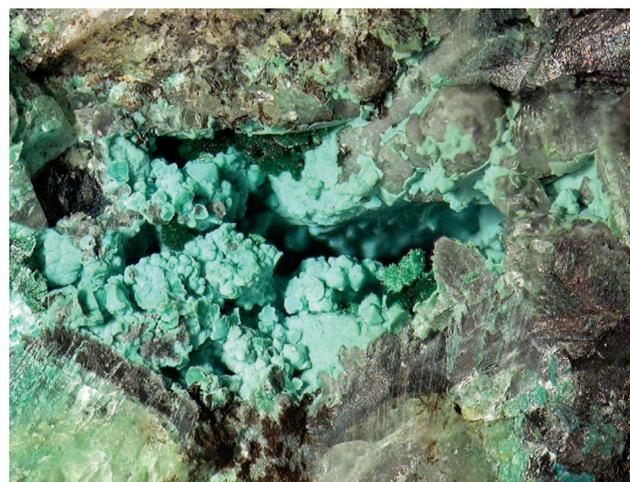
1. A calcite vein (up to 120 mm wide, strike northwest, dip 70° northeast) is exposed on the southeast face of the lower (partly water filled) part of the quarry [SK 4860 1030]. This vein may be a continuation of the vein described by Eskrigge (1868) and Powell (1868); however, the 1 m blocks of reddish calcite mentioned by Ince (*Russell Society Newsletter*, (1992), No. 23, 19-20) were not found during a more recent visit to the quarry (in 2010). The light reddish-brown calcite is associated with minor dark red hematite and dark green chlorite. The calcite displays a red fluorescence under short-wave ultraviolet light (SUV) and, in common with the specimens of calcite from the Groby area (see Ince, 2011), it is assumed that manganese is the activator for the red fluorescence under SUV. It is worth noting that some specimens also have small areas that are a light pinkish-cream with a pearly lustre that display a pale yellow fluorescence under SUV.
2. A smaller quartz-calcite vein (up to 50 mm wide, strike northeast) was noted by Ince (*Russell Society Newsletter*, (1992), No. 23, 19-20) near the previous locality [at SK 4861 1031]; during re-investigation of the material from this vein no quartz could be found. The vein contains colourless to pale green calcite that displays a red fluorescence under SUV and has a few cavities that are lined with singly terminated scalenohedral crystals (up to 10 mm). The calcite is associated with malachite, 'chrysocolla', cuprite and native copper (Fig. 4) and, where they are present on the surface of the calcite crystals, the copper minerals appear to have inhibited the red fluorescence under SUV.

At Old Cliffe Hill Quarry calcite has also occurred in a number of different situations:

1. Evans and King (1962) noted that calcite was associated with palygorskite.
2. King (1973) recorded that "large veins are exposed from time to time...these lens-like masses, which are up to 420 mm thick, are aligned along a shear zone with an average strike of 338° and usually dip steeply to the E. The calcite is always completely anhedral...pinkish-white to red...occasionally green stained due to chlorite...with minor specular hematite and perfectly euhedral cubic pyrite". In 1966 on the north side of No. 3 level (the lowest level at that time) a 1.3 m wide lens contained a stock-work of chlorite-stained calcite veins (up to 13 mm wide). This lens also contained

lustrous brass-yellow cubes of pyrite (up to 32 mm) and the occurrence caused significant problems for the quarry plant (King, 1973). LU 23444 may be related to this occurrence as it contains some calcite veins (up to 10 mm wide) in diorite associated with striated brass-yellow pyrite cubes (up to 10 mm).

3. A quartz-carbonate vein system exposed on the top level of the northwest face in 1959 contained calcite associated with bornite, 'chrysocolla', malachite, goethite and quartz (King, 1973).
4. Thin crusts of calcite occurred with grayish-blue microcrystalline films of tourmaline on slickenside surfaces of faults that were exposed on the top level of the north face of the quarry (King, 1973). In 2010 similar material was found amongst the debris on floor of the lowest level on the west side of the quarry; the calcite displays a red fluorescence under SUV.
5. LU 24746, labelled as: "Calcite; showing strain oscillations, in diorite", has a polished vein section (20 mm thick) with cream and mottled red-brown to greenish-brown calcite on diorite.
6. Calcite has been collected more recently from Old Cliffe Hill Quarry as small (up to 4 mm) colourless to red-brown scalenohedral crystals with rhombohedral terminations lining cavities in a quartz-chlorite-hematite matrix and associated with baryte (Neil Hubbard, *personal communication*).
7. In 2007 cavities the breccia associated with the Precambrian-Triassic unconformity on the west side of the quarry afforded some heavily iron-stained scalenohedral calcite together with lustrous dark brown laths of goethite.
8. In 2010, grey veins (up to 30 mm wide) in an isolated boulder of dark greenish-grey altered diorite on the incline near the lowest level of the quarry were found to be composed of calcite containing numerous very small black magnetite crystals and granular hematite (Neil Hubbard, *personal communication*); interestingly, this calcite has minimal fluorescence under SUV. Treatment of a small sample of this material with dilute hydrochloric acid revealed that there were 2 generations of calcite



**Figure 4.** 'Chrysocolla', malachite and calcite from Hill Hole Quarry, Markfield (15 mm x 10 mm); Frank Ince specimen and photograph.

(light grey followed by white); an acid-insoluble residue was also produced (this is described in more detail in the hematite and magnetite sections).

9. Also in 2010 masses of pinkish-grey calcite with a marked curved cleavage were collected from some quartz-carbonate veins in northeast corner of the lowest level of the quarry. The calcite has a marked deep red fluorescence under SUV and contains some small striated cubes of yellow pyrite.

### CHALCOPYRITE, $\text{CuFeS}_2$

In 2010, one of the boulders of diorite adjacent to the incline above the lowest level of Old Cliffe Hill Quarry contained several yellow anhedral masses of chalcopyrite (up to 20 mm) (Steve Critchley, *personal communication*).

### CHLORITE GROUP

King (1973) noted that the calcite in some of the quartz-carbonate veins at Old Cliffe Hill Quarry was stained green by inclusions of chlorite. Dark green masses of chlorite can still be found and are usually associated with the quartz-carbonate veins. Chlorite has been collected more recently from Old Cliffe Hill Quarry as aggregates of minute dark green plates where it occurred in a quartz-chlorite-hematite matrix associated with calcite and baryte (Neil Hubbard, *personal communication*). At Hill Hole Quarry dark green chlorite is a minor component of a vein (up to 120 mm wide, strike northwest, dip 70° northeast) of light reddish-brown calcite containing minor hematite that was exposed on the southeast face of the lower (partly water filled) part of the quarry [SK 4860 1030]. Green earthy chlorite also occurred in veins containing iron-stained colourless to white prismatic quartz crystals (Ince, *Russell Society Newsletter*, (1992), No. 23, 19-20). In common with specimens from the Groby area that contain minerals of the chlorite group, it is possible that some of this material is chamosite (see Ince, 2011).

### Chrysocolla, $(\text{Cu,Al})_2\text{H}_2\text{Si}_2\text{O}_5(\text{OH})_4 \cdot n\text{H}_2\text{O}$ (Copper-containing silica gel)

A number of recent articles have noted that many specimens labelled as chrysocolla consist of an amorphous copper-containing silica gel (Moreton, 2007; Bridges *et al.*, 2008; Green *et al.*, 2008). Bearing in mind this *proviso*, material from the Markfield area will be described as 'chrysocolla'.

King (1973) described the occurrence of 'chrysocolla' at Old Cliffe Hill Quarry in a quartz-carbonate vein system exposed on the top level of the northwest face in 1959. It was associated with bornite, malachite, goethite, calcite and quartz and formed small masses, cavity infills and encrustations in a halo (up to 8 mm across) surrounding the blebs of bornite. More recently small amounts of pale blue to pale blue-green 'chrysocolla', associated with malachite, azurite, native copper and cuprite, were collected from joints in diorite boulders in the Triassic breccia close to the Precambrian-Triassic unconformity on the west side of the quarry.



Figure 5. 'Chrysocolla' pseudomorphs after cuprite with malachite and calcite from Hill Hole Quarry, Markfield (3 mm x 2 mm); Frank Ince specimen; Franz Werner photograph.



Figure 6. 'Chrysocolla' pseudomorphs after cuprite with malachite and calcite from Hill Hole Quarry, Markfield (3 mm x 2 mm); John Jones specimen; Franz Werner photograph.

Ince (*Russell Society Newsletter*, (1992), No. 23, 19-20) noted the occurrence of some pale to mid-blue material from a small vein (up to 50 mm wide, strike northeast) in the southeast face of the lower (partly water filled) Hill Hole Quarry [SK 4861 1031]. It was not possible to obtain a distinct XRD pattern (John Faithfull, *personal communication*); however, this material was shown to contain copper (identified by wet chemistry) and it was assumed to be 'chrysocolla' (Fig. 4). The majority of the 'chrysocolla' occurs as a coating on the surface of a small cavity lined with singly-terminated colourless to pale green calcite crystals (up to 10 mm). Some of the 'chrysocolla' forms pseudomorphs after an octahedral mineral, presumably cuprite (Figs. 5 and 6); where an octahedron is broken the replacement is complete with a greenish-blue core and a lighter blue surface. In addition to the calcite, the 'chrysocolla' is associated with malachite, cuprite and native copper.

### COPPER, Cu

Ince (*Russell Society Newsletter*, (1992), No. 23, 19-20) noted the tentative identification of native copper from Hill Hole Quarry. It occurred in a small vein in the southeast

face of the lower (partly water filled) part of the quarry [SK 4861 1031] as red-brown dull metallic dendrites enclosed in calcite and associated with cuprite, 'chrysocolla' and malachite.

In 2007, joints in diorite boulders in the Triassic breccia close to the Precambrian-Triassic unconformity on the west side of Old Cliffe Hill Quarry afforded very small amounts of typical metallic masses of native copper associated with 'chrysocolla', malachite, azurite, and cuprite.

### CUPRITE, $\text{Cu}_2\text{O}$

The collection of cuprite from Hill Hole Quarry was noted by Ince (*Russell Society Newsletter*, (1992), No. 23, 19-20). It occurred in a small vein in the southeast face of the lower (partly water filled) part of the quarry [SK 4861 1031] and specimens consist of grey to black masses that are lustrous when broken and contain copper (identified by wet chemistry); small fragments are a deep red colour and have a red-brown streak. The cuprite is partly enclosed in calcite and associated with 'chrysocolla', malachite and native copper; some of the 'chrysocolla' occurs as pale to mid-blue rounded octahedra that are presumably 'chrysocolla' pseudomorphs after cuprite (Figs. 5 and 6).

Small deep red masses of cuprite, associated with 'chrysocolla', malachite, azurite and native copper, were found in 2007 on joints in diorite boulders in the Triassic breccia close to the Precambrian-Triassic unconformity on the west side of Old Cliffe Hill Quarry.

### DOLOMITE, $\text{CaMg}(\text{CO}_3)_2$

King (1973) described a wadi in the Precambrian rocks at Old Cliffe Hill Quarry that contained a coarse Triassic breccia that was poorly cemented by dolomite associated with 'wad' and occasional patches of microcrystalline malachite. Two specimens from Old Cliffe Hill Quarry (LU 20390 and LU 20393) have cavities lined with small cream to pale pink rhombs (up to 2 mm) of dolomite. The dolomite on LU 20390 is associated with some earthy hematite and that on LU 20393 is associated with very small amounts of azurite and malachite. Veins of pink dolomite (up to 50 mm wide) have occurred in both New and Old Cliffe Hill quarries (Neil Hubbard, *personal communication*).

### EPIDOTE, $\text{Ca}_2\text{Al}_2(\text{Fe}^{3+}, \text{Al})\text{Si}_3\text{O}_{12}(\text{OH})$

King (1973) described the occurrence of epidote from Old Cliffe Hill Quarry as "veins up to 29 mm wide... the pattern of infilling is characteristic of the quarry, being an abnormally strong prismatic development (up to 20 mm in length) from the footwall side of the veins and a shorter length of growth from the hanging wall, producing a complete fill and no possibility of crystal terminations. What voids may remain are filled with younger quartz... the colour of this epidote is a greyish-green and the lustre is normally high"; as may be seen on K2566 (NMW 83.41G.M9151). LU 20429 consists of a vein section with mid-green to brown prismatic epidote (up to 18 mm) associated with quartz and brown dolomite. Epidote similar to that described above can still be found in the quarry; although

some of the voids have been filled with calcite. This calcite could be removed with dilute hydrochloric acid; unfortunately under these conditions the remainder of the epidote-containing vein breaks up. Epidote similar to that described above has also occurred in New Cliffe Hill Quarry (Neil Hubbard, *personal communication*).

### GOETHITE, $\alpha\text{-FeO}(\text{OH})$

King (1973) noted the occurrence of goethite, associated with 'chrysocolla', malachite, calcite and quartz, in the remnant of a bornite-containing quartz-carbonate vein system with a strike of  $\sim 312^\circ$  that was exposed on the top level of the northwest face of Old Cliffe Hill Quarry in 1959. In 2007 some lustrous dark brown laths (up to 4 mm x 1 mm) were found lining cavities in an iron-rich, calcite-containing component of the breccia associated with the Precambrian-Triassic unconformity on the west side of Old Cliffe Hill Quarry. These laths contain iron (identified by wet chemistry), have a yellow-brown streak, are biaxial (+) and have been confirmed as goethite (identified by XRD; David Green, *personal communication*).

### Graphite, C

The occurrence of graphite at Old Cliffe Hill Quarry was recorded by King (1967): "the dioritic Southern type "Syenite" is seen in contact with upper divisions of the Charnian succession... certain horizons of these slaty facies adjacent to the contact, have been metamorphosed to a highly siliceous flinty hornfels with well-developed "spotting". These spots are said to be graphite (T.D. Ford, *personal communication*)". In a later description King (1973) described this occurrence as "doubtful"; given this uncertainty, the occurrence of graphite at Old Cliffe Hill Quarry remains to be confirmed.

### HEMATITE, $\alpha\text{-Fe}_2\text{O}_3$

At Old Cliffe Hill Quarry hematite has occurred in a number of different situations:

1. King (1973) noted that minor specular hematite occurred in calcite veins; the hematite, together with euhedral cubic pyrite, was collected from lens-like masses of pinkish-white to red calcite that were occasionally stained green due to inclusions of chlorite.
2. Specular hematite has also been found more recently as small (up to 1 mm) dark red to black plates in a quartz-chlorite matrix associated with calcite and baryte (Neil Hubbard, *personal communication*).
3. LU 20393 consists of some red-brown earthy hematite with dolomite.
4. K4019 (NMW 83.41G.M3820) has dark grey veins (to 8 mm) that contain a mixture of hematite and magnetite (identification by XRD; Tom Cotterell, *personal communication*) in greenish altered diorite (Tom Cotterell and Jana Horák, *personal communication*).
5. In 2010, grey veins (up to 30 mm wide) in an isolated boulder of dark greenish-grey altered diorite on the incline near the lowest level of the quarry (Neil Hubbard, *personal communication*) were found to contain hematite (red-brown streak) and magnetite embedded

in white to light grey calcite. After removal of some of the calcite (with dilute hydrochloric acid) from a small sample it could be seen that the hematite was present as minute granules in thin layers (up to 15 mm x 7 mm x 0.5 mm) and irregular aggregates (up to 2 mm across) together with some very small black octahedral magnetite crystals.

### *Limonite, powdery iron oxides and oxyhydroxides*

Limonite is not a well-defined mineral species and material from the Markfield area will be described as 'limonite'. King (1973) reported an occurrence of 'limonite' at Old Cliffe Hill Quarry as arborescent or dendritic growths on joint planes and cleavage surfaces in the Charnian rocks (that are now classified as the Maplewell Group). He noted that "a good example was donated to the geological collections of the University of Leicester by the former Cliffe Hill Granite Company...was collected from the hornfelsed sediments of the Woodhouse and Bradgate Beds on the NE face of the quarry"; unfortunately this specimen could not be found in the course of this study.

### MAGNETITE, $\text{Fe}_3\text{O}_4$

K4019 (NMW 83.41G.M3820), from Old Cliffe Hill Quarry, has dark grey veins (to 8 mm) that contain a mixture of magnetite and hematite (identified by XRD; Tom Cotterell, *personal communication*) in greenish altered diorite (Tom Cotterell and Jana Horák, *personal communication*). In 2010, grey veins (up to 30 mm wide) in an isolated boulder of dark greenish-grey altered diorite on the incline near the lowest level of Old Cliffe Hill Quarry were found to contain light grey and white calcite enclosing numerous very small black magnetite crystals and granular hematite (Neil Hubbard, *personal communication*). The removal of the calcite (with dilute hydrochloric acid) from a small sample afforded a black insoluble residue. This residue contained the magnetite as small lustrous black octahedral crystals (up to 0.8 mm, but with the majority being less than 0.1 mm) and granules composed of aggregates of small octahedral crystals with a black streak. The residue also contained some granular hematite and anhedral quartz grains; however, the magnetite was easily separated from the non-magnetic material using a magnet. It is tempting to think that this recently-collected material is related to the occurrence represented by K4019 (NMW 83.41G.M3820).

### MALACHITE, $\text{Cu}_2(\text{CO}_3)(\text{OH})_2$

King (1973) described two occurrences of malachite at Old Cliffe Hill Quarry:

1. Pale green malachite occurred with goethite and 'chrysocolla' in the remnant of a bornite-containing quartz-calcite vein system with a strike of  $\sim 312^\circ$  that was exposed on the top level of the northwest face of Old Cliffe Hill Quarry in 1959.
2. Occasional patches of microcrystalline malachite, associated with a deposit of 'wad', were found near the base of a wadi filled with aeolian sand and a coarse dolomite-cemented Triassic breccia.

A specimen from Old Cliffe Hill Quarry (LU 20393) has very small amounts of malachite and minute amounts of azurite on dolomite. More recently small amounts of malachite occurred on joints in diorite boulders close to the Precambrian-Triassic unconformity on the west side of the quarry; the malachite was associated with 'chrysocolla', cuprite, copper and azurite.

The occurrence of malachite at Hill Hole Quarry was noted by Ince (*Russell Society Newsletter*, (1992), No. 23, 19-20). It occurred as sprays and rounded aggregates of green acicular crystals (Figs. 4, 5 and 6) associated with calcite, 'chrysocolla', 'chrysocolla' pseudomorphs after cuprite, native copper and cuprite in a small vein (up to 50 mm wide, strike northeast) in the southeast face of the lower part of the quarry [SK 4861 1031].

### PALYGORSKITE, $(\text{Mg},\text{Al})_2\text{Si}_4\text{O}_{10}(\text{OH})\cdot 4\text{H}_2\text{O}$

There are a number of occurrences of palygorskite in Leicestershire (Evans and King, 1962; King and Ford, 1968; King, 1973). Large areas of palygorskite ( $\sim 1 \text{ m}^2$ ) associated with fine-grained calcite were found at Old Cliffe Hill Quarry and K2197 (NMW 83.41G.M6785) consists of pale brown to apricot yellow palygorskite variety mountain leather. It is composed of multiple-leaved very flexible sheets with each sheet containing up to six leaves that are  $\sim 0.02 \text{ mm}$  thick (Fig. 7). In 2007 material similar to that described above, but cream to white in colour and in more substantial sheets, was collected from joints in the South Charnwood Diorites on the west face of the quarry.

### PYRITE, $\text{FeS}_2$

King (1973) reported an occurrence of pyrite at Old Cliffe Hill Quarry in 1966 on the north side of No. 3 level (the lowest level at that time) that caused significant problems for the quarry plant. The 1.3 m wide pale grey exposure consisted of a lens comprising a stock-work of chlorite-containing calcite veins (up to 13 mm wide) that included many lustrous brass-yellow cubes of pyrite (up to 32 mm). LU 23444 may have come from this occurrence as it has striated brass-yellow pyrite cubes (up to 10 mm) in



**Figure 7.** Palygorskite variety mountain leather from Old Cliffe Hill Quarry, Markfield (145 mm x 105 mm); K2197 (NMW 83.41. M6785); Frank Ince photograph.



**Figure 8.** Ramsdellite and pyrolusite in a Triassic breccia from New Cliffe Hill Quarry, Stanton under Bardon (70 mm x 50 mm); Neil Hubbard specimen; Frank Ince photograph.

diorite containing some calcite veins (up to 10 mm wide) in diorite. In 2010 some quartz-carbonate veins in northeast corner of the lowest level of the quarry were found to contain some small striated cubes of yellow pyrite (up to 1.5 mm) embedded in masses of pinkish-grey calcite.

#### PYROLUSITE, $\text{MnO}_2$

Some grey metallic-looking crystalline material associated with the Triassic breccia containing clasts of Precambrian volcanoclastic rocks (Fig. 8) was collected from the northwest corner of New Cliffe Hill Quarry in 2003 (Neil Hubbard, *personal communication*). Analysis of this material has shown it to be a mixture of pyrolusite and ramsdellite (identified by XRD; Tom Cotterell, *personal communication*).

#### PYRRHOTITE, $\text{Fe}_{0.8-0.9}\text{S}$

King (1973) described the occurrence of pyrrhotite at Old Cliffe Hill Quarry: “on the NE face there is a fine exposure [SK 4768 1062] of a faulted contact between the Southern-type diorite and the Charnian sediments... the formerly finely-bedded dust tuffs, containing abundant diagenetic pyrite, have been strongly metamorphosed into spotted hornfels. In the process the pyrite has been metamorphosed into bronze-coloured pyrrhotite”. Carney and Pharaoh (2000) noted that thermal metamorphism was associated with the intrusion of the South Charnwood Diorites into the Charnian volcanoclastic sediments.

#### QUARTZ, $\text{SiO}_2$

Quartz veins have been recorded as occurring in the small quarries on the southwest side of Billa Barra Hill (McGrath, 2004). Lightly iron-stained colourless to white prismatic quartz crystals (up to 20 mm) and dark green earthy chlorite occurred in veins at Hill Hole Quarry (Ince, *Russell Society Newsletter*, (1992), No. 23, 19-20). Quartz-carbonate veins containing epidote or chlorite with hematite or bornite have been exposed at Old Cliffe Hill Quarry (King, 1973). More



**Figure 9.** Tourmaline from Old Cliffe Hill Quarry, Markfield (135 mm x 75 mm); K8671 (NMW 83.41.M7392); Frank Ince photograph.

recently quartz has been found at Old Cliffe Hill Quarry in a quartz-chlorite-hematite matrix associated with calcite and baryte (Neil Hubbard, *personal communication*).

#### RAMSDELLITE, $\text{MnO}_2$

Some grey metallic crystalline material, associated with the Triassic breccia containing clasts of Precambrian volcanoclastic rocks, that was collected from the northwest corner of New Cliffe Hill Quarry in 2003 (Neil Hubbard, *personal communication*) has been analysed and has been shown to be a mixture of ramsdellite and pyrolusite (identified by XRD; Tom Cotterell, *personal communication*). Ramsdellite is an uncommon mineral in the UK having been found at Lecht Mine, Tomintoul, Scotland and Drosgol Mine, Ponterwyd, Wales (Tindle, 2008); consequently, this appears to be the first report of the occurrence of ramsdellite in England. The XRD pattern (NMW X-2342) of the ramsdellite from New Cliffe Hill Quarry is interesting as it also contains a set of peaks consistent with an isostructural phase with unit-cell parameters intermediate between those of ramsdellite and groutite [ $\text{MnO}(\text{OH})$ ]; reported by Post and Ross (1989) as being present in most natural ramsdellite samples. This phase was subsequently shown by Post and Heaney (2004) to be identical to the synthetic phase, ‘groutellite’, described by Klingsberg and Roy (1959). ‘Groutellite’ has never been approved as a new mineral, but (somewhat confusingly) was discredited by Burke (2006) who described it as a “pseudomorph of ramsdellite after groutite” citing the reference by Post and Heaney (2004). Post and Heaney (2004) do not mention ‘groutellite’ as pseudomorphs of ramsdellite after groutite, but instead put forward details suggesting that ‘groutellite’ is a distinct intermediate phase between ramsdellite and groutite (Tom Cotterell, *personal communication*). Additional specimens of the breccia collected from the northwest corner of New Cliffe Hill Quarry (Neil Hubbard, *personal communication*) contain clasts of Precambrian volcanoclastic rocks cemented by a similar-looking grey metallic phase (Fig. 8). It is interesting to note that some of this grey material contains rectangular cavities that may be epimorphs after a bladed mineral.

TOURMALINE,  $\text{Na}(\text{Mg}, \text{Fe}^{2+})_3\text{Al}_6(\text{BO}_3)_3\text{Si}_6\text{O}_{18}(\text{OH})_4$   
(dravite-schorl series)

Tourmaline has occurred in small amounts in the majority of the working quarries of Charnwood Forest (King, 1973). It was perhaps most abundant in Old Cliffe Hill Quarry and several specimens were recovered from an exposure on the northwest working face of the quarry [SK 4735 1071] (King, 1973). The identification was made by Dr T. Deans and Mr D. Atkin (of the then Geochemical Division, IGS, London) and the tourmaline was shown to be in the dravite-schorl series. It was similar to the material from Foyers (on the east side of Loch Ness, Scotland) that was reported by Deans *et al.* (1971). At Old Cliffe Hill Quarry the tourmaline took the form of encrustations on slickenside surfaces which in a shear zone (strike  $329^\circ$ , dip of  $65^\circ$  to the southwest) with at least two phases of mineralisation (King, 1973):

1. First-generation quartz-calcite-chlorite mineralization.
2. Subsequent movement of the faults producing slickenside surfaces on the first-generation minerals.
3. Second-generation mineralization consisting entirely of tourmaline and calcite.

The tourmaline occurred most commonly as greyish-blue, with occasional streaks of darker blue, microcrystalline films no more than a fraction of a millimeter thick and occasionally as minute spherical masses embedded in calcite (King, 1973); K8671 (NMW 83.41G.M7392), labelled as “dravite”, is shown in Figure 9. Its physical characteristics are rather atypical for the species; with the possible exception of the so-called ‘blue-peach’ of the Cornish Hercynian tin veins (King, 1973). In 2010, mid to dark blue-grey material, similar to that described above, was found amongst the debris on floor of the lowest level on the west side of the quarry.

### *Wad, powdery manganese oxides and oxyhydroxides*

Wad is not a well-defined mineral species and material from the Markfield area will be described as ‘wad’. King (1973) described an interesting occurrence of ‘wad’ at Old Cliffe Hill Quarry: “In the process of extending the quarry in a northerly direction, a wadi on the Precambrian diorite surface was exposed on the eastern side of an access road. The wadi (5.2 m wide and 3.2 m deep) was cut in an E-W direction, almost at right angles to its length. The base of the wadi was occupied by a coarse breccia (1.2 m thick) composed of Charnian clasts, poorly cemented by dolomite, with occasional patches of microcrystalline malachite. The rest of the wadi fill (to a height of 1.8 m) consisted of fine-grained aeolian sand. A concentration of black wad, partially ponded on an argillaceous horizon within the sand, occurred 600 mm from the base of the section. The concentration, consisting of quite thick pellicles on the sand grains, formed a bed 37 mm thick. The concentration was thickest at the base and gradually weakened upwards. In places fingers of the black cementation passed below the base of the horizon to the depth of a few millimetres. The bed of wad died out laterally, on neither side reaching the



**Figure 10.** ‘Wad?’ in Triassic sandstone from Old Cliffe Hill Quarry, Markfield (90 mm x 45 mm); Neil Hubbard specimen; Frank Ince photograph.

wadi walls. Partial analyses (A.R.L. 29000B Direct-Reading Spectrometer) showed high values of Mn, Ba, Sr and V”. There are a number of specimens in the King Collection, e.g. K65-11 (NMW Research Collection), that are probably related to this occurrence; they contain bands or patches of an amorphous black powdery material cementing a light orange to brown sandstone.

A specimen from Old Cliffe Hill Quarry has been rediscovered recently (Neil Hubbard, *personal communication*; Richard Taylor label: “Pyrolusite. Cliffe Hill Pit, 1 mile NW of Markfield, N Leicestershire”) and it consists of some dark brown to black powdery material impregnating orange sandstone (Fig. 10). An earlier label with this specimen provides additional information: “Dendritic Manganese Ore from Keuper of Cliffe Hill Pit. Approx. 10 FT. from Base of Keuper deposited in an irregularity (wadi?) in surface of Markfieldite. According to Mr. J.R. [sic] King (Curator, Leicester Univ.) - very probably a mixed ore with Cobalt, etc. Cliffe Hill Pit, c.1 ml. SW of Copt Oak and 1 mile NW of Markfield, Leicestershire”. The label also states that the specimen was collected by P. Mouldes in March 1966, a year later than the material in the King Collection (1965); however, it could still be related to the same occurrence. Analysis of this poorly crystalline material has shown that it contains either lithiophorite,  $(\text{Al}, \text{Li})\text{Mn}^{4+}\text{O}_2(\text{OH})_2$  or todorokite,  $(\text{Mn}^{2+}, \text{Ca}, \text{Na}, \text{K})(\text{Mn}^{4+}, \text{Mn}^{2+}, \text{Mg})_6\text{O}_{12} \cdot 3\text{H}_2\text{O}$  (analysis by XRD; Tom Cotterell, *personal communication*).

## DISCUSSION

The mineralisation hosted by the South Charnwood Diorites and the adjacent rocks in the area around Markfield occurs in three distinct settings:

1. Thermal metamorphism of the volcanoclastic rocks of the Bradgate Formation associated with the intrusion of the South Charnwood Diorite.
2. Hypogene (hydrothermal) mineralisation in veins and shear zones in the South Charnwood Diorites and adjoining rocks.
3. Supergene mineralisation adjacent to the Precambrian-Triassic unconformity.

## Thermal metamorphism associated with the intrusion of the South Charnwood Diorites

The South Charnwood Diorites were intruded into the rocks of the Bradgate Formation. A faulted contact between the rocks of the Bradgate Formation and the South Charnwood Diorites has been seen at various times during quarrying at Old Cliffe Hill Quarry; however, the majority of the contact appears to be related to the process of intrusion with the occurrence of a chilled margin in the South Charnwood Diorites and thermal metamorphism in the rocks of the Bradgate Formation (Carney and Pharaoh, 2000). Thermal metamorphism of the Charnian volcanoclastic sediments close to the contact with the South Charnwood Diorites resulted in the diagenetic pyrite being altered to pyrrhotite (King, 1973).

## Hypogene (hydrothermal) mineralisation in veins and shear zones

Over the last 150 years a number of mineralised veins and shear zones have been exposed in the quarries in the Markfield area; unfortunately, the temporal relationship between the intrusion of the South Charnwood Diorites and the hypogene mineralisation(s) of these veins and shear zones is far from clear. Some were probably late-stage events associated with the intrusion process and others may have occurred during subsequent tectonic activity.

The most well-described veins and shear zones have a ~northwest strike, possibly related to Acadian (late Silurian) tectonic activity (Carney *et al.*, 2008), and the majority of these occur at Old Cliffe Hill Quarry (King, 1973):

1. A shear zone (strike 329°; dip 65° to the southwest) contained two phases of mineralisation. A first generation quartz-chlorite-calcite mineralisation was followed by tectonic movement in the shear zone producing slickenside surfaces; it was on these surfaces that a second generation tourmaline-calcite mineralisation was deposited.
2. A shear zone (strike ~338°; dip steeply to the east) with calcite-chlorite-hematite-pyrite mineralisation.
3. A vein (strike ~312°) contained quartz-calcite-bornite mineralisation.
4. A prominent vein at Hill Hole Quarry (strike northwest, dip 70° northeast) contains calcite (Ince, *Russell Society Newsletter*, (1992), No. 23, 19-20) and may be related to the occurrences of calcite in the Markfield area that were noted by Eskrigge (1868) and Powell (1868).
5. Whilst it has a northeast strike, a vein containing calcite (associated with malachite, 'chrysocolla', cuprite and native copper) occurs at Hill Hole Quarry (Ince, *Russell Society Newsletter*, (1992), No. 23, 19-20) and may be related to the prominent calcite-containing northwest striking vein mentioned above.

Quartz-chlorite-hematite mineralisation (associated with calcite and baryte) also occurs at Old Cliffe Hill Quarry and a small quartz-chlorite vein occurs at Hill Hole Quarry. Quartz-epidote and quartz-epidote-calcite mineralisation occurs in both of the Cliffe Hill quarries. Quartz veins also occur at Billa Barra Hill. The relationship of these veins to

the other quartz-hosted mineralisation is not clear. In the absence of more details of the occurrences at Old Cliffe Hill Quarry, the relationship of the magnetite-hematite or magnetite-hematite-calcite veins in greenish altered diorite to the other mineralised veins is also difficult to interpret.

Dolomite-containing veins have occurred at Old Cliffe Hill Quarry (associated with earthy hematite or supergene azurite and malachite) and also at New Cliffe Hill Quarry; however, the genesis of the dolomite is uncertain and could be related to hydrothermal mineralisation or a late- or post-Triassic remobilisation.

## Supergene mineralisation adjacent to the Precambrian-Triassic unconformity

The occurrences of the supergene, copper-dominated mineralisation adjacent to the Precambrian-Triassic unconformity at Old Cliffe Hill and Hill Hole quarries are not as impressive as those seen in other Leicestershire quarries, e.g. Newhurst Quarry (Ince, 2005), Bardon Hill Quarry (Ince, 2007) and, most spectacularly, New Cliffe Hill Quarry (Hubbard *et al.*, 2005; Ixer *et al.*, 2005; Bridges, 2007). At Old Cliffe Hill Quarry small amounts of native copper, cuprite, azurite and malachite occur in the Triassic breccia. Goethite occurs in an iron-rich, calcite-containing component of the breccia associated with the Precambrian-Triassic unconformity on the west side of Old Cliffe Hill Quarry. At Hill Hole Quarry 'chrysocolla', 'chrysocolla' pseudomorphs after cuprite, malachite, cuprite and native copper occur in a small vein (Ince, *Russell Society Newsletter*, (1992), No. 23, 19-20); the presence of 'chrysocolla' pseudomorphs after cuprite indicates that there were at least two periods of supergene mineralisation.

Manganese mineralisation is present in both of the Cliffe Hill quarries. King (1973) described an interesting occurrence of 'wad' at Old Cliffe Hill Quarry. It was found in a wadi in the Precambrian rocks that had been filled with a coarse Triassic breccia. The breccia was composed of Charnian clasts, poorly cemented by dolomite, with occasional patches of microcrystalline malachite overlain by fine-grained aeolian sand and the 'wad' was partially ponded on an argillaceous horizon within the sand. Analysis of this 'wad' indicated that it contained significant quantities of manganese, barium, strontium and vanadium (King, 1973). An additional sample of poorly crystalline material from Old Cliffe Hill Quarry contains either lithiophorite or todorokite (Tom Cotterell, *personal communication*). Material from New Cliffe Hill Quarry that is more crystalline has been shown to be a mixture of pyrolusite and ramsdellite (Tom Cotterell, *personal communication*) and further specimens from New Cliffe Hill Quarry consist of similar-looking grey material cementing a breccia containing clasts of Precambrian volcanoclastic rocks. Pearson and Jeffery (1997) suggested that saline brines associated with the development of evaporites in Permo-Triassic sediments could account for the unconformity-hosted copper and manganese mineralisation; they also suggest that the same mechanism gave rise to the palygorskite mineralisation (see below). Further study of the distribution and composition of the manganese-containing oxides/hydroxides that occur

in Leicestershire will be required in order to establish their relationship to the other components of the unconformity-hosted base-metal mineralization.

Palygorskite (with calcite) occurs at the base of the breccia-filled Triassic wadis and adjacent fractures in the Precambrian rocks at Old Cliffe Hill Quarry. Evans and King (1962) suggested that the palygorskite was “deposited from downward-moving waters that were in direct connection with lakes and rivers in which the basal Triassic sediments of the area were deposited and not from post-Triassic ascending hydrothermal solutions”; this theory implies that palygorskite formation was in progress during the late Triassic. Pearson and Jeffery (1997) agreed with this mechanism; however, they also suggested that some palygorskite might have been formed by the reaction of smectite group minerals with dolomite.

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## A REVIEW OF THE MINERALOGY OF THE AREA AROUND GROBY, LEICESTERSHIRE

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**The Precambrian, Cambrian and Triassic rocks exposed in the area around Groby, Leicestershire are the hosts for both hypogene (hydrothermal) and supergene minerals. Hypogene minerals are present in a number of quartz- and carbonate-containing veins and shear zones in the Precambrian rocks. Supergene minerals are present in the Precambrian rocks and the Triassic sediments adjacent to the Precambrian-Triassic unconformity. This article describes the history of the quarrying activity, geology and mineralogy of the area around Groby and makes some observations on the processes responsible for the formation of the hypogene and supergene minerals.**

### INTRODUCTION

The area around Groby, Leicestershire contains exposures of Precambrian, Cambrian and Triassic rocks (Worssam and Old, 1988; Carney *et al.*, 2000; Ambrose *et al.*, 2007). In this area, the South Charnwood Diorites (Carney and Pharaoh, 2000) are the southeastern part of a late Precambrian intrusion in the earlier Precambrian

volcaniclastic rocks of the Bradgate Formation of the Maplewell Group of the Charnian Supergroup (Moseley and Ford, 1985). The Cambrian rocks are parts of the Brand Group: the Stable Pit Member of the Brand Hills Formation and the Swithland Formation. In the Groby area the quarries listed below (Figure 1 and Table 1) provide exposures of the Precambrian, Cambrian and Triassic rocks and, as quarrying has progressed, a number of quartz- and carbonate-rich

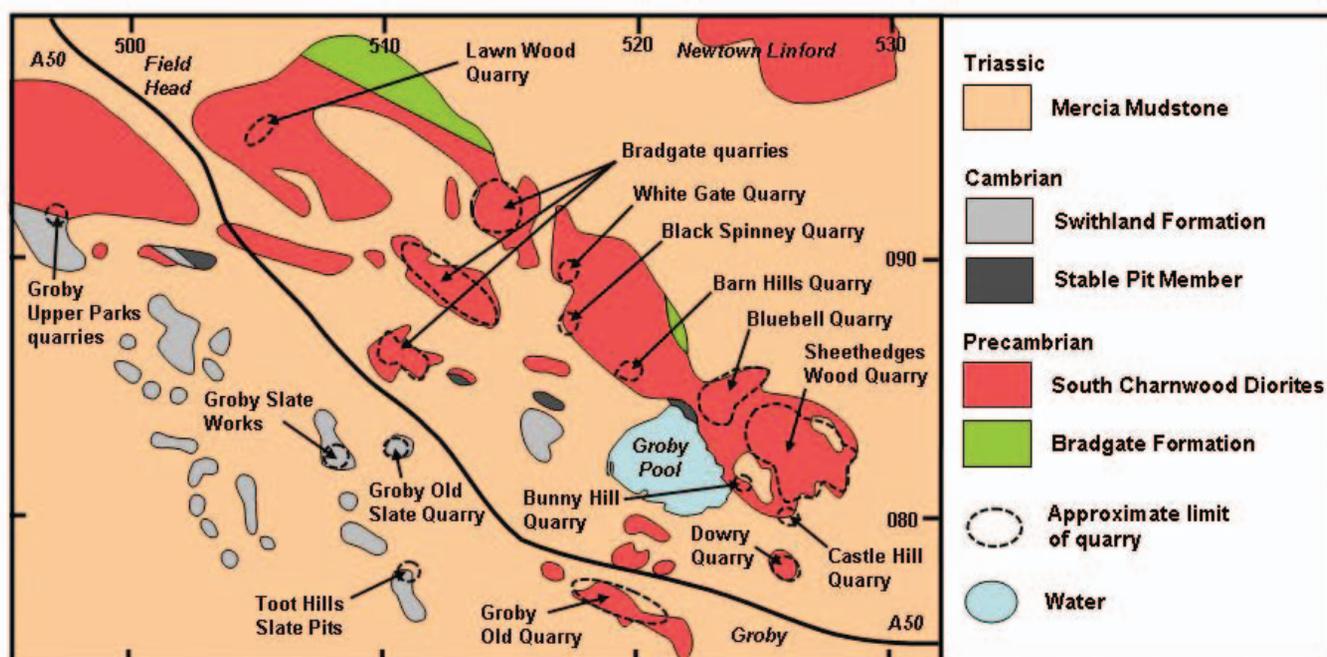


Figure 1. Geological map of the area around Groby; modified from Ambrose *et al.*, 2007.

#### South Charnwood Diorites

Quarry Name	NGR	Alternative Quarry Name
Groby Upper Parks quarries <sup>1</sup>	SK 497 092 (GPS)	
Groby Upper Parks quarries <sup>1</sup>	SK 497 092 (GPS)	
Lawn's Wood Quarry <sup>2</sup>	SK 505 093	Lawn Wood Quarry <sup>3</sup>
Bradgate quarries <sup>4</sup>		Bradgate Hill quarries <sup>3</sup>
Bradgate Southwest Quarry	SK 511 086	Bradgate Quarry 1 <sup>2</sup> , Southwest Bradgate Granite Quarry <sup>5</sup>
Bradgate Middle Quarry <sup>2</sup>	SK 513 089	Bradgate Quarry 2 <sup>2</sup> , Middle Bradgate Granite Quarry <sup>5</sup>
Bradgate Northeast Quarry	SK 514 092	Bradgate Quarry 3 <sup>2</sup> , Northeast Bradgate Granite Quarry <sup>5</sup> , Bradgate Top Quarry <sup>6</sup> , Bradgate House Quarry <sup>6</sup>
White Gate Quarry <sup>2,3,7</sup>	SK 517 089 (GPS)	
Black Spinney Quarry <sup>2,3,7</sup>	SK 517 087 (GPS)	
Barn Hills Quarry <sup>2,3,7</sup>	SK 519 085 (GPS)	
Bluebell Quarry <sup>2,3,5</sup>	SK 523 084	Bluebell Wood Quarry <sup>6</sup> , Blue Bell Quarry <sup>7</sup>
Sheethedges Wood Quarry <sup>3,4,6</sup>	SK 526 082	Sheet Hedges Wood Quarry <sup>2,7,8</sup> , Groby Quarry <sup>5</sup> , Main Groby Quarry <sup>5</sup>
Bunny Hill Quarry <sup>2,7</sup>	SK 524 081 (GPS)	
Castle Hill Quarry <sup>2,7</sup>	SK 526 080	
Dowry Quarry <sup>2,7</sup>	SK 526 078 (GPS)	Darey Quarry <sup>3</sup> , Dowry Hill Quarry <sup>7</sup> , Downy Quarry <sup>7</sup>
Groby Old Quarry <sup>5</sup>	SK 519 076 (GPS)	Old Groby Quarry <sup>2</sup> , Village Quarry <sup>3,6</sup> Old Quarry <sup>7</sup> , Groby Village Quarry <sup>8</sup>

#### Swithland Formation

Quarry Name	NGR	Alternative Quarry Name
Groby Upper Parks quarries <sup>1</sup>	SK 497 092 (GPS)	
Groby Old Slate Quarry <sup>1,2,9</sup>	SK 510 083 (GPS)	
Groby Slate Works <sup>1,2,9</sup>	SK 507 081	
Toot Hills slate pits <sup>10,11</sup>	SK 510 077 (GPS)	

References: 1 Ramsey (2007); 2 McGrath (2007); 3 Miller (1972); 4 King and Ford (1968); 5 Worssam and Old (1988); 6 King (1973); 7 Ramsey (1982); 8 Bosworth (1912); 9 Woodward (1984); 10 Harwood (2008); 11 Franz Werner (*personal communication*)

**Table 1.** The names, national grid references (NGR) and alternative names of the quarries in the area around Groby (see Figure 1)

veins and shear zones have been exposed. A combination of the effects of these structures, the nature of the Triassic sediments and the presence of marked Precambrian-Triassic and Cambrian-Triassic unconformities has resulted in suites of hypogene and supergene minerals. The mineralogy of the area around Markfield, Leicestershire (to the northwest of the Groby area) is described in the preceding article (Ince, 2011).

## LOCATIONS

A number of small to medium sized quarries in the Groby area have exploited the Precambrian South Charnwood Diorites for use in the construction industries and some horizons of the Cambrian sequence, in particular the Swithland Formation of the Brand Group (the 'Swithland Slate'), have also been quarried for use in the construction industry, e.g. the production of roofing slates (Ramsey, 1982; McGrath, 2007; Ramsey, 2007). Over the last 250 years, several of these quarries have been given a number of different names; for the purposes of this article the names used are listed in Table 1 (in most cases, one of the previously used names has been chosen). Where possible, the grid reference of some of the smaller quarries has been checked by a global positioning system (GPS).

## HISTORY OF QUARRYING

McGrath (2007) has reviewed the history of the quarrying activity in Charnwood Forest and her article contains a section on the area around Groby. Ramsey (1982; 2007) has also described the history of the quarrying of the South Charnwood Diorites and the Swithland Formation (the 'Swithland Slate') in the parish of Groby; both of his contributions include a number of useful maps and photographs. Ramsey (2007) also suggested a possible derivation of the name of the village of Groby: "Grü' Germanic (pit or quarry) 'by' village - pit village - later became Gr oo by [Gr-oo-by] and in 1823 Groby".

### South Charnwood Diorites

In the Roman period the hilly outcrops that would have been present in the Groby area were one of the closest sources of resistant building material to Leicester and it seems unlikely that they would have been overlooked by the Roman engineers. Bearing this in mind, it is not surprising that the remains of the Roman buildings in Leicester (*Ratae Corieltauorum*) contain foundations and walls that incorporate the South Charnwood Diorites and roofing slates produced from the Swithland Formation (Ramsey, 2007). It has been difficult to identify the exact locations of any Roman quarries and it is probable that many of them will have been obliterated by more recent quarrying activity (McGrath, 2007; Woodward, 1984); having said this, there is a contact between the South Charnwood Diorites and the Swithland Formation in the Groby Upper Parks quarries and both rock types were found in the same context during the excavations of Roman remains at Vine Street in Leicester where blocks of the South Charnwood Diorites were found in wall foundations together with roofing slates of 'Groby Green Slate' derived from the Swithland Formation. Thus

it is possible that the Romans extracted both rock types from the same location, even though the Groby Upper Parks quarries were further from Leicester than alternative sources of the South Charnwood Diorites and the Swithland Formation that were closer to Groby (Ramsey, 2007).

There are reports of the South Charnwood Diorites being extracted in the Groby area during the Middle Ages, e.g. hard stone from Barn Hills was purchased for Kirby Muxloe Castle in 1480 (Ramsey, 2007); however, the more systematic quarrying of the South Charnwood Diorites was initiated in the early 1800s by the Fifth Earl of Stamford and Warrington with the expansion of work at the Groby Old Quarry (McGrath, 2007; Ramsey, 1982). In 1832 Robert Stephenson was engaged to build a railway to link the Groby quarries to the Leicester and Swannington Railway; his steam engine "Comet" was used to haul the first 24 wagons of Groby 'granite' from the Groby Old Quarry to West Bridge in Leicester. The railway line was gradually extended and by the early 1900s had reached Dowry, Bunny Hill, Castle Hill and Sheethedges Wood quarries. In 1898 a further extension of the railway to the east was proposed, but never built; this extension would have linked up with the Great Central Railway at Rothley. In 1865 the Groby Granite Company was formed and acquired the lease to Groby Old Quarry. Groby Old Quarry was gradually extended and Bosworth (1912, pp. 20-21) includes photographs, a large-scale map and a section of the quarry. Stone was extracted from Groby Old Quarry until the 1950s after which time the north-western half was backfilled by the National Coal Board with waste from the coal mines in the Leicestershire Coalfield, the area was landscaped and is now a playing field; the remainder of the old quarry is occupied by an industrial estate.

By the early 1900s the Groby Granite Company was also operating Dowry, Bunny Hill, Castle Hill and Sheethedges Wood quarries. In the 1880s the Patent Victoria Stone Company established their paving slab manufacturing operations as a sublet at Sheethedges Wood Quarry (McGrath, 2007; Ramsey, 1982). The description of Sheethedges Wood Quarry by Bosworth (1912, pp. 21-23) contains photographs, a large-scale map and section; the map also shows workings in the areas occupied by Bunny Hill, Castle Hill and Dowry quarries (although they are not named). White Gate, Black Spinney and Barn Hills quarries were active in the early 1900s and the stone was transported by cart or lorry to the railway in the Sheethedges Wood area; the poor quality of the stone meant that extraction in these small quarries appears to have ceased after 1940. Bluebell Wood Quarry was opened after the First World War; again, given the poor quality the stone, it was not a favoured site. Miller (1972) provided a very interesting map of Sheethedges Wood and Bluebell quarries towards the end of their productive period (Fig. 2) and he noted the location of some of the minerals that had been found in the quarries. Sheethedges Wood Quarry is currently operated by Midland Quarry Products. Dowry Quarry now contains a shooting range, Bunny Hill Quarry has been back-filled with overburden from Sheethedges Wood Quarry and Castle Hill Quarry has been

back-filled and landscaped. The Bradgate quarries were opened in 1919 and were worked by Redland Roadstone until 1971 (McGrath, 2007); more recently they have been used as a land fill site.

### Swithland Formation (the ‘Swithland Slate’)

It has been assumed that the roofing slates found in various excavations of Roman sites originated from the slate quarries in the area around the villages of Swithland and Woodhouse Eaves; however, analysis of the material found during the excavations at Vine Street in Leicester (in 2006) has shown that some of the roofing slates appear to have been produced from ‘Groby Green Slate’ and probably came from the Groby Upper Parks quarries (see Figure 1); thus, as mentioned above, it is possible that the Romans extracted both the slates of the Swithland Formation and South Charnwood Diorites from the same location (Ramsey, 2007).

During the Middle Ages the Swithland Formation was being quarried at various sites to the west of the A50 (see Figure 1), e.g. slate from Groby Park was purchased for Kirby Muxloe Castle in 1480 (Ramsey, 2007). Harwood (2008) noted that the building accounts for Kirby Muxloe Castle (dated 1490) recorded the acquisition of 10 loads of slate from ‘Shawe’ (the mediaeval name for Martinshaw Wood); he also described an excavation in the Toot Hills area of Martinshaw Wood and suggested that this provides evidence for early slate extraction. By 1766 slate quarries in the Groby area were being leased from the Earl of Stamford and land tax records for 1773-1823 indicate that there were three quarries to the north of the Slate Brook: Groby Slate Works near Alder Spinney and two older quarries near Bradgate Home Farm (McGrath, 2007); one or both of the latter quarries was presumably the Groby Old Slate Quarry. Accounts for the years 1837-1863 show that the products from the Groby slate quarries were being transported to Leicester by rail (Ramsey, 1982). It is worth noting that the steps of the Albert Memorial in Hyde Park and the roof of St. Pancras Station, London were constructed using

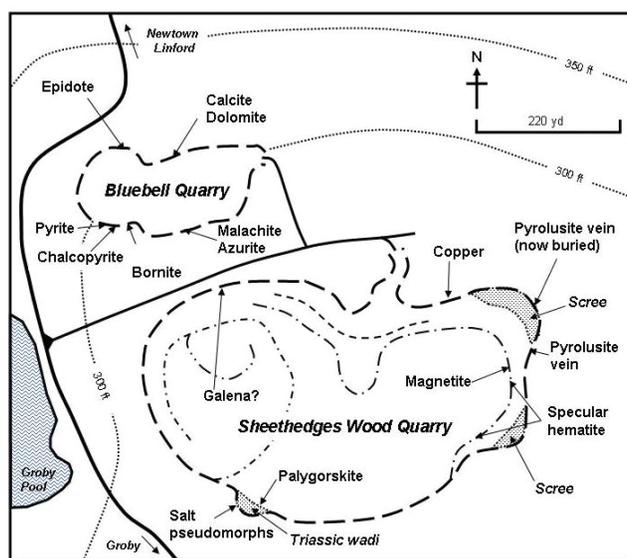
‘Groby Blue Slate’ whilst ‘Groby Grey Slate’ was used for the roof of Buckingham Palace (see [www.leics.gov.uk/building\\_blocks.pdf](http://www.leics.gov.uk/building_blocks.pdf), *Building Blocks - exploring the geological heritage of our built environment*. Leicestershire County Council, Environment and Heritage Services). The slate from Groby (and Swithland) was of inferior quality to that extracted from quarries in North Wales and a report commissioned by the Earl of Stamford in 1858 suggested that there was already severe competition from the Welsh slate quarries; by 1885 the Groby slate quarries had closed (Ramsey, 1982; Woodward, 1984; McGrath, 2007).

### GEOLOGY

The exposures of the Precambrian rocks in the area around Groby (Fig. 1) are a continuation of the rocks that are exposed to the northwest in the area around Markfield. They are the volcanoclastic rocks of the Bradgate Formation of the Maplewell Group of the Charnian Supergroup and the intrusive granophyric diorites of the South Charnwood Diorites and their geology, together with that of the Triassic rocks and Pleistocene deposits, is described in the accompanying article (Ince, 2011).

Cambrian rocks are also exposed in the area around Groby (Carney, 2000; Ambrose *et al.*, 2007). Until relatively recently they were assigned to the late Precambrian (Worssam and Old, 1988); however, the discovery of trace fossils (*Teichichnus* burrows) in some horizons has resulted in their reassignment to the Lower Cambrian (Brand Group): the Stable Pit Member of the Brand Hills Formation and the Swithland Formation. As thin sections of the Stable Pit Member contain fragments of the South Charnwood Diorite, there must have been an unconformity between the Precambrian and Cambrian rocks; although, only faulted contacts are exposed (John Carney, *personal communication*). The Stable Pit Member is the earliest component of the Cambrian sequence exposed in the Groby area (between Groby Pool and New Plantation) and Carney (2000) noted that, at the type locality (Stable Pit, Bradgate Park, Leicestershire), it is composed of “grey- to pink-weathering, medium-grained, quartz-rich sandstones (quartz-arenites) that are extremely compact and ‘glassy’ on fresh surfaces”. The Swithland Formation comprises a sequence of coarse- to fine-grained, purple, grey or green greywacke; in the area to the northwest of Groby these beds dip 30°-45° to the south-southwest and they have a cleavage that dips north-northeast (Worssam and Old, 1988, p. 18; in their description of the Precambrian rocks). Some horizons of the Swithland Formation (the ‘Swithland Slate’) have been quarried for use in the construction industries, e.g. for roofing slates.

Folding of the Precambrian and Cambrian rocks, particularly during the late Silurian (Carney *et al.*, 2008), has resulted in an anticline plunging to the southeast and the beds dip to the southwest - south-southwest in the Groby area (Worssam and Old, 1988). The Precambrian and Cambrian sequences have been affected by faulting and some these faults and shear zones appear to have controlled aspects of the mineralisation.



**Figure 2.** Sketch Map of Sheethedges Wood Quarry c.1972; reproduced with permission from Miller (1972).

## THE MINERALS

During the preparation of this article a number of collections of specimens from the Groby area were studied: the King Collection (now at the National Museum of Wales, Cardiff), the collections of the Department of Geology at the University of Leicester, Neil Hubbard, John Jones and Joe Miller. A number of specimens from these collections are described below; those from the King Collection are identified as Kxxxx (NMW 83.41G.Myyyy) and those from the Department of Geology at the University of Leicester identified as LUzzzzz.

During a recent investigation of the smaller exposures of the South Charnwood Diorites in the Groby area, there were no obvious signs of mineralisation at the Groby Upper Parks, White Gate, and Black Spinney quarries or in the Cambrian rocks exposed at the Groby Upper Parks quarries and Toot Hills slate pits. There do not appear to be any reports of mineralisation occurring at Lawn's Wood, Bunny Hill, Castle Hill and Dowry quarries.

A variety of techniques, including wet chemistry, X-ray (XRD) and electron beam (EDS) methods, have provided data that support the identification of the individual minerals described below (a table of analytical data will be provided on request). The minerals noted in lower case are those where further work is required to confirm their occurrence. The materials in lower case and italics are those that are no longer well-defined mineral species (Back and Mandarino, 2008) or have an ill-defined chemical composition.

### AZURITE, $\text{Cu}_3(\text{CO}_3)_2(\text{OH})_2$

Miller (1972) indicated that azurite occurred with malachite on the south face of Bluebell Quarry (Fig. 2). Minor azurite, associated with quartz and malachite, on massive grey copper sulphide occurs on two specimens from Bluebell Quarry in the Joe Miller Collection (these are labelled as "bornite?"; however, see bornite section); it is possible that this material was collected from the occurrence of bornite shown on Figure 2. King (1973) described a specimen of malachite with minor, badly bruised, microcrystalline masses of azurite on South Charnwood Diorites from the collections of the Leicester City Museum labelled as: "67'25. Malachite and azurite on syenite. Master Peter Jones" and he commented that "unfortunately the locality is vague and the quarry from which it originated cannot be determined, though the diorite matrix suggests Sheethedges Wood Quarry".

### BARYTE, $\text{BaSO}_4$

At Sheethedges Wood Quarry baryte has been found in two distinct environments:

1. King (1973) recorded that "baryte occurs in north-westerly striking veins made up principally of carbonates, chlorite, pyrite and specular hematite, and is restricted to those above a width of 24 mm...it is obviously a young member of the paragenesis being situated in cavities in the carbonates, and sometimes enclosing goethite pseudomorphs after pyrite...in habit the baryte adopts crystal aggregation, either in sub-parallel groups of

'cockscomb' crystals, or rosettes and fan-shaped groups of tabular forms...individual crystals and groups vary greatly in size, the former being 6.9 mm in average length, and the latter the average radius of 11 mm...the normally paper-thin tabular forms develop a thickness up to 1.3 mm thick and then additional faces are visible... these include, the pinacoid {001} and rhombic prisms {101} and {210}...the colour is usually opaque white, but the presence of 'rusting' iron minerals produces a greyish-red and reddish-orange colouration". K847-50 (NMW 83.41G.M3861) is probably representative of this material and consists of a small aggregate of thin tabular pinkish baryte crystals (up to 4 mm) in a cavity lined with brown-coated scalenohedral calcite crystals (up to 6 mm) in a dark reddish-brown carbonate-quartz matrix.

2. A minor occurrence of baryte was also noted by King (1973); it was found in the wider portions (>16 mm wide) of a pyrolusite vein that was exposed at the southern extremity of the quarry as thin white tabular crystals (up to 6 mm square) that were completely enclosed in black sooty pyrolusite.

Evans (1964) reported that baryte, associated with pyrite, quartz, hematite, chlorite and malachite, was found in a shear-zone in the South Charnwood Diorites (2.4 m wide with slickenside surfaces and a northerly strike) exposed in a service trench excavated during the construction of the Groby Bypass [SK 520 078].

### BORNITE, $\text{Cu}_5\text{FeS}_4$

King and Ford (1968) reported the occurrence of "low-chalcocite nodules" (see chalcocite section) with dolomite and oxidised copper minerals on several faces of the Bradgate quarries; this material was subsequently shown to be bornite (King, 1973). A quartz-rich vein system (up to 124 mm wide) with a northwest strike was exposed in the north face of Bradgate Middle Quarry in 1962 (King, 1973) and he noted that, in addition to the quartz, the vein contained small amounts of carbonates and very small amounts of bornite that sometimes enclosed "brilliant cubes of pyrite". The bornite was present as "isolated masses, sometimes up to 4.3 mm in diameter, but occasionally occupying the whole width of the vein and then reaching 25 mm in width...the mineral was completely unoxidised and fresh fractures showed a colour best described as aurora-red... but this tarnished after 24 h to iridescent reds and blues... in one specimen (K2694-64) planar but microscopically rough surfaces at right angles to each other suggest euhedral development...rarely, bornite has been seen as irregular-shaped blebs, up to 8 mm in diameter, embedded in ferroan dolomite in the same vein...masses of up to 110 g in weight have been obtained from this locality" (King, 1973). A recent analysis of K2694-64 (NMW 83.41G.M.347) has shown that it contains a finely-intergrown mixture of bornite with minor hematite and djurleite (identified by XRD; Tom Cotterell, *personal communication*).

A specimen from Sheethedges Wood Quarry (LU 24616) has green to pink calcite containing a small mass of yellow chalcopyrite (about 7 mm in diameter) with a bluish-purple

rim that is probably bornite. Haloes of bornite (up to 0.2 mm wide) surrounding small irregular masses of chalcopyrite (up to 3 mm across) with minor calcite in loose blocks of white quartz were recovered from Bluebell Quarry (King, 1973; King, 1998); the exact location where this material was collected in the quarry is unknown.

Miller (1972) indicated that bornite was found on the south face of Bluebell Quarry (Fig. 2) and two specimens from Bluebell Quarry in the Joe Miller Collection (labelled as “bornite?”) may be from this occurrence. They contain a grey granular material associated with quartz, malachite and minor azurite. Partial dissolution of this grey material in 6M nitric acid produced a pale blue solution and spot tests indicated that copper was present (steel needle) but failed to confirm the presence of iron (potassium thiocyanate); further analyses will be required in order to establish if this grey material is one of the copper sulphides: chalcocite, djurleite, etc.

### CALCITE, CaCO<sub>3</sub>

King (1973) noted minute scalenohedra of colourless calcite with earthy films of goethite in the Fe-rich calcite and Fe-rich dolomite (see below) components of the northwest-striking multi-mineralic veins in the South Charnwood Diorites masses of the Groby area. A specimen from Bradgate Northeast Quarry, K5525 (NMW 83.41G.M7154), consists of calcite associated with green prismatic epidote (Fig. 3). Miller (1972) noted that calcite occurred with dolomite on the north face of Bluebell Quarry (Fig. 2). Cream to red-brown banded calcite occurs as thin veins (up to 1 mm) in the rocks of the Swithland Formation exposed in Old Groby Slate Quarry; the calcite was identified by wet chemistry (CO<sub>2</sub> evolution with 2M nitric acid and a positive Ca<sup>2+</sup> test).

There are several reports of the occurrence of calcite at Sheethedges Wood Quarry:

1. Brecciated quartz veins on the east and west faces contained calcite with nacrite and pyrite whereas the calcite-containing quartz veins on the south and west faces contained pyrite, dolomite, specular hematite and chalcocite (King and Ford, 1968).
2. King (1973) gave a detailed description of the calcite associated with the multi-carbonate vein systems that



**Figure 3.** Epidote with quartz and calcite from Bradgate Northeast Quarry (120 mm x 60 mm); K5525 (NMW 83.41G.M7154); Frank Ince photograph.

have been relatively persistent features in the quarry. These veins (up to 160 mm wide) most commonly contained massive coarsely crystalline calcite with a well-developed cleavage that commonly showed strain structures and could be strongly curved. It occurred in pale-tinted masses that ranged from yellowish-white to pale green (when enclosing chlorite) to pink (when containing iron oxides) and grey (when enclosing microplates of specular hematite). Cavities in the calcite were usually lined with small (up to 5 mm) scalenohedral crystals that are transparent and colourless; however, these were frequently stained or coated by iron oxides. Occasionally larger highly modified crystals (up to 30 mm), were found and these consisted of various combinations of the prism and scalenohedron with rhombohedral terminations. King (1973) also described an additional feature of interest “the apparent superficial loss of crystalline structure...the external surfaces and, in part, the internal cleavage planes, become coated with white powdery films, which, under high-powered magnification, appear as dispersions of microscopic rhombs approximately 25 µm cross section...scrapings of this loosely aggregated powder showed all the physical features of calcite”. King (1973) noted that most of the calcite specimens from Sheethedges Wood Quarry displayed a strong pale red fluorescence under short-wave ultraviolet light (SUV); fluorescence was less obvious under long-wave ultraviolet light (LUV). Low magnification showed that the fluorescence was rather patchy under SUV, suggesting that the activator is unevenly distributed. King (1973) also indicated that the fluorescent calcite contained manganese and it is probable that manganese is the activator for the pale red fluorescence (Chang *et al.*, 1996, p. 119); this topic is considered again in the Mn-rich calcite section (see below).

3. K847-50 (NMW 83.41G.M3861) has a cavity in a dark reddish-brown carbonate-quartz matrix lined with brown-coated scalenohedral calcite crystals (up to 6 mm) containing a small aggregate of thin tabular pinkish baryte crystals (up to 4 mm).
4. K38 (NMW Research Collection) contains a small geode (30 mm dia.) lined with small (to 4 mm) brown-stained rhombohedral calcite crystals; however, it is possible that this specimen was derived from the Mercia Mudstones rather than from the South Charnwood Diorite.
5. LU 25616 consists of green to pink calcite containing chalcopyrite with a bluish-purple rim (of bornite?).

### *Fe-rich calcite*

King (1973) used the term ‘ferrocalcite’ to describe some iron-containing calcite specimens; however, its use should be discontinued and such material from the Groby area will be described as Fe-rich calcite (Bayliss *et al.*, 2005). King (1973) noted that Fe-rich calcite had been identified by the use of staining and other chemical techniques and that “like ferroan dolomite...[Fe-rich calcite] is most abundant as a member of the northwesterly-striking multi-mineralic veins in the diorite masses of the Groby area...

here it is usually associated with ferroan dolomite, being interdigitated with it and occupying the central portions of the wider veins...it is late in the paragenetic sequence... occurs as coarsely crystalline well-cleaved masses and veinlets...cavities within the latter are sometimes occupied by minute scalenohedra of colourless calcite and earthy films of goethite...the colour...varies between reddish-brown...and greyish-red...but it may be partially masked by the presence of chlorite...contemporaneous subhedral quartz may be embedded in it and pyrite, specular hematite, and a little baryte may also be present”.

### *Mn-rich calcite*

King (1973) used the term ‘manganocalcite’ to describe some manganese-containing calcite specimens; however, its use should also be discontinued and such material from the Groby area will be described as Mn-rich calcite (Bayliss *et al.*, 2005). An unusual occurrence of Mn-rich calcite in the southeastern portion of Sheethedges Wood Quarry was described by King (1973). It occurred as “aggregated masses of minute scalenohedra in parallel orientation...the colour was unusual being a shade of grey and possessing a greasy lustre quite unlike calcite...its most striking feature is that of its reaction to ultraviolet light, for, under both wavelengths it fluoresces a brilliant red...similar to the manganese-rich calcite from Franklin Furnace, New Jersey, in the United States of America”. King (1973) also gave a quantitative chemical analysis of the Mn-rich calcite from Sheethedges Wood Quarry demonstrating that it contained “an excess of 3% MnCO<sub>3</sub>...suggesting that MnCO<sub>3</sub> is here acting as a fluorescence activator”; with a higher manganese content (>3.3 mol % MnCO<sub>3</sub>) the fluorescence of calcite is known to decrease (Chang *et al.*, 1996, p. 119).

### CHALCOCITE, Cu<sub>2</sub>S

High-chalcocite is a term that has been used to describe the high-temperature, hexagonal polymorph of chalcocite that forms above 103°C; low-chalcocite has been used to describe the low-temperature, monoclinic polymorph of chalcocite that forms below 103°C (Evans, 1981; Posfai and Buseck, 1994). It is worth noting that the identification of chalcocite needs to be confirmed by XRD (David Green, *personal communication*).

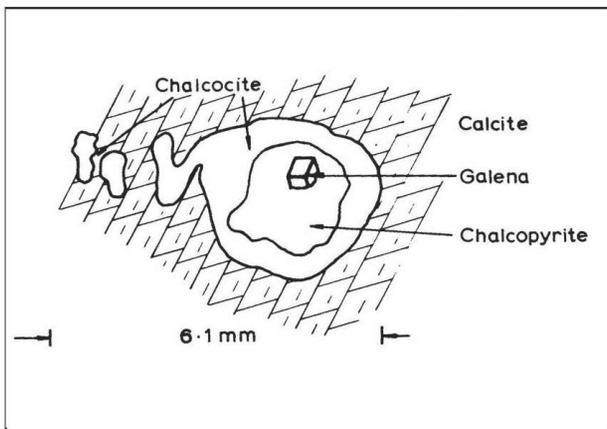
Worssam and Old (1988) noted that “copper mineralisation at the sub-Triassic unconformity is usually malachite or other oxidised copper minerals, sometimes with chalcocite, cuprite and native copper...occurrences of this type are exposed at Bradgate Quarry...[and] Sheethedges Wood Quarry”; these occurrences are described in more detail below. Two specimens from the Bradgate quarries, K2633 (NMW 83.41G.M392 and K2694-64 (NMW 83.41G.M347), both consist of a brownish-grey mineral (possibly chalcocite) with some quartz; however, a recent analysis of K2694-64 (NMW 83.41G.M347; collected from the north face of Bradgate Middle Quarry in 1962) has confirmed that it contains a finely-intergrown mixture of bornite with minor hematite and djurleite (identified by XRD: Tom Cotterell, *personal communication*).

King and Ford (1968) recorded that “calcite-quartz veins, spasmodically rich in pyrite, dolomite, specular hematite and high-chalcocite, may be seen on the south and west faces” of Sheethedges Wood Quarry. Two distinct occurrences of chalcocite at Sheethedges Wood Quarry were described in some detail by King (1973):

1. Chalcocite occurred as “anhedral masses associated with specular hematite and minor carbonate in a quartz gangue” in a vertical vein that was exposed in 1948 on the northeast-southwest face and was 320 mm wide with a maximum visible height of 870 mm. This vein was later proved to be part of lens-like quartz body striking 314° that, despite serious evaluation, was not of commercial value. The outer zones of the lens consisted of veinlets of Fe-rich dolomite, calcite, minor chalcocite and chalcopyrite in quartz. The core of the vein consisted mainly of pink ferruginous quartz, chalcocite (as irregular masses up to 8 mm wide), minor Fe-rich dolomite and specular hematite. LU 24617; (labelled as being collected from the “South end of bottom level (1948), Sheethedges Wood Quarry”) is probably from this occurrence; it contains small masses (up to 10 mm) of dark brown to dark grey chalcocite with some malachite in a quartz-rich diorite. The chalcocite was partly coated with powdery dark brown material; in common with many specimens that contain copper sulphides, it is not unusual to find that the areas containing, say, chalcocite have been partly coated with deep purple to dark brown powdery post-collection ‘covellite’ (as noted by Wirth, *Russell Society Newsletter*, (2002), No. 41, 20-23). The freshly-collected chalcocite showed a characteristic blackish lead-grey colour and metallic lustre; however, after some time an iridescent tarnish formed and subsequently a strong bronze-coloured tarnish concealed these features. King (1973) also noted that “the coarseness of the texture of this Groby chalcocite suggests a high temperature hypogene origin, as does its geological environment...the material may therefore have originally been high-chalcocite”. The chalcocite was originally identified at the Natural History Museum, London as covellite (Lab V, 179). Subsequent studies (NHM X-ray film No. 5407) indicated that it was chalcocite (with up to 15% covellite) and additional studies (at Leicester University) indicated that it had the orthorhombic symmetry of low-chalcocite; however, Evans (1971; 1981) has determined that low-chalcocite has monoclinic symmetry. There are a number of specimens related to the description by King (1973): K957-48 (NMW 83.41G.M353) has a number of small masses of dark grey chalcocite with some secondary ‘covellite’ and chalcopyrite in a light pink calcite-quartz matrix; K958-48 (NMW 83.41G.M360) has patches of dark grey chalcocite (to 10 mm) with some secondary ‘covellite’, chalcopyrite, malachite and “limonite” in a quartz-rich matrix (Fig. 4). King (1973, Figure 1) provided a sketch of K957-48 that is related to this description (Fig. 5) depicting a minute cube of galena embedded in an anhedral mass of chalcopyrite that was itself enclosed in an anhedral mass of chalcocite (up to 4 mm across) with the whole assemblage embedded in



**Figure 4.** Chalcocite with chalcopyrite, malachite and 'limonite' from Sheethedges Wood Quarry (150 mm x 105 mm); K958-48 (NMW 83.41G.M360); Frank Ince photograph.



**Figure 5.** Galena embedded in chalcopyrite in chalcocite in calcite from Sheethedges Wood Quarry; reproduced with permission from King (1973, Figure 1).



**Figure 6.** Chalcocite in quartz (polished block) from Sheethedges Wood Quarry (30 mm x 25 mm); K8019-66a (NMW 83.41G.M349a); Frank Ince photograph.

calcite. K66-44 (NMW Research Collection), collected from a northwest-trending shear zone on the lower level of Sheethedges Wood Quarry, afforded two cut and polished specimens: K8019-66a/b (NMW 83.41G.M349a/b). Both specimens contain dark grey chalcocite in a purplish quartz matrix; K8019-66a (NMW 83.41G.M349a) is shown in Figure 6. King (1973) concluded that this occurrence of chalcocite probably represented hypogene (primary) mineralisation. Surprisingly some of the chalcocite specimens displayed a bright greenish-yellow fluorescence under SUV and at high magnification this was seen to be patchily distributed and coincident with areas of marked tarnishing. Additional analytical studies did not reveal any trace elements that might have contributed to the fluorescence (Cu, S, Fe and Si were the only elements found). King (1973) proposed two hypotheses to account for the observed fluorescence: 1. The change in symmetry from high-chalcocite (hexagonal) to low-chalcocite (monoclinic) produces lattice distortion effects which "provide surfaces and points which are active to fluorescence under ultraviolet light"; 2. Following the development of the iridescent tarnish "it is likely that the film consists of djurleite and that the fluorescence is activated at the interface between the two phases [chalcocite-djurleite]...the coincidence of the tarnish and the fluorescence places a favourable bias on the second of the two concepts". King (1973) also noted that chalcocite specimens from other localities had a similar bright greenish-yellow fluorescence: those from Cornwall (Dolcoath and Condurrow Mines, Camborne; Tresavean Mine, Lanner; Geevor Mine, Pendeen; Wheal Abraham, Crowan) and Montana, USA (Mt. Con Mine, Butte); whereas specimens from other localities: some specimens from Groby (see below); Santa Rita Mine, New Mexico, USA; from the Kupferschiefer of Central Europe; Zambian Copperbelt, were not fluorescent. A recent re-investigation of the fluorescence of some of the Sheethedges Wood Quarry chalcocite specimens has shown (in order of decreasing yellow fluorescence under SUV): K958-48 (NMW 83.41G.M.360) > K1897-58 (NMW 83.41G.M.361) > K957-48 (NMW 83.41G.M.353) with K8019-66a/b (NMW.83.41G.M349a/b) being virtually non-fluorescent (Tom Cotterell, *personal communication*).

2. The occurrence of chalcocite "in calcite veining is probably a replacement phenomenon" where the veins of white or pink calcite (up to 56 mm wide) carried small masses of sulphides. King (1973) noted that these masses "may be monomineralic or composed of several sulphides including chalcocite, chalcopyrite, pyrite and galena...the pure chalcocite masses are usually anhedral...the largest mass observed had a maximum dimension of 4.2 mm in cross section...these masses are blackish lead-grey in colour, granular in texture and do not tarnish, though they readily break down to malachite so that the surrounding calcite is often stained green...the granular texture, occasionally preserved cubic forms and iron staining, suggest the former presence of pyrite"; possibly an example of the replacement of pyrite by chalcocite.

Two specimens from Bluebell Quarry in the Joe Miller Collection are labelled as “bornite?”; however, microchemical analysis of the grey granular material did not confirm the presence of iron (see bornite section). Further analysis will be required in order to establish if this grey material is one of the copper sulphides, e.g. chalcocite.

### CHALCOPYRITE, $\text{CuFeS}_2$

Small irregular masses of chalcopyrite (up to 3 mm diameter) with haloes of bornite (up to 0.2 mm wide) with minor calcite were collected from loose blocks of white quartz from Bluebell Quarry (King, 1973; King, 1998). The exact location of this material in the quarry is unknown; however, Miller (1972) indicated that chalcopyrite was found in the southwest corner of Bluebell Quarry (Fig. 2).

King (1998) described three distinct occurrences of chalcopyrite at Sheethedges Wood Quarry:

1. As small anhedral masses (up to 20 mm x 6 mm) in the chlorite-carbonate-sulphide-hematite vein systems (average width 35 mm with a strike between 320° and 335°) that have been exposed at various times. Some of the masses of chalcopyrite were “threaded through by a mosaic of goethite veinlets, but were generally untarnished and possessed the characteristic brass-yellow colour”. In this description mention was made of K2266-52 (NMW 83.41G.M445); see Figure 7); although the veinlets of goethite were not obvious when this specimen was examined. K958-48 (NMW 83.41G.M360) contains some chalcopyrite together with chalcocite, covellite, malachite and “limonite” in a quartz-rich matrix (see Figure 4).
2. As a small anhedral mass of chalcopyrite enclosing a minute cube of galena with that combination itself being embedded in an anhedral mass of chalcocite (up to 4 mm across) with the whole assemblage surrounded by calcite. Figure 5 shows a sketch of K957-48 (NMW 83.41G.M353) that is related to this description (King, 1973, Figure 1).
3. A minor development of chalcopyrite at the south end of the quarry where small anhedral masses were totally enclosed in a vertical vein of pyrolusite. K8684-66 (NMW 83.41G.M3768) answers to this description and



**Figure 7.** Chalcopyrite with calcite on diorite from Sheethedges Wood Quarry (65 mm x 50 mm); K2266-52 (NMW 83.41G.M445); Frank Ince photograph.



**Figure 8.** A vein containing chlorite, quartz and pyrolusite with probable manganite from Sheethedges Wood Quarry (80 mm x 80 mm); K8684-66 (NMW 83.41G.M.3768); Frank Ince photograph.

contains a vein section (up to 10 mm wide) composed of massive dull-grey material (labelled as pyrolusite; see Figure 8); however, the chalcopyrite was not immediately apparent. The composition of K8684-66 (NMW 83.41G.M3768) has been investigated recently and it has been shown to contain chlorite (probably clinocllore) with quartz, minor pyrolusite and traces of probable manganite (identification by XRD: Tom Cotterell, *personal communication*).

A specimen from Sheethedges Wood Quarry (LU 24616) consists of green to pink calcite containing a small mass of yellow chalcopyrite (about 7 mm in diameter) with a bluish-purple rim that is probably bornite.

### CHAMOSITE, $(\text{Fe}^{2+}, \text{Mg}, \text{Al})_6(\text{Si}, \text{Al})_4\text{O}_{10}(\text{OH})_8$

In his description of the chlorite group minerals, King (1973) described “Brunsvigite,  $(\text{Fe}^{2+}, \text{Mg}, \text{Al})_{12}(\text{Si}, \text{Al})_8\text{O}_{20}(\text{OH})_{16}$ ... a very common mineral in the Southern-type diorite quarries of Charnwood Forest, especially in Sheethedges Wood Quarry”. The use of the name brunsvigite as a variety of chlorite has been discontinued and chlorite with this composition will be described as chamosite (Bayliss, 1975).

King (1973) provided a chemical analysis that confirmed the occurrence of chamosite and recorded that it was found in a system of quartz-carbonate-pyrite-hematite veins that occupy a prominent shear zone in Sheethedges Wood Quarry. Chamosite was one of the younger members of the paragenesis and occurred as dark green to blackish-green plates (up to 0.6 mm<sup>2</sup>) that formed masses (up to 26 mm<sup>2</sup>) and disseminations within the veins. The chamosite was rather prone to oxidation; consequently, brownish-black coatings of goethite sometimes concealed its presence. K1896-58 (NMW 83.41G.M7129) matches this description and contains a mass of dark grey-green chamosite in diorite.

### CHLORITE GROUP

In addition to the chamosite from Sheethedges Wood Quarry, there are a number of reports of the occurrence of chlorite group minerals in the Groby area. King (1973) noted two reports of the occurrence of chlorite in the quarries exploiting the Swithland Formation: “chloritic veins running through the Swithland Slates worked at

Groby” and “the purplish tint of the Swithland Slates at Groby Slate Pits...with yellowish chloritic veins running through it”. Miller (1972) also mentioned that veins of pale yellow and green chlorite, together with quartz veins, occur in the quarries that exploit the Swithland Formation. Evans (1964) reported that chlorite, associated with pyrite, quartz, hematite, baryte and malachite, was found in a shear-zone in the South Charnwood Diorites, now buried under the Groby Bypass (see baryte section for details). There are two specimens in the John Jones Collection from Bradgate Northeast Quarry (labelled as being from “Bradgate House Quarry”) containing chlorite group minerals (possibly chamosite; see above): 755050 contains aggregates of thin dark green plates of chlorite lining both sides of an quartz-carbonate vein and J915 contains a chlorite-carbonate-quartz matrix enclosing some striated pyrite crystals. During a re-evaluation of some of the pyrolusite specimens from Sheethedges Wood Quarry, K8684-66 (NMW 83.41G.M3768), see Figure 8, was shown to contain chlorite (probably clinocllore) with quartz, minor pyrolusite and traces of probable manganite (identified by XRD: Tom Cotterell, *personal communication*).

**Chrysocolla,  $(\text{Cu,Al})_2\text{H}_2\text{Si}_2\text{O}_5(\text{OH})_4 \cdot n\text{H}_2\text{O}$**   
(Copper-containing silica gel)

A number of recent articles have noted that many specimens labelled as chrysocolla consist of an amorphous copper-containing silica gel (Moreton, 2007; Bridges *et al.*, 2008; Green *et al.*, 2008). Bearing in mind this proviso, material from the Groby area will be described as ‘chrysocolla’. King (1973) noted that ‘chrysocolla’ sometimes replaced thin coatings of malachite on chalcocite from Sheethedges Wood Quarry.

**COPPER, Cu**

Small amounts of native copper have been found in the Groby area (King, 1967). Worssam and Old (1988) noted that native copper, usually associated with other oxidised copper minerals, occurred near the sub-Triassic unconformity at Bradgate Middle Quarry and SheethedgesWood Quarry. Minute wires of native copper occur at Bluebell Wood Quarry in “masses [of cuprite] up to 7.5 mm in diameter... in intimate association with comparatively well-crystallised malachite” and “as minute thin film associated with unusually well-developed malachite, a rich deposit of which was exposed in 1952, lining and partly filling an open east-west joint in the diorite” (King, 1973); K2184 (NMW 83.41G.M4708) matches this description (see Figure 9). At Sheethedges Wood Quarry, King (1967; 1973) noted that there are “reports from the older quarrymen, who were familiar with the older upper levels...their description, “flexible red and green copper ore in clay”, resembles most nearly the Bardon Hill occurrences”. Miller (1972) indicated that native copper was found on the north face of Sheethedges Wood Quarry (Fig. 2).

King (1967; 1973) described the native copper recovered from Groby Old Quarry that occurred “on the surfaces of the diorite immediately at and below, the Upper Keuper Marl unconformity, particularly on the NE face of the



**Figure 9.** Cuprite and malachite (and minor native copper) from Bluebell Wood Quarry (50 mm x 35 mm); K2184 (NMW 83.41G.M4708); Frank Ince photograph.



**Figure 10.** Three groups of arborescent crystals of native copper from Groby Old Quarry (Maximum length of crystal group 14 mm); LU 25982; Frank Ince photograph.

quarry...they took the form of small carbonate-encrusted dendrites”. Three small specimens (LU 25982: labelled as being collected from the “North face, on diorite surfaces immediately below the Precambrian unconformity... Village Quarry, Groby”) are probably from such an occurrence and are composed of arborescent crystals of native copper (up to 14 mm) partly coated with malachite (Fig. 10).

**COVELLITE, CuS**

Covellite occurred with chalcocite, specular hematite and Fe-rich dolomite at Sheethedges Wood Quarry (King, 1973) and occurred in two distinct habits:

1. Intimately associated with the chalcocite where it occurred “as partly exsolved CuS along chalcocite cleavage planes” (King, 1973). K66-44 (NMW Research Collection) appears to match this description and was collected from a northwest-trending shear zone on the lower level of Sheethedges Wood Quarry. K66-44 provided two cut and polished specimens and one of these, K8019-66a (NMW 83.41G.M349a),

contains dark grey chalcocite-covellite in a purplish quartz matrix (Fig. 6).

2. More commonly “as flower-like rosettes of minute plates dispersed through select areas of the chalcocite” (King, 1973). This habit may represent a late-stage alteration or post-collection phenomenon as, in common with many specimens that contain copper sulphides, it is not unusual to find that the areas containing chalcocite have been partly coated with deep purple to dark brown powdery post-collection ‘covellite’ (as noted by Wirth, *Russell Society Newsletter*, (2002), No. 41, 20-23).

### CUPRITE, $\text{Cu}_2\text{O}$

Worssam and Old (1988) noted that cuprite, usually associated with other oxidised copper minerals, occurred near the sub-Triassic unconformity at Bradgate Middle Quarry and Sheethedges Wood Quarry. Small amounts of cuprite, associated with chalcocite and malachite, have been collected at Sheethedges Wood Quarry and King (1973) noted that “the masses tend to be powdery in form and not exceed the diameter of 1.8 mm”.

Cuprite occurred at Bluebell Wood Quarry as “masses up to 7.5 mm in diameter, containing minute wires of native copper...in intimate association with comparatively well-crystallised malachite” (King, 1973). A specimen in the King Collection (K2184; NMW 83.41G.M4708) that can be matched to this description contains a ‘vein’ of reddish-grey cuprite (to 15 mm) with malachite on a quartz-hematite matrix (Fig. 9).

### DJURLEITE, $\text{Cu}_{31}\text{S}_{16}$

A recent analysis of a specimen from Bradgate Middle Quarry, K2694-64 (NMW 83.41G.M.347), has shown that it contains djurleite as a finely-intergrown mixture with bornite and minor hematite (identified by XRD; Tom Cotterell, *personal communication*).

Two specimens from Bluebell Quarry in the Joe Miller Collection are labelled as “bornite”; however, microchemical analysis of the grey granular material (see bornite section) did not confirm the presence of iron. Further analysis will be required in order to establish if this grey material is one of the copper sulphides, e.g. djurleite.

### DOLOMITE, $\text{CaMg}(\text{CO}_3)_2$

King and Ford (1968) reported the occurrence of dolomite on several faces of the Bradgate quarries and noted that it was associated with low-chalcocite, subsequently shown to be bornite (King, 1973), and oxidised copper minerals. Miller (1972) indicated that dolomite (with calcite) was found on the north face of Bluebell Quarry (Fig. 2).

King (1973) noted that, of all the localities in the Charnwood Forest area, dolomite was most common at Sheethedges Wood Quarry. It occurred in at least two distinct environments:

1. King and Ford (1968) reported that dolomite occurred in the calcite-quartz veins, occasionally rich in pyrite, specular hematite and high-chalcocite.

2. King (1973) noted that dolomite occurred in the polyminerale veins and that “the common paragenetic sequence in these persistently trending northwesterly veins is: Pyrite-Dolomite-specular hematite-ferroan dolomite-specular hematite”. King (1973) also described that the dolomite “when completely fresh...is grey in colour...since both pyrite and hematite are often present...the dolomite is often tinted by iron oxides to shades of pink and orange...is frequently cavernous and shows minute but attractive groups of tiny crystals (1.2 mm average)”. K1087-54 (NMW 83.41G.M3863) appears to match this description and consists of a vein section (up to 50 mm wide) that contains pale orange dolomite with dark grey specular hematite, chlorite, white calcite and quartz (Fig. 11).

LU 23545, LU 23546, LU 23546, LU 23548, LU 24939, LU 24940, LU 24942, LU 87154 and LU 87155 all contain, variously, dolomite with specular hematite, Fe-rich



**Figure 11.** Dolomite with specular hematite from Sheethedges Wood Quarry (75 mm x 50 mm); K1087-54 (NMW 83.41G.M3863); Frank Ince photograph.



**Figure 12.** Dolomite with specular hematite in a quartz-carbonate vein from Sheethedges Wood Quarry (100 mm x 75 mm); LU 23545; Frank Ince photograph.



**Figure 13.** Brownish-yellow Fe-rich dolomite (with some golden-brown surface oxidation) and quartz from Sheethedges Wood Quarry (100 mm x 75 mm); LU 82656; Frank Ince photograph.

dolomite (see below), calcite and quartz. Figure 12 shows LU 23545 with aggregates (to 7 mm) of blades of grey specular hematite in an orange dolomite and white quartz vein (up to 15 mm wide) embedded in purplish carbonate containing some pyrite.

Bosworth (1912, p. 44) noted that “in Sheet Hedges Wood Quarry, a curious breccia rests on the craggy uneven floor, exposed in the east part of the quarry...this is 7 feet and less in thickness, composed of angular stones cemented together with a large proportion of yellow dolomitic material, some parts of which consists of pistoles about the size of millet seed”. King and Ford (1968) also noted that dolomite forms the cement for a breccia that filled a large Triassic wadi on the west face of Sheethedges Wood Quarry where it was associated with palygorskite and malachite; Miller (1972) showed a Triassic wadi in southwest corner of the quarry (Fig. 2).

### *Fe-rich dolomite*

King (1973) used the term ‘ferroan dolomite’ to describe some iron-containing dolomite specimens; however, its use should be discontinued and such material from the Groby area will be described as Fe-rich dolomite (Bayliss *et al.*, 2005). King (1973) referred to Fe-rich dolomite as “any iron-rich dolomite” that he identified mainly by the use of staining techniques. At the Bradgate quarries Fe-rich dolomite occurred in a central position in veins that also contained specular hematite; when present in significant amounts it could be grey in colour and subsequent oxidation produced a golden-yellow surface alteration. At Sheethedges Wood Quarry Fe-rich dolomite was an important constituent of the northwest-tending veins that formed a shear-zone (with evidence of slickenslided surfaces and several phases of re-opening/mineralisation) in the central portion of the quarry; the Fe-rich dolomite was usually late in the paragenetic sequence and associated with specular hematite and minor quartz. The Fe-rich dolomite occurred in various shades of pink to red and brown and was commonly reddish-brown when oxidised; it could be coarsely crystalline with cavities (up to 22 mm) lined with minute rhombic crystals (up to 0.2 mm) and analyses indicated that it contained an average of 8.4% FeO (6.4-12.4%). Fe-rich dolomite was

also found as pink masses (up to 120 mm across) that were occasionally mistaken for orthoclase (King, 1973). LU 82656, from Sheethedges Wood Quarry, consists of veins (up to 25 mm) of Fe-rich dolomite with white quartz; the fresh Fe-rich dolomite is a light brownish-yellow colour, oxidation has produced a golden-brown colouration on any exposed surfaces (Fig. 13).

### EPIDOTE, $\text{Ca}_2\text{Al}_2(\text{Fe}^{3+},\text{Al})\text{Si}_3\text{O}_{12}(\text{OH})$

King (1973) noted that Hill and Bonney (1878) recorded that “specks and nests of bright yellow-green” epidote occurred at Groby Old Quarry. A number of collections include specimens of epidote from Bradgate Northeast Quarry, e.g. J910 and 755099 (John Jones Collection) and K5525 (NMW 83.41G.M7154); all of these specimens contain veins of green prismatic epidote (up to 20 mm) associated with quartz or calcite or both quartz and calcite (see Figure 3).

King (1973) indicated that epidote occurred on the north face of Bluebell Quarry “16 m east of the northwest corner” and Miller (1972) also noted that epidote occurred “as good samples” near the northwest corner of Bluebell Quarry (Fig. 2). King (1973) described the occurrence of “a number of relatively thick veins trending in an approximately northwesterly direction... the thickest observed was 54 mm...with evidence of reopening...on the footwall side of the vein, a zone, 24 mm wide, shows a concentration of fine-grained granular epidote...threaded through by veinlets composed of prismatic epidote lying at right-angles to the vein walls, the maximum length of the crystals being 5 mm...the remainder of the vein (c.30 mm) is filled with more coarsely crystalline epidote, with prism lengths up to 22 mm and widths of 0.7 mm... the crystals have attempted aggregation into spheroids but mutual interference has prevented any strong development of that form, only a maximum 64° of arc being produced... the colour varies through shades of yellowish-green and the lustre is characteristically high...the associated quartz is interstitial quartz and...is almost certainly late in the paragenetic sequence”. LU 24615 and LU 87156 contain veins of granular and prismatic green epidote with some quartz or calcite or both quartz and calcite on South Charnwood Diorites.

King (1973) described the occurrence of epidote at Sheethedges Wood Quarry as “strong veins of epidote, minor quartz in diorite...average width 30 mm and composed of aggregations of spheroids...(never completely spherical)... of acicular crystals up to 8 mm... from pale green to greenish grey... associated with films of iron oxides, quartz, chlorite (all interstitial)”.

### GALENA, PbS

Worssam and Old (1988) noted that galena occurred in the Bradgate Southwest Quarry where “the diorite in the SW of the quarry...is veined with quartz along joints...some of which are bordered by a fine-grained, green zone, up to 15 cm wide, rich in pyrite...small galena crystals occur in the quartz veins”.

Miller (1972) indicated the possible occurrence of galena on the north face of Sheethedges Wood Quarry (Fig. 2). King (1973) described the occurrence of galena at Sheethedges Wood Quarry where it was “associated with chalcocite and chalcopyrite (anhedral masses) in calcite... very rare... minute cubes (0.4 mm in cross-section) always embedded in the chalcopyrite (never in the chalcocite)”. Figure 5 shows a sketch of K957-48 (NMW 83.41G.M353) that is related to this description (King, 1973, Figure 1).

### GOETHITE, $\alpha$ -FeO(OH)

King (1973) described two distinct occurrences of goethite at Sheethedges Wood Quarry:

1. Many of the quartz-carbonate-chlorite-hematite-sulphide veins contained iron oxides and films of brownish-black goethite often mask the chlorite below. Where the oxidation of the veins had been particularly intense, “cavities may be partially, and sometimes wholly filled, by crystallised goethite...the goethite may either be loosely aggregated masses of microscopic crystals, or as well-oriented crystallised groups...all possess brilliant lustre...the habit is usually tabular {010}...these brilliant plates seldom exceed 2 mm across...tend to aggregate into rosettes...towards the extremities of these tabular crystals, there is a change of habit to a comb-like growth of capillary crystals... the tabular portion is very highly lustrous and blackish-brown in colour, but the capillary extremities are dull and dark brown”.
2. The quartz-carbonate-chlorite-hematite-sulphide veins also contained goethite pseudomorphs of pyrite (as both cubes and pyritohedra); thin films of lepidocrocite occasionally coated the crystal faces.

Veinlets of goethite in anhedral masses of chalcopyrite were noted by King (1998) as occurring at Sheethedges Wood Quarry and K2266-52 (NMW 83.41G.M445) was described (Fig. 7); however, the veinlets of goethite were not obvious when this specimen was examined.

### GYP SUM, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$

During a recent investigation of the exposures of the South Charnwood Diorites at the eastern end of Barn Hills Quarry, some small (up to 1 mm) white to cream gypsum crystals (identified by wet chemistry) were collected from an area containing a number of brecciated quartz-chlorite veins.

### HEMATITE, $\alpha$ -Fe<sub>2</sub>O<sub>3</sub>

Hematite variety specular hematite occurred in a similar environment in all three of the Bradgate Quarries and Sheethedges Wood Quarry. King (1973) provided a description of these occurrences where “the most striking of the specular hematite occurrences in Leicestershire is that associated with ferroan carbonate veins...the association of white quartz, green chlorite, pink ferroan dolomite and the large splendant plates of hematite make beautiful material... the diameter of individual plates varies from 0.9 mm to 14 mm... these plates are always thin, in places thin enough to transmit crimson light, and they are very brittle and highly

lustrous...rare hexagonal outlines to flat-lying plates have been observed...most commonly the hematite takes the form of sheaves of crystals or felted masses of sub parallel plates or rosettes...these occasionally form radial aggregates and approach the development shown by the ‘eisenrosen’ of the Alpine-type veins of Switzerland...the veins themselves are remarkably consistent in their width, an average of 34 mm... their strike varies little, being an average of 330°, with very steep dips to the northeast...the infilling is complex and shows a complicated history of re-opening...the hematite is a late member of the paragenetic sequence, being dispersed upon the surfaces of older members”. Several collections contain specimens that are related to these occurrences, e.g. K1087-54; NMW 83.41G.M3863 from Sheethedges Wood Quarry (Fig. 11), LU 23545 from Sheethedges Wood Quarry (Fig. 12) and the John Jones Collection (specimens from both Bradgate Northeast and Sheethedges Wood quarries). A recent analysis of K2694-64 (NMW 83.41G.M.347) from Bradgate Middle Quarry has shown that it contains some hematite in a finely-intergrown mixture with bornite and minor djurleite (identified by XRD; Tom Cotterell, *personal communication*). Miller (1972) indicated that specular hematite was found at two different places on the southeast face of Sheethedges Wood Quarry (Fig. 2). King (1973) noted that at Sheethedges Wood Quarry specular hematite was also a minor associate of the chalcocite present in some quartz-carbonate veins where oxidation has resulted in a pinkish matrix; he also described an occurrence of micaceous hematite at Sheethedges Wood Quarry as small plates (up to 2.8 mm), associated with small masses of sulphides (chalcocite, chalcopyrite, pyrite and galena).

Evans (1964) reported that hematite, associated with pyrite, quartz, chlorite, baryte and malachite, was found in a shear-zone in the South Charnwood Diorites, now buried under the Groby Bypass (see baryte section for details)

### LEPIDOCROCITE, $\gamma$ -FeO(OH)

King (1973) noted that thin films of lepidocrocite occasionally coat the crystal faces of goethite pseudomorphs after pyrite (as both cubes and pyritohedra); these were found in some of the quartz-carbonate-chlorite-hematite-sulphide veins at Sheethedges Wood Quarry.

### *Limonite, powdery iron oxides and oxyhydroxides*

Limonite is not a well-defined mineral species and material from the Groby area will be described as ‘limonite’. King (1973) noted that earthy films and powdery coatings of ‘limonite’, in various shades of brown, were present in the oxidised portions of the Fe-rich dolomite-pyrite-hematite veins at Sheethedges Wood Quarry; ‘limonite’ also appears to have replaced some of the goethite pseudomorphs after pyrite.

### MAGNETITE, Fe<sub>3</sub>O<sub>4</sub>

Miller (1972) indicated that magnetite was present in the east face of Sheethedges Wood Quarry (Fig. 2).

## MALACHITE, $\text{Cu}_2(\text{CO}_3)(\text{OH})_2$

Worssam and Old (1988) noted that malachite, usually associated with other oxidised copper minerals, occurred near the sub-Triassic unconformity at Bradgate Middle Quarry and Sheethedges Wood Quarry. They also reported that the diorite at Bradgate Northeast Quarry has strong joints containing chlorite and hematite with some cross joints invested with white quartz veins that, on the east face, contained small patches of malachite.

King (1973) recorded that “excellent malachite has been observed in Bluebell Quarry...very fine crystallizations [sic], perhaps the best in the county...the principal form is that of rosettes of acicular crystals, some of which are quiet large, their radii being as much as 12 mm...the surface expression of some rosettes is perfectly spherical, but, in cross section, there is no colour banding along the prism length...bi-individual twins are common, and in these the prisms width is relatively great, widths up to 0.4 mm being common...the crystals are twinned on {001}, the form {110} producing re-entrant angles between the two individuals”. The twinned and broken prisms were emerald green in colour; however, the spheroidal surfaces tended to be darker shades of green. K2184 (NMW 83.41G.M4708) can be matched to this description and has a ‘vein’ of reddish-grey cuprite (to 15 mm) with aggregates of acicular emerald green malachite crystals (to 5 mm) on a quartz-hematite matrix (Fig. 9). King (1967) also noted that malachite, associated with cuprite containing minute wires of native copper, was found in Bluebell Quarry “in 1952, lining and partly filling an open east-west joint in the diorite”. Miller (1972) indicated that malachite occurred with azurite on the south face of Bluebell Quarry (Fig. 2).

Malachite occurred in a number of distinct environments in Sheethedges Wood Quarry:

1. King (1973) noted that malachite occurred as thin encrustations coating the slickensided surfaces of re-opened veins and was associated with limonitic films; both the result of the oxidation of chalcopyrite. Worssam and Old (1988) described a similar occurrence where malachite was found in some thin quartz-pyrite veins associated with some slickensided joints.
2. As noted in an earlier section, small amounts of malachite were associated with chalcocite (King, 1973).
3. King and Ford (1968) described the occurrence of malachite, associated with dolomite and palygorskite, in a Triassic wadi on the west face of the quarry. It is possible that this Triassic wadi is the one shown by Miller (1972) in southwest corner of Sheethedges Wood Quarry (Fig. 2).

Evans (1964) reported that malachite, associated with pyrite, hematite, quartz, chlorite and baryte, was found in a shear-zone in the South Charnwood Diorites, now buried under the Groby Bypass (see baryte section for details).

## MANGANITE, $\text{MnO}(\text{OH})$

King (1973) noted that Gresley (1886, p. 4) described some hematite nodules that occurred in the Permian



**Figure 14.** Aggregates of fine needles of manganite and pyrolusite from Sheethedges Wood Quarry (85 mm x 60 mm); K8683-68 (NMW 83.41G.M.3770); Frank Ince photograph.

breccias of South Derbyshire and Leicestershire where “in the ‘limonite’ (or goethite) nodules streaks or veins of manganite sometimes are present”. During a recent re-investigation of some specimens from Sheethedges Wood Quarry that contain manganese oxides, it was found that at least three specimens, labelled as pyrolusite, contained some manganite (identified by XRD; Tom Cotterell, *personal communication*):

1. K8683-68 (NMW 83.41G.M.3770) contains massive dull grey manganese oxides with aggregates of fine needles that are a mixture of manganite and pyrolusite (Fig. 14).
2. K8684-66 (NMW 83.41G.M.3768) appears to be a complete vein section (up to 10 mm wide) of pyrolusite; however, the dark grey material is dominated by chlorite (probably clinocllore) with quartz, minor pyrolusite and traces of probable manganite (Fig. 8).
3. K2565 (NMW 83.41G.M.3769): the massive manganese oxide is dominated by pyrolusite with some manganite and quartz.

Manganite is relatively common in the British Isles (Tindle, 2008); however, other than the poorly provenanced report by Gresley (1886), its occurrence at Sheethedges Wood Quarry would appear to be the first verifiable record of manganite in Leicestershire.

## NACRITE, $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$

Claringbull (1952) noted that “X-ray powder photographs show that a white mineral associated with quartz veins in syenite in the shatter zone of the main fault of Sheet Hedges Wood quarry, Groby, Leicestershire, is nacrite...this is believed to be the first British record of the mineral”; see also, Tindle (2008). King and Ford (1968) indicated that the nacrite occurred in brecciated quartz veins with calcite and pyrite on the east and west faces of Sheethedges Wood Quarry. King (1973) described the occurrence in more detail: the nacrite was “present as a late member of the NW striking quartz-chlorite-ferroan dolomite-hematite-pyrite veins that occupy a shear zone...the nacrite is restricted to the wider veins, especially those within the limits of 60 to 132 mm, and occurs in them as irregular microcrystalline



**Figure 15.** Nacrinite with quartz and chlorite from Sheethedges Wood Quarry (100 mm x 70 mm); K1000-51 (NMW 83.41G.M.6489); Frank Ince photograph.

masses up to 48 mm in diameter...are pure white and frequently show a shining satin-like lustre". K1000-51 (NMW 83.41G.M.6489) can be matched to this description and consists of cream nacrinite, associated with quartz and chlorite, infilling voids in fractured South Charnwood Diorites (Fig. 15). LU 24618, collected from the west side of the lowest level of the quarry (in 1953), has a crust of cream nacrinite on brecciated diorite.

#### PALYGORSKITE, $(\text{Mg},\text{Al})_2\text{Si}_4\text{O}_{10}(\text{OH})\cdot 4\text{H}_2\text{O}$

Palygorskite has been reported to occur in the Bradgate quarries; where it developed below a Triassic wadi (King and Ford, 1968). King and Ford (1968) also described the occurrence of palygorskite, associated with dolomite and malachite, on the west face Sheethedges Wood Quarry in a Triassic wadi in the South Charnwood Diorites. This Triassic wadi may be the same as the one shown by Miller (1972) in the southwest corner of Sheethedges Wood Quarry (Fig. 2) where the palygorskite was associated with pseudomorphs after halite; however, Miller (1972) also noted that "in the east face a deep wadi...is filled with red marl above a basement of pebbles and fragments of diorite and other rocks...below the wadi, and formed by percolating water, the buff-coloured mineral palygorskite can be seen in joints in the diorite".

#### PYRITE, $\text{FeS}_2$

Pyrite has been reported from all of the Bradgate Quarries:

1. Miller (1972) noted that "brassy iron pyrites...can be found at any of the quarry faces...particularly good samples have come from" Bradgate Northeast Quarry.
2. King (1973) described the occurrence of pyrite at Bradgate Middle Quarry where "pyrite, as brilliantly lustrous cubes, ranging in size from 1.2 to 2.3 mm across, or aggregates of crystals up to 3 mm square, completely embedded in bornite, occur in a NW striking

quartz vein exposed on the N face...in the same vein, pyrite occurs as strongly striated cubes up to 4 mm across, embedded in ferroan dolomite...the latter are, however, often oxidised".

3. Worssam and Old (1988) noted that pyrite occurred at Bradgate Southwest Quarry where "the diorite in the SW of the quarry...is veined with quartz along joints...some of which are bordered by a fine-grained, green zone, up to 15 cm wide, rich in pyrite...small galena crystals occur in the quartz veins".

Miller (1972) indicated that pyrite occurred on the south face of Bluebell Quarry in the same area as chalcopryrite and bornite (Fig. 2). Brecciated quartz veins on the east and west faces of Sheethedges Wood Quarry contained pyrite with calcite and nacrinite whereas the calcite-bearing quartz veins on the south and west faces contain pyrite, dolomite, specular hematite and chalcocite (King and Ford, 1968). In his more detailed description of the occurrence of pyrite at Sheethedges Wood Quarry, King (1973) noted that "pyrite is found in the common multi-mineralic veins, which in places form northwesterly striking shear zones many metres across...the maximum width of an individual vein is 48 mm, and there are at least 4 stages of mineralization present...each stage had been preceded by transcurrent movement on the vein... this has produced slickensided surfaces on the mineral of the previous stage... the whole vein shows a pronounced development of crustiform banding...pyrite is usually deposited in the early stages, grey coloured dolomite...these crystals vary considerably in size, from as small as 0.2 mm, across, to over 10 mm... there appears to be a regional distribution of pyrite... as the quarry face advances, so the pyrite is either abundant or absent...on rare occasions the shear zone may be literally brass coloured by the great quantity of pyrite...aggregated masses up to 242 square mm are common...elsewhere single crystals, partially embedded in dolomite may form high density spreads...crystals are normally strongly striated, and rounded faces are common...the colour...is a pale brass yellow, slightly paler than usual...when exposed to the atmosphere it quickly oxidises...the pyrite is either replaced by limonitic compounds or goethite or leached out completely". Worssam and Old (1988) also reported the occurrence of pyrite (with some malachite) in Sheethedges Wood Quarry in thin quartz-sulphide veins [SK 5246 0826] associated with some slickensided joints.

Evans (1964) reported that pyrite, associated with hematite, quartz, chlorite, baryte and malachite, was found in a shear-zone in the South Charnwood Diorites, now buried under the Groby Bypass (see baryte section for details).

#### PYROLUSITE, $\text{MnO}_2$

King (1973) provided a detailed description of the occurrence of pyrolusite at Sheethedges Wood Quarry where "a solid vein-like body...strikes  $334^\circ$ , dipping  $86^\circ$ ... on the most southerly face...and extends from the bottom... to the top level...the footwall side...is a slickensided surface from which the vein readily and clearly parts... the hangingwall is irregular and tight onto the diorite...



**Figure 16.** Pyrolusite from Sheethedges Wood Quarry (40 mm x 25 mm); K66-33 (NMW Research Collection); Frank Ince photograph.

the vein matter is composed almost entirely of crystalline pyrolusite, as anhedral groupings, with minor, pure-white tabular plated of baryte, up to 6 mm in length, small masses of calcite and blebs of chalcopryrite...the majority of the crystals [of pyrolusite] are acicular and are often grouped together as radiating aggregates...in small cavities, euhedral forms have developed, usually as complicated and repeated twins...the colour...varies from bluish-black in the polycrystalline aggregates to pitch-black in denser material... the lustre is also varied, from dull in the softer material, to brilliantly metallic in the harder". K66-33 (NMW Research Collection) can be matched with this description and consists of acicular crystals of pyrolusite on massive manganese oxides (Fig. 16). Miller (1972) indicated that pyrolusite occurred in two separate areas of the east face of Sheethedges Wood Quarry (Fig. 2); however, neither of these occurrences would appear to be those described above.

The recent investigation of specimens containing manganese oxides from Sheethedges Wood Quarry in the King Collection was described in the manganite section. At least three of the specimens that were labelled as "pyrolusite" also contain some manganite (identified by XRD; Tom Cotterell, *personal communication*): K8683-68 (NMW 83.41G.M.3770), see Figure 14; K8684-66 (NMW 83.41G.M.3768), see Figure 8; K2565 (NMW 83.41G.M.3769).

## QUARTZ, SiO<sub>2</sub>

Quartz veins, or shear zones containing quartz, or both, crop out in most of the quarries in the Groby area; however, euhedral crystals are rare. King (1973) noted that "crystallised quartz is common in the veins of Sheethedges Wood Quarry...but is usually hidden by younger generations of minerals in these re-opened veins...it frequently appears as hexagonal cross sections or prism lengths completely enclosed in such minerals as ferroan dolomite and dolomite...the rare occasions when the pyramid is exposed shows that no additional faces are present". During a recent investigation of the exposures of the South Charnwood Diorites at the eastern end of Barn Hills Quarry, a number of brecciated quartz-chlorite veins were found that contained



**Figure 17.** Halite pseudomorphs from Sheethedges Wood Quarry (75 mm x 55 mm); Joe Miller Collection; Frank Ince photograph.

poorly-formed quartz crystals (some enclosing greenish chlorite) together with some small white to cream gypsum crystals. Evans (1964) reported that quartz, associated with pyrite, hematite, chlorite, baryte and malachite, was found in a shear-zone in the South Charnwood Diorites, now buried under the Groby Bypass (see baryte section for details). Miller (1972) noted that quartz veins, together with veins of pale yellow and green chlorite, occurred in the quarries exploit the Swithland Formation.

## OTHER FEATURES

### Halite Pseudomorphs

Pseudomorphs after halite, formed from fine-grained Triassic sediments, are fairly common in many of the exposures of the Mercia Mudstones in Leicestershire (King, 1973). Miller (1972) indicated that pseudomorphs after halite were found with palygorskite in a Triassic wadi on the southwest face of Sheethedges Wood Quarry (Fig. 2). One of the specimens from this locality in the Joe Miller Collection (Fig. 17) contains some pseudomorphs after halite that are up to 12 mm on edge, some of them with preserved 'hopper'-faces (a habit typical of halite crystals).

## DISCUSSION

### Hypogene mineralisation

The shear zones (occasionally many metres across) and veins (up to 320 mm across) that have been exposed in the Groby area have a west to northwesterly trend (from 274° to 335°); in this respect they are similar to those that have been described as occurring in the Markfield area (Ince, 2011) and, more generally, in the Precambrian rocks of Leicestershire (Watts, 1947; Worssam and Old, 1988; Carney *et al.*, 2000). One exception is a shear-zone in the South Charnwood Diorites with a northerly strike that was exposed in a service trench that was excavated during the construction of the Groby Bypass (Evans, 1964); this shear zone was within ~15 m of a fault with an easterly strike and a dip of 55° south.

The mineralisation that is present in these shear zones and veins is probably more complex than that seen at other localities in the Charnwood Forest area and has a complicated history of re-opening with at least 4 stages

of mineralisation being present (King, 1973). Carbonates dominate the mineralisation; calcite (also Fe-rich calcite and Mn-rich calcite) and dolomite (also Fe-rich dolomite) are particularly common and they are usually associated with quartz, chlorite or epidote. A range of sulphides are present: chalcopyrite, bornite, pyrite, galena and chalcocite (some of the chalcocite is thought to be of hypogene origin). Pyrite and galena have been found as euhedral crystals; however, chalcopyrite, bornite and chalcocite are usually found as anhedral masses (King, 1973) embedded in the carbonates (the sequence being: galena embedded in chalcopyrite, embedded in chalcocite embedded in, say, calcite). Well-crystallised hematite (variety specular hematite) is common in the Groby area and is a late member of the paragenetic sequence, being dispersed upon the surfaces of older members (King, 1973). Baryte, pyrolusite (and manganite) are also late in the paragenetic sequence; however, it is less certain that they are hypogene minerals.

### Supergene mineralisation adjacent to the Precambrian-Triassic unconformity

In common with many other localities in Leicestershire (Worssam and Old, 1988; Pearson and Jeffrey, 1997; Hubbard *et al.*, 2005; Ince, 2005; Ixer *et al.*, 2005; Bridges, 2007; Ince, 2007; Ince, 2011), supergene mineralisation has been found close to the Precambrian-Triassic unconformity in the Groby area. Both chalcopyrite and bornite (and hypogene chalcocite) have been oxidised and the copper released has resulted in the formation of supergene chalcocite, djurleite, cuprite, copper, malachite, azurite and 'chrysocolla'. Pyrite, chalcopyrite and bornite have also been oxidised and the iron released has resulted in the formation of goethite, lepidocrocite and 'limonite'; with occasional goethite pseudomorphs after pyrite.

The formation of palygorskite at the base of the breccia-filled Triassic wadis and adjacent fractures in the Precambrian rocks in the Markfield area (and more generally in Leicestershire) was described by Ince (2011). Both palygorskite,  $(\text{Mg,Al})_2\text{Si}_4\text{O}_{10}(\text{OH})\cdot 4\text{H}_2\text{O}$ , and nacrite,  $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$ , have been found at Sheethedges Wood Quarry; however, it is unclear if there they were formed at the same, or different, times.

### Copper sulphides

Most of the 'simple' copper sulphides in the series covellite ( $\text{CuS}$ ), yarrowite ( $\text{Cu}_9\text{S}_8$ ), spionkopite ( $\text{Cu}_{38}\text{S}_{28}$ ), geerite ( $\text{Cu}_8\text{S}_5$ ), anilite ( $\text{Cu}_7\text{S}_4$ ), digenite/roxbyite ( $\text{Cu}_9\text{S}_5$ ), djurleite ( $\text{Cu}_{31}\text{S}_{16}$ ) and chalcocite ( $\text{Cu}_2\text{S}$ ) have been found in Leicestershire (King, 1973; Hubbard *et al.*, 2005; Ince, 2005; Ixer *et al.*, 2005). They have relatively similar stability fields, and alteration, particularly between anilite, digenite, djurleite and chalcocite, is not uncommon:

1. Whilst discussing the possible causes of the greenish-yellow fluorescence seen under SUV in some chalcocite specimens, King (1973) summarised the work of Cook (1972) who provided a number of examples of the instability of chalcocite and its conversion to djurleite and digenite. Evans (1981) also commented that "many specimens labelled as 'chalcocite' are actually primarily

djurleite, or an intimately intergrown mixture of low chalcocite and djurleite".

2. Whiteside and Goble (1986) noted that "since the change from digenite to anilite occurs with great ease (simple physical grinding can cause this transformation)...at the very least, it can be said that the readily observable transformation from the digenite to the anilite structure is reversible and does not require a compositional change".
3. Posfai and Buseck (1994) indicated that "if both djurleite and chalcocite occur in the same sample, chalcocite easily converts to djurleite under the electron beam through the rearrangement of Cu atoms...crushed grains of chalcocite typically convert to djurleite when exposed to an electron beam strong enough to readily produce high-resolution images...monoclinic chalcocite [low chalcocite] converts to a high-temperature polymorph at 103°C, and the upper limit of stability of digenite is 93°C...digenite is stable at room temperature only if it contains a small amount of Fe".
4. In their description of the copper sulphides that occurred at Judkins and New Cliffe Hill quarries, Ixer *et al.* (2005) noted that "the visual identification of the blue copper sulphides in this...material is difficult...despite careful preparation, differential polishing can change the surficial optical properties".

Bearing these points in mind, the reports of the investigation of the various copper sulphides occurring in the Charnwood Forest area and the analyses of material from the Groby area mentioned in the chalcocite, covellite and djurleite (and bornite) descriptions (see above), a more detailed characterisation of the Leicestershire copper sulphide specimens should be considered.

### Manganese-containing oxides/hydroxides

Specimens from various localities in Leicestershire that were assumed to be pyrolusite have been shown to contain other manganese-containing oxides/hydroxides: hollandite (Pearson and Jeffrey, 1997), ramsdellite and possibly todorokite or lithiophorite (Ince, 2011) and manganite (see above). As was noted by Ince (2011), further studies of the distribution and composition of the manganese-containing oxides/hydroxides that occur in Leicestershire are required to establish their relationship to the other components of the unconformity-hosted base-metal mineralisation.

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## A REPORT ON HAY GILL MINE, CALDBECK FELLS, CUMBRIA

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**The spoil heaps of Hay Gill Mine in the Caldbeck Fells, Cumbria have long been known to be somewhat barren of mineralisation. This report summarises the findings of a visit made in 2010, combined with observations on material in the Natural History Museum, London (NHM) and private collections. Primary mineralisation consisted of quartz, probable ankerite and lesser amounts of baryte and dolomite with pyrite, chalcopyrite and galena as the main sulphides. Oxidation has given rise to minor amounts of a small number of supergene species including goethite, malachite and ‘chrysocolla’. The Kingsbury Collection in the NHM contains a mixture of highly improbable species such as atacamite, with others such as calcite and malachite which could be genuine.**

### INTRODUCTION

The remains of Hay Gill Mine are situated in Hay Gill a steep sided valley which bears slightly south of east off the main Dale Beck valley in the Caldbeck Fells. The bottom of Hay Gill is at NY 301 361 and it continues up to the point where the valley splits into Long Grain and Short Grain gills at NY 308 360. It is a very steep sided valley with numerous natural scree slopes and all the workings are in the valley bottom close to the stream.

The mine has long been known for being relatively barren of mineralisation (Cooper and Stanley, 1990) and has never been popular with collectors for this reason. There is very little old material in collections to aid describing the mineralogy of the site. However, it was investigated as part of the ongoing reviews of mining sites in the Caldbeck

Fells and to this end a Russell Society visit was arranged in 2010 with the permission of the Lake District National Park Authority (LDNPA).

### LOCATION AND HISTORY

There are inconsistencies in the history of the workings in Hay Gill. Shaw (1970) describes it as a copper mine ‘thought to date back to the Elizabethans’. He describes levels driven into both sides of the valley in its upper reaches, but without National Grid References it was not possible to locate these precisely on the 2010 visit, there being no obvious mineralisation in a number of natural looking surficial scrapes. Lower down the valley he describes a shaft and wheel pit which were located close to the stream. Figure 1 shows this site, the position of the shaft, which is marked with an ‘x’, is at NY 3081 3600.



**Figure 1.** Site of the Lady Charlotte Shaft, Hay Gill Mine.



**Figure 2.** Site of the Deep Level and associated dump, Hay Gill Mine.

The water wheel pit is obvious in the foreground of the photograph. Much lower down at NY 3061 3606 is what he calls the No. 1 Crosscut, with an associated dump. Shaw only refers to 19<sup>th</sup> century workings, but Cooper and Stanley (1990) note a period of working from 1785 to 1792 and then nothing until 1839 when the Hay Gill Mining Company was formed. In the period until final closure in 1874, relatively small quantities of copper ore were produced, with some lead ore, probably from intermittent working. Tyler (2009) gives a much more detailed history of the workings and provides a plan, but by giving locations in ‘feet above OD’ rather than grid references, locating specific parts of the site is still very difficult. He gives the name of the shaft as the Lady Charlotte Shaft, which was commenced in 1785 and in the same year work started on what Tyler calls the ‘Deep Level’ which corresponds to Shaw’s No 1 Crosscut. Tyler also describes a level entrance found on this visit at NY 3068 3607 and suggested that it provided ventilation for the Deep Level. A further level with its entrance near the bottom of the gill never reached the vein.

Regarding specimen material, there is no exposed mineral matter associated with the Lady Charlotte Shaft and it seems likely that waste was dumped in the stream and has subsequently been washed away. Figure 2 (see p. 63) shows the workings around the Deep Level (Shaw’s No. 1 Crosscut). The level, now completely run in, is in the large obvious scar in the upper middle of the photograph and the associated dump which is on the south side of the stream is quite large and with what appears to be a dressing area on top. At the bottom (west) end of the dump a stone ore bin (marked with an ‘x’ on Figure 2), for holding ore prior to transportation down the gill, can be seen on the photograph. The dump is surprisingly barren of any form of vein-stuff and it is probable that this has long been the case since Davidson and Thomson (1951) state under Hay Gill Mine ‘Old records give account of Malachite crystals from this mine but traces of the ore are hard to find’. Cooper and Stanley (1990) list 10 species from the site, but some are the work of Hartley (1984) which is based on material A.W.G. Kingsbury claimed to have collected from the site. In view of the now established fraudulent claims made by Kingsbury (Ryback *et al.*, 1998; 2001 and Tindle, 2008) these have to be regarded with suspicion, several being considered highly improbable.

## GEOLOGY

The workings are all within rocks of the Eycott Volcanic Group and where exposed are hard dark grey-green andesitic lavas. There are numerous blocks of porphyritic lava in the valley, containing large phenocrysts of an intermediate plagioclase feldspar, which at one time was called ‘bytowntite’, but no exposures of this were found in the gill.

The vein, worked by the mine, strikes NE-SW across Hay Gill, just below the point where it splits into Short and Long Grain gills, but could not be seen in situ in 2010. British Geological Survey Sheet No. 23, Cockermouth, indicates that the vein was no more than 1/3 km long.

## THE MINERALS

On the 2010 visit, no mineralisation, apart from a few blocks of quartz, was found above the Deep Level and the dump from the latter was nearly devoid of mineralisation. The notes that follow are based on findings from the Deep Level dump on the visit, combined with examining the small number of specimens in private collections, particularly that of Mike Leppington.

Minerals, about which there is some doubt with regard to identification or provenance, are given in lower case. Where it is considered a mineral should not be included in the list for the site it is given in italics.

### Ankerite, Ca(Fe,Mg,Mn)(CO<sub>3</sub>)<sub>2</sub>

On the 2010 visit, several lumps of a carbonate, highly oxidised to brown goethite, were found, usually associated with quartz. Rarely small curved rhombohedral crystals up to 2 mm across and pseudomorphed by goethite had formed in small cavities. All this material is considered to have been ankerite, but it is not possible to be certain (see also dolomite below) and for this reason, throughout the rest of this paper, references to ankerite are placed in inverted commas to indicate its unproven nature. On some



**Figure 3.** Dump specimen of oxidised ‘ankerite’ and quartz from the Deep Level dump. Specimen width 7 cm.



**Figure 4.** Baryte in quartz, Deep Level dump. Image width 4 cm.

specimens quartz had apparently been brecciated and then cemented with the 'ankerite', indicating that it had formed later in the paragenesis than the quartz. Figure 3 shows a typical dump specimen, 7 cm wide, of the 'ankerite' and quartz.

### BARYTE, BaSO<sub>4</sub>

Several small lumps of primary baryte were found on the dump, suggesting it was a significant component of the vein, although much less so than quartz. When associated with quartz it is the later mineral, sometimes growing in cavities lined with quartz crystals. Figure 4 shows part of a small specimen of baryte in quartz. Small diamond shaped thin plates of baryte, reaching 2 mm on edge in small cavities in quartz and in one case growing on goethite, are considered to be supergene in origin.

### BROCHANTITE, Cu<sub>4</sub>SO<sub>4</sub>(OH)<sub>6</sub>

Brochantite is rare, but has been found as crusts of very minute emerald green crystals covering areas up to 20 mm across on iron stained quartz. On one specimen the individual crystals reach 0.1 mm long. They are all clearly of post-mining origin.

### CALCITE, CaCO<sub>3</sub>

Calcite was found infilling cracks and cavities in 'ankerite' and quartz. Nailhead crystals up to 3 mm across have formed in some incompletely filled cavities. Two specimens in the Mike Leppington Collection show larger crystals which reach 10 mm across.

### CERUSSITE, PbCO<sub>3</sub>

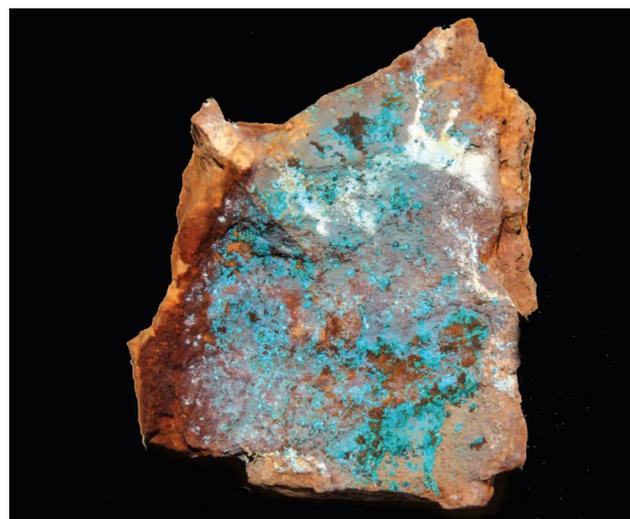
Although not found on the 2010 visit, in the 1990s, a few small specimens were found where plates of cerussite up to 5 mm long occurred in cavities in quartz with galena in association.

### CHALCOPYRITE, CuFeS<sub>2</sub>

Despite the fact that it was the main ore from the workings, only small (2 mm) blebs in quartz could be found on the 2010 visit. However, significantly larger specimens were found in the 1990s, one reaching 5 cm across. 1 to 2 mm crystals were also found in small cavities in quartz. All have oxidised surfaces except on recent fractures. On some specimens alteration to goethite has taken place and it is possible minor alteration to grey copper sulphides has occurred, but there is too little material to establish this with certainty.

### Chrysocolla, Copper-rich silica gel

Examination of the surface of the dump revealed a number of small specimens with blue to green encrustations of 'chrysocolla'. However, there is now considerable doubt about the status of this mineral and certainly all specimens examined from this and other mines in the Dale Beck valley (Green *et al.*, 2008 and Bridges *et al.*, 2008), including the nearby Ingray Gill workings (Green *et al.*, 2009) are copper-rich silica gels. These findings are supported by Farges



**Figure 5.** 'Chrysocolla' on partly oxidised 'ankerite' from the Deep Level dump. Specimen width 6 cm.

*et al.*, (2006) who analysed specimens from localities in North and South America and the Congo and found all to be mixtures of copper in the form of spertiniite, Cu(OH)<sub>2</sub>, mixed with hydrous amorphous silica. For convenience, in this paper, this material is called 'chrysocolla', placed in inverted commas to indicate its doubtful status. Figure 5 shows the best 'chrysocolla' specimen found on the 2010 visit.

### CORONADITE, PbMn<sub>8</sub>O<sub>16</sub>

An 8 cm quartz specimen in the Mike Leppington collection is partly coated on one side with an arborescent manganiferous encrustation, which at one time would have been called 'dendritic pyrolusite'. A combination of EDS and XRD showed the encrustation to be coronadite.

### DOLOMITE, CaMg(CO<sub>3</sub>)<sub>2</sub>

In the 1990s a small number of specimens were collected by one of us (ML) which have subsequently been shown by EDS to be an iron-bearing dolomite with a trace of manganese. Small cavities in the specimens contain saddle-shaped crystals up to 1 mm across. This dolomite weathers to a light brown colour on the surface and in places grades into the highly oxidised phase described as 'ankerite' above.

### GALENA, PbS

Galena is remarkably rare on the dumps, but has been found as small blebs in quartz and in one case as 2 mm crystals in cavities in quartz. Much of the galena is corroded, with a grey-white surface encrustation.

### GOETHITE, FeO(OH)

Limonitic ochres and stains are common at the site as the result of oxidation of pyrite and 'ankerite'. Much of this material is dark compact goethite.

### Jarosite, KFe<sub>3</sub>(SO<sub>4</sub>)<sub>2</sub>(OH)<sub>6</sub>

A small area of an earthy yellow encrustation typical of jarosite and containing iron and sulphate, with no lead, was



**Figure 6.** Malachite on goethite. The specimen is 6 cm wide and is from the Deep Level dump.



**Figure 7.** Specimen of pyrite, approx. 30 cm wide, partly oxidised to goethite. Deep Level dump.

found on quartz which was enclosed in an area of oxidised pyrite on one of the larger blocks of this mineral. It is almost certainly jarosite, but could possibly be hydroniumjarosite.

### MALACHITE, $\text{Cu}_2(\text{CO}_3)(\text{OH})_2$

A few small specimens of malachite were found, but the mineral is very much subordinate to 'chrysocolla'. Figure 6 is typical of the malachite found on the dump.

### PYRITE, $\text{FeS}_2$

Pyrite is the only sulphide found in reasonable quantity on the dump. Blocks of the order of 30 cm long were found, consisting of pyrite in a cellular matrix of quartz (Fig. 7). In places on the specimens the pyrite has partially or completely oxidised leaving clean cavities in quartz with a cellular appearance. Rarely pyrite crystals up to 1 mm across occur in cavities in the quartz.

### QUARTZ, $\text{SiO}_2$

Quite large lumps of quartz were found on the main dump and in the stream. Most were barren of other minerals beyond iron staining. Cavities are sometimes lined with pyramidal crystals up to 5 mm across and baryte has formed in some of these cavities. Quartz was probably the main gangue mineral in the vein.

### SPHALERITE, $\text{ZnS}$

Several specimens have been found where small blebs of pale yellow-brown sphalerite, generally no more than 1 to 2 mm across, occur in quartz and dolomite. On one specimen, found in the 1990s, a 2 mm plate of very pale yellow transparent sphalerite bridges a cavity in dolomite.

### SULPHUR, S

In addition to a jarosite group mineral, oxidation of pyrite has resulted in the formation of pale yellow anhedral sulphur crystals which reach 0.25 mm across on one specimen. The position of the sulphur on fractured and oxidised pyrite shows it has formed on the dump.

### Tenorite, $\text{CuO}$

Gregg and Lettsom (1858) record tenorite from Hay Gill, but at that time it would not have been possible to definitely identify the mineral. It has not been found in this study and it seems preferable not to include it in the list of minerals for the site.

## THE KINGSBURY COLLECTION

Hartley (1984) lists nine minerals which Kingsbury claimed to have collected from Hay Gill. Some of these could be found in the Kingsbury Collection or the main collections of the NHM, but brochantite, pyrite and the now discredited mineral psilomelane could not be found and may never have been included in his collection. Dealing with the remaining specimens in turn:

### Atacamite, $\text{Cu}_2\text{Cl}(\text{OH})_3$

There are three specimens of atacamite in the NHM collections that Kingsbury claimed to have found at Hay Gill. Figure 8 is a photograph of the largest specimen which is 6 cm wide and claimed to have been collected in 1951. There are sound geochemical reasons for saying there is no possibility that a specimen as rich as this could have originated in the Caldbeck Fells and the same is true for the two lesser specimens. They are all virtually certainly fraudulent.



**Figure 8.** Atacamite specimen, 6 cm wide, claimed to have been collected in 1951 and donated to the NHM by Kingsbury.

## Calcite, $\text{CaCO}_3$

There are two small lumps in the collection. They both contain areas of small nailhead crystals and while they are better than anything found in this study, they are reasonably similar to the specimens in the Mike Leppington Collection and may well be genuine.

## Chalcopyrite, $\text{CuFeS}_2$

The collection contains two small pieces of partly oxidised chalcopyrite in brown goethite, but with minor azurite on one side. If it was not for the azurite, which is a very rare mineral in the Caldbeck Fells, the specimens could have well have been genuine, but with the azurite they are considered to be doubtful.

## *Chrysocolla, Copper-bearing silica gel?*

The main collections of the NHM contain two specimens of 'chrysocolla' donated by Kingsbury in 1967 and purporting to be derived from Hay Gill. Figure 9 shows the two specimens, which are both quite solid lumps, the larger being 5 cm wide. No specific locality in Hay Gill is provided, but both are almost certainly fraudulent, since no other specimens as rich as this are known to have been found in the Caldbeck Fells.

## Cuprite, $\text{Cu}_2\text{O}$

There are several specimens of cuprite in the collection, which are from a single specimen which has been broken up. The associated labels say the specimens were collected in 1951 from what Kingsbury describes as the 'upper level', presumably the Deep Level. The largest of the specimens is shown on Figure 10 and is 5 cm wide. All the specimens almost certainly originate from the south-west of England.



**Figure 9.** Two specimens of 'chrysocolla', donated to the NHM by Kingsbury. The larger specimen is 5 cm wide.



**Figure 10.** A 5 cm wide specimen of cuprite Kingsbury claimed he collected from the 'upper level' of Hay Gill Mine in 1951.



**Figure 11.** Two trays of malachite from Hay Gill in the Kingsbury Collection.



**Figure 12.** Specimen of malachite, 8 cm across, possibly originating from Hay Gill.

### Malachite, $\text{Cu}_2(\text{CO}_3)(\text{OH})_2$

There are two trays of malachite, labelled from a 'level about ½ way up the gill' in the Kingsbury Collection. Figure 11 (see p. 67) is of the two trays and a comparison with Figure 6 shows the left hand tray could well be genuine. Regrettably there is more doubt about the specimen in the right hand tray which is shown in close-up in Figure 12. It is just possible that in the 1950s a specimen this good could have been found, but it seems unlikely.

### DISCUSSION

On the basis of the relatively small amount of veinstuff on the Deep Level dump and in collections, the main gangue minerals in the vein were quartz and 'ankerite', with significant amounts of baryte and some sulphides. The only sulphide found in any quantity was pyrite, but presumably chalcopyrite and galena were important at one time.

Oxidation of the veinstuff has given rise to a number of supergene minerals of which goethite, 'chrysocolla' and malachite are the only relatively common species, but even they only occur in small amounts.

Hay Gill Mine is a fairly remote site and, as at the nearby Ingray Gill (Green *et al.*, 2009), Kingsbury seems to have used it to make a number of fraudulent claims. However, mixed with these in the collections are a number of specimens, which while better than recently collected material, could still be genuine. Regrettably it is impossible to be certain that any of the material is actually from the site.

Finally, it is interesting to speculate on why the site is almost devoid of mineralisation. Once the ore bin had been built on the end of the tip (Fig. 2) it would not have been practical to extend the dump further down the gill. Waste material may then have been dumped on the north side of the present dump where it would have been vulnerable to being washed down the gill by periodic floods in the 130 years since the mine was last worked. The north slope of the present dump is where most mineralisation was found, excluding small pieces on the dressing area.

### SPECIMENS

Typical specimen material from this study has been placed in the collections of the Great North Museum, Hancock

### ACKNOWLEDGEMENTS

One of us (TFB) would like to thank the Russell Society members who accompanied him on the visit. Thanks are also due to Norman Thomson for information on collecting in the 1950s in Hay Gill and to Tom Cotterell for XRD work on the 'dendritic pyrolusite'.

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# GOETHITE PSEUDOMORPHS AFTER MARCASITE FROM THE NORTHERN PENNINE OREFIELD

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**Dome-like crusts of pseudomorphs of massive goethite, after well-formed spear-shaped crystals of marcasite, plentiful locally in the spoil from former lead mines in Wensleydale, Swaledale and Arkengarthdale, indicate that monomineralic crusts of euhedral crystals of the latter mineral must at some stage have been locally abundant within these deposits. This is noteworthy as iron sulphides are generally very scarce within the veins and associated deposits in the Askrigg Block portion of the Northern Pennine Orefield, of which these deposits form part. A few specimens from Whitaside Mine reveal evidence of growth of original marcasite upon a substrate of ‘cockscorb’ baryte; evidence of substrate minerals has not been found at other locations. At all locations described, specimens reveal evidence of growth of marcasite crystals on the ‘reverse’ side of the dome-like crusts apparently after these crusts became detached from their original substrate. Rare, poorly preserved casts of fossils within the ‘reverse’ sides of a handful of specimens, together with the occurrence of these pseudomorphs locally still embedded in limonitised and dolomitised limestone at Faggergill mines, may suggest that at least some of the euhedral marcasite may have formed within metasomatic replacement ‘flat’ deposits, perhaps as a result of re-mobilisation of disseminated iron sulphides within the host limestone.**

## INTRODUCTION

The Northern Pennines, between the Craven Fault Belt in the south and the Stublick Fault System in the north, includes two substantial orefields. Centred respectively upon the Askrigg Block and, north of the Stainmore Trough, the Alston Block, these orefields each include an abundance of vein and related replacement deposits of Mississippi Valley Type (MVT) hosted almost wholly within the comparatively thin successions of Carboniferous sedimentary rocks which cover basement highs (‘blocks’) composed of Lower Palaeozoic sedimentary and volcanic rocks (Dunham, 1967). Substantial Caledonian granite batholiths within these Lower Palaeozoic rocks underpin both blocks, and are believed to have played an essential role in creating and focussing the centres of mineralisation (Dunham, 1934; Dunham *et al.*, 1961; Dunham *et al.*, 1965; Dunham, 1974; Dunham, 1990; Cann and Banks, 2001; Kimbell *et al.*, 2010). Deposits within the Northern Pennine orefields include formerly workable concentrations of lead, zinc, copper and iron ores, together with economic quantities of such spar minerals as fluorite, baryte and witherite. Described here is the local abundance within the Askrigg orefield of remarkably well-developed goethite pseudomorphs after marcasite, a feature unknown in the Alston orefield.

## GEOLOGICAL BACKGROUND

The deposits which yield the specimens described in this paper lie in Wensleydale, Swaledale and Arkengarthdale within the northern portion of the Askrigg Block. Veins and associated replacement deposits are here hosted within cyclothem successions of Carboniferous limestones, sandstones, mudstones and locally cherts (Dunham, 1959; 1974). In common with deposits elsewhere throughout both

the Askrigg and Alston portions of the Northern Pennine orefields, these veins have proved most productive of both ore and spar minerals within limestone wall rocks where, in addition, significant metasomatic replacements of the adjoining limestones have, in places, proved to be richly mineralised (Dunham and Wilson, 1985). Many of these deposits, including the sites discussed in this paper, have been subjected to significant supergene alteration, though the timing of this is unknown.

Whereas the two orefields share many characteristics in their component mineralogy and in the distribution of these minerals, which serve to unite them as examples of MVT mineralisation, they also exhibit significant differences (Dunham and Wilson, 1985; Dunham, 1990). For example, the clear zonal distribution, and almost ubiquitous mutual exclusivity of fluorite and barium minerals within the deposits of the Alston area is manifested in the Askrigg area by a much weaker and more limited expression of fluorite zone mineralisation and the comparatively common interbanding of fluorite and barium minerals. Quartz, a common and widespread component of deposits in the Alston area is generally uncommon or rare in those of the Askrigg area. A third, and in the context of the material described here much more significant difference, is the general scarcity of iron minerals, both carbonates and sulphides, within the deposits of the Askrigg area compared to the abundance of these in the Alston deposits (Dunham and Wilson, 1985; Dunham, 1990).

The pseudomorphs which are the subject of this paper are derived from deposits which lie within the B and C zones of Dunham and Wilson (1985). In these, galena and locally some sphalerite are accompanied by gangue assemblages dominated by barium minerals and calcite respectively.

## GOETHITE PSEUDOMORPHS AND THEIR DISTRIBUTION

Striking pseudomorphs of massive goethite, after well-formed crystals of marcasite have been found in abundance in the spoil heaps from mines at Virgin Moss [SE 002 934], and Beezy [SD 946 946] in Wensleydale, from Whitaside [SD 986 958] in Swaledale and Fagnergill [NY 990 071] in Arkengarthdale.

Although brief reference has been made to the presence of these pseudomorphs at the first of these locations (Young *et al.*, 1992), and to the occurrence of apparently similar pseudomorphs at Fagnergill (Small, 1977; Dunham and Wilson, 1985), no detailed descriptions of the material from these, or the other localities discussed here, have ever been published. As discussed below, supposed hematite replacements, presumably pseudomorphs, of siderite, at the Beezy mines on Askrigg Common, referred to by Raistrick (1975, p. 85) have proved during this investigation to be further examples of goethite pseudomorphs after original marcasite.

As the pseudomorphs found at the four localities described here exhibit generally very similar morphologies, their main characteristics are outlined, followed by comments on distinctive features and variations recorded at individual locations.

At all of these localities goethite occurs in some abundance as hard, compact dark brown pseudomorphs after well-developed spear-shaped crystals, which commonly exhibit curved side faces, giving a distinctive 'gothic arch' form to many of the crystals. Many of these are aggregated into distinctive 'cockscomb-like' groups of twins. Where unweathered, the pseudomorphs are typically very sharp replacements of the original mineral with fine details of former twinning beautifully preserved on many faces. Whereas most specimens display a dull outer surface, some examples exhibit a pronounced rather resinous lustre. The morphology of these replaced crystals, which range in size from around 1 mm up to about 11 mm in length, closely resembles forms of marcasite illustrated in numerous standard mineralogical textbooks (e.g. Palache *et al.*, 1944, p. 312) and there seems little doubt that the original mineral, now represented by the pseudomorphs, was indeed marcasite. The pseudomorphs typically occur as plate, or crust-like, monomineralic aggregates up to 140 mm across and 20 mm thick. None has been observed in close association, or intergrown, with other ore or gangue minerals, though a few specimens have been found in which aggregates of pseudomorphs occur embedded in dolomitised or limonitised limestone. Many of these crusts exhibit a distinctive low dome-like form, suggesting that the original marcasite occurred as encrustations on gently rounded aggregates of other vein minerals. Although a few specimens collected from the Whitaside Mine [SD 986 958] in Swaledale, exhibit casts of what appear to be cockscomb baryte crystals on the inner surfaces of the dome-like crusts, and single specimens from Virgin Moss Mine and the Beezy mines exhibit small casts of fossil shells and corals respectively, no other specimens have been seen which

offer insights into the nature of any substrate minerals or materials.

### Virgin Moss Mine, East Bolton Moor, Wensleydale [SE 0024 9335]

The substantial dumps from this level, which worked galena from the NNW-SSE trending Virgin Moss Vein, in Namurian strata ranging upwards from the Main Limestone to beds above the Little Limestone, reveal that the vein was here richly mineralised with galena, baryte, calcite and witherite (Dunham and Wilson, 1985). It is known that some replacement 'flat' mineralisation occurred in the Main Limestone, from which a small amount of witherite was mined (Dunham and Wilson, 1985). In addition, Young *et al.*, (1992) recorded the local abundance here of the rare zinc-rich kaolinite – serpentine group mineral fraipontite which, together with abundant concentrations of hemimorphite, they interpreted as products of supergene alteration of primary sphalerite. These authors also commented very briefly, in passing, on the abundance of goethite pseudomorphs after marcasite.

The goethite pseudomorphs at this site, which exhibit the characteristic morphology summarised above, occur abundantly as sharply defined dull brown spear-shaped crystals individually up to around 5 mm long, commonly aggregated into twinned groups and forming plate-like crusts up to 110 mm across. Also present are curved dome-like crusts up to 60 mm across (Fig. 1). In the majority of these crusts the distinctive pseudomorphs occur only on one side of the specimen, with the 'reverse' side exhibiting a smooth to rather irregular surface that is usually devoid of any traces of the nature or form of an original substrate. However, a single specimen has been seen in which the otherwise featureless 'reverse' surface exhibits a very few hollows, up to about 5 mm across, that appear to be casts of indeterminate, concentrically ribbed, brachiopod or bivalve



**Figure 1.** Virgin Moss Mine. Dome-like mass of spear-shaped pseudomorphs up to 5mm long. Specimen is approximately 60 mm across (BY5710\*; \* Accession number of specimen in B. Young Collection)

shells. In a very few instances, small clusters of goethite pseudomorphs of identical morphology to those which comprise the bulk of the specimens, have been observed on the 'reverse' sides of the crusts. Such clusters are up to 20 mm across and are typically composed of rather smaller original crystals up to a maximum individual length of about 3 mm.

**Beezy mines, Askrigg Common, Wensleydale**  
[SD 9460 9460, SD 9460 9410 and SD 9475 9422]

The Beezy mines include a number of old shallow shaft and opencast excavations on the moorland east of Oxnop Beck Head, between Wensleydale and Swaledale. Here, galena was extracted from three sub-parallel NNW-SSE trending veins which cut Namurian strata, including the Little and Red Beds limestones and associated cherts (Dunham and Wilson, 1985). The small scattered spoil heaps from these workings, and from the Beezy Level [SD 9475 9422], indicate that gangue minerals, including baryte and calcite, were generally scarce, though an abundance of dolomitised, and some limonitised, limestone suggests the widespread occurrence here of replacement 'flat' mineralisation in the limestones.

In an historical description of these mines, Raistrick (1975, p. 85) referred to the abundance on some of the old spoil heaps of "...sheets of perfectly crystallised chalybeate (iron carbonate)...entirely replaced by hematite...". Dunham and Wilson (1985, p. 167) correctly referred to this material as goethite, which they assumed to have been derived from the vein known as Simon Grooves String, and suggested that it may have resulted from the alteration of pyrite. A field examination by one of the present authors (BY) revealed that this material consists of the characteristic pseudomorphs after marcasite described here, but that the material is most abundant in the spoil from old workings in Beezy Vein [SD 9460 9460] which lies about 150 metres east of the Simon Grooves String. No trace of hematite has been found at this or any of the other sites studied.

The pseudomorphs of individual marcasite crystals at Beezy mines are typically up to about 4 mm long, but exceptionally may attain lengths of around 10 mm. They most commonly form dome-like crusts up to about 80 mm across, though examples up to 130 mm across have been seen. Although the form of these crusts suggests that they may have grown over curved dome-shaped surfaces of a pre-existing mineral, no traces of the nature or form of any such substrate have been found here. Indeed, most of these crusts display sharply developed spear-shaped goethite pseudomorphs on both the outer dome-like surfaces and on their curved interiors (Figs. 2 and 3). However, as at Virgin Moss, the pseudomorphs on the inner surfaces are invariably of much smaller size, typically only up to around 2 mm long.

Whereas the finest examples, and greatest concentration, of these pseudomorphs at Beezy mines has been observed in the dumps from old workings at the northern end of Beezy Vein [SD 9460 9460], similar, though very weathered, specimens are common further south in dumps from old



**Figure 2.** Beezy mines. Dome-like crust of goethite pseudomorphs up to approx. 4 mm long. Specimen is approximately 80 mm across (BY8681/C).



**Figure 3.** Beezy mines. Reverse side of specimen shown in Figure 2, showing smaller spear shaped pseudomorphs up to 2 mm long on concave inner surface (BY8681/C).

shafts on the Simon Grooves Vein [SD 9460 9410]. So far as can be seen in these rather weathered and abraded specimens, pseudomorphs occur here mainly as single-sided crusts.

A handful of small, but mainly very similar, specimens has been collected from the debris at an old dressing floor adjacent to the Beezy Level [SD 9475 9422]. One specimen from this site exhibits the cast of what appears to be a rugose coral on the reverse side of the crust of pseudomorphs.

**Whitaside Mine, Whitaside Moor, Swaledale**  
[SD 986 958]

Whitaside Mine, on the south side of Swaledale, worked galena from a productive portion of the prominent WNW-ESE trending Arngill Todd – Whitaside – Apedale Head Vein in the Main Limestone and overlying cherts, as well as from associated replacement 'flats' within the Main



**Figure 4.** Whitaside mines. Crust of lustrous spear-shaped pseudomorphs up to 10 mm long. Specimen is approximately 90 mm across (BY7292).

Limestone (Dunham and Wilson, 1985). The dumps from various shafts and levels here reveal that the mineralisation included, in addition to galena, an abundance of dolomitised limestone, baryte, some witherite and aragonite. Supergene minerals include hemimorphite and smithsonite.

Conspicuous in parts of the dumps are goethite pseudomorphs after marcasite which exhibit the characteristic morphology outlined above. Individual pseudomorphs are here up to 10 mm long and the faces of some of these display a comparatively bright resinous lustre (Fig. 4). In common with specimens from the other locations described, these pseudomorphs form monomineralic plate-like or dome-like crusts up to 90 mm across. Here again, the pseudomorphs most commonly occur on only one side of the crusts: in most instances the ‘reverse’ side is rough and irregular with no indication of the nature of the original substrate. Only a few specimens exhibit rather poorly developed spear-shaped pseudomorphs on the ‘reverse’ side of the crusts. A notable feature of this locality is the occurrence of some particularly well-formed dome-like masses, up to 50 mm across and 20 mm high, which exhibit the characteristic spear-shaped pseudomorphs on their outer surfaces (Fig. 5a) with epimorphous casts of dome-like mounds of what appear to be ‘cockscomb’ baryte crystals on their inner surfaces (Fig. 5b). Silicone casts taken from these specimens confirm this morphology (Fig. 5c).

### **Fagnergill mines, Arkengarthdale [NY 9895 0710]**

The Fagnergill mines comprise an extensive group of workings which extracted lead ore from underground workings in a complex of veins and associated replacement flats within the Main Limestone near the head of Fagnergill, a left bank tributary of Arkengarthdale (Raistrick, 1975; Dunham and Wilson, 1985; Tyson, 1995). The huge spoil heaps from the main, or Fagnergill No. 1 Level, together with much smaller dumps from associated workings on the east and west sides of the valley are composed predominantly of dolomitised and, in part limonitised, limestone, no doubt derived from extensive flat workings. Apart from galena, for which the mines were worked, the most common mineral on the dumps is calcite, accompanied locally by very small



**Figure 5a.** Whitaside mines. Dome-like mass of goethite pseudomorphs approximately 50 mm across (BY7294/A).



**Figure 5b.** Whitaside Mines. Reverse of specimen shown in Figure 5a, showing casts of ‘cockscomb’ baryte (BY7294/A).



**Figure 5c.** Whitaside mines. Silicone cast of ‘cockscomb’ baryte from specimen shown in Figures 5a and 5b (BY7294/B).

amounts of baryte and a little aragonite. Small (1977) noted the presence here of massive brown goethite and commented briefly on well-developed pseudomorphs after marcasite. Dunham and Wilson (1985, p. 108) also commented on the presence here of goethite ‘boxworks’ which they suggested may have been derived from supergene alteration of original marcasite.

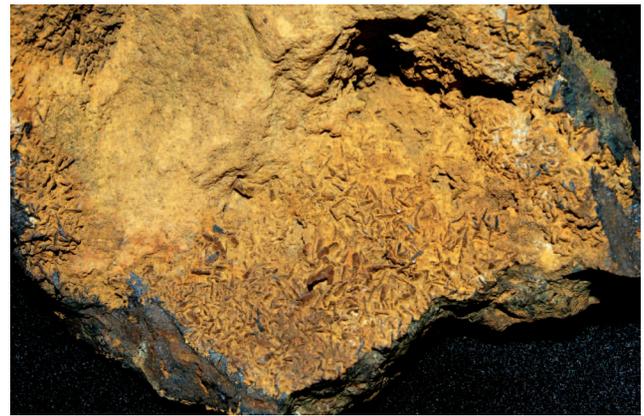


**Figure 6.** Fagnergill mines. Spear-shaped pseudomorphs lining cavities in massive goethite. Specimen is approximately 120 mm across (BY8670).



**Figure 7.** Fagnergill mines. Masses of goethite pseudomorphs protruding from partially weathered dolomitised limestone. Specimen is approximately 80 mm across (BY8673).

During the course of the present investigation, parts of the dumps were found to be rich in fragments of hard dark brown cavernous goethite. Numerous cavities in this material are lined with distinctive spear-shaped pseudomorphs, in places up to 11 mm long (Fig. 6). As at other localities described in this paper, these commonly occur as monomineralic crusts up to 110 mm across, some of which are in the form of dome-like crusts. Several specimens have been obtained in which plate-like masses of massive compact goethite up to 20 mm thick exhibit elongated flattened central cavities lined with sharp euhedral pseudomorphs. However, more commonly, the pseudomorphs occur here as rather irregularly shaped aggregates up to around 60 mm across from which spear-shaped pseudomorphs project in all directions. A few specimens have been collected in which such irregular masses of pseudomorphs, up to 50 mm across, protrude from partially weathered yellowish brown limonitic dolomitised limestone (Fig. 7). A single specimen, obtained from the dumps of the Nut Hole Level [NY 9840 0695], a short distance west of the main Fagnergill dumps, exhibits a box-like aggregate of goethite up to 70 mm across, into the centre of which sharp spear-shaped pseudomorphs, individually up to 3 mm long, project from beneath a thick



**Figure 8.** Fagnergill mines. Spear-shaped goethite pseudomorphs protrude from coating of earthy limonitic dolomite. Specimen is approximately 65 mm across (BY8668).



**Figure 9.** Fagnergill mines. Pseudomorphs, up to 4 mm across, after cubic pyrite. Specimen is approximately 70 mm across (BY8665).

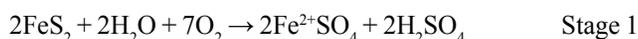
coating of pale yellowish brown earthy limonitic dolomite (Fig. 8). In these latter specimens it seems that the original marcasite crystals may have grown as irregular crystallised aggregates within the altered limestone.

A single specimen, composed of a 70 mm wide plate-like aggregate of interpenetrant cubic pseudomorphs, individually up to 4 mm across, composed of dark brown goethite, may represent original pyrite crystals (Fig. 9). Poorly developed, though clearly recognisable, spear-shaped pseudomorphs after marcasite, form a crust on the 'reverse' side of this specimen.

## FORMATION OF GOETHITE PSEUDOMORPHS

In damp or wet conditions marcasite (and pyrite) readily oxidise in the presence of air. The oxidation process is very complex, with numerous steps, many transient intermediate compounds and more than one pathway. The whole process takes place in solution until, usually, limonitic ochres or goethite precipitate, the latter often forming dark brown botryoidal crusts. Rarely pseudomorphs of goethite after marcasite are the final end product of the reactions.

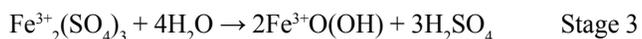
The oxidation to goethite can be divided into three broad stages, the first being the addition of four oxygen atoms, one by one, to each sulphur in the marcasite, to form iron(II) sulphate (ferrous, Fe<sup>2+</sup>) and sulphuric acid, the reaction for which can be summarised simply in the following equation:



The second stage results in the oxidation of the iron(II) sulphate to iron(III) sulphate (ferric, Fe<sup>3+</sup>), the reaction in its simplest form being being:



In solution iron(III) sulphate is only stable at very low pH and usually rapidly breaks down to form hydroxy iron oxides such as goethite, the reaction being:



#### Goethite

The formation of pseudomorphs has never been properly explained, but it is possible to define certain conditions which must be met for goethite to replace marcasite. Stage 1, above, results in complete fracturing of the original crystals, in the process often called 'pyrite disease', unless some of the oxidation products are leached away. The reason for this is that the molecular volume of all the iron sulphates is at least double that of the original marcasite. However, too much leaching would completely remove the iron sulphate, which needs to quickly oxidise to the iron(III) state to complete Stage 2. It is possible that the iron as Fe<sup>2+</sup> and then Fe<sup>3+</sup> has to stay adsorbed onto the already oxidised surface in order to form a pseudomorph. Finally, the right amount of leaching is required to remove the abundant sulphuric acid released in Stage 3. It is interesting to note that the molecular volume of goethite is about 20% less than that of marcasite, (David Green, *personal communication*). This contraction in volume should result in slight porosity in the goethite which might be important in aiding the leaching of sulphate from the site of oxidation. Finally, it is common to find marcasite (and pyrite) crystals coated with a thin layer of brown goethite and it is possible this is the essential start of the pseudomorphic process, with subsequent alteration continuing into the original crystal on a molecule by molecule basis at the goethite surface. While partial pseudomorphs of goethite after marcasite have not been found in this study, it is not uncommon to find partial pseudomorphs of goethite after pyrite, where the latter mineral is present in the depths of the crystal.

## DISCUSSION

Pseudomorphs of the sort described in this paper are uncommon in British mineral deposits. However, large pseudomorphs of goethite after pyrite cubes and bladed marcasite crystals are known from similar MVT type deposits in South Wales (Bevins, 1994; Tom Cotterell, *personal communication*). In the Derbyshire orefield large (up to 3 cm) goethite pseudomorphs after tabular marcasite crystals have been reported from Hubberdale Mine, near Taddington and elsewhere (Ford and Sarjeant, 1964; Ford *et al.*, 1993).

The very distinctive pseudomorphs described here are replacements of euhedral marcasite crystals, the presence of which, within deposits in this part of the Northern Pennine orefield, is noteworthy.

As noted above, the comparative scarcity of iron minerals, whether sulphides or carbonates, is one of a number of features that serves to distinguish the Askrigg from the Alston portion of the Northern Pennine Orefield. In the latter area, marcasite is a common constituent of numerous veins and replacement deposits, and is especially common in the Great Sulphur Vein and in comparable parageneses in deeper levels within major fluorite-bearing veins in the central zones of the orefield. (Dunham, 1990). However, in these occurrences it is almost invariably found as coarse-grained crystalline masses embedded in fluorite or quartz and seldom exhibits euhedral crystal faces.

Within the Askrigg portion of the orefield, iron sulphide minerals are typically present only in minor amounts and have never been found in the abundance seen in the Alston area (Dunham and Wilson, 1985). Small iron sulphide inclusions, which are conspicuous locally within fluorite in the Askrigg deposits, have mostly been identified as the nickel-rich variety of pyrite, bravoite (Rogers, 1974; Ixer, 1978; Vaughan and Ixer, 1980). In addition, Dunham and Wilson (1985) noted the presence of both pyrite and marcasite, though without any detailed descriptions of the distribution of these species either geographically or within the zonal parageneses of the area's deposits.

The specimens of goethite pseudomorphs described here, reveal that at some stage in the evolution of the host deposits, monomineralic crusts, or aggregates, of euhedral marcasite crystals were at least locally abundant. The dome-like crusts that are so common at most localities suggest that these may have formed as encrustations on earlier deposited minerals.

However, only at Whitaside Mine has evidence been seen of the likely nature of this substrate mineral, where epimorphous casts, almost certainly of 'cockscomb' baryte have been observed beneath the goethite crusts. The absence of any remnant of baryte on these specimens could be due to dissolution of the baryte at some stage subsequent to the growth of the original marcasite crystals, or even perhaps in places subsequent to the alteration of the latter to goethite. Alternatively, its absence may simply be a result of the parting, due to poor adhesion along the baryte/marcasite (or goethite) interface. It may be worth noting that 'cockscomb' baryte with the morphology represented by the casts, has not been observed on the abundant mineralised material remaining on the same parts of the spoil heaps as the goethite pseudomorphs. There is, however, insufficient evidence to adduce the reasons for the absence of baryte from these specimens and thus it is impossible to suggest the process that may have influenced the evolution of mineral parageneses before and after the formation of the pseudomorphs.

The close similarity in form of the widespread dome-like crusts of pseudomorphs to those that appear to have

grown upon pre-existing baryte at Whitaside, albeit without the evidence of baryte crystal morphology, may suggest that comparable dome-like masses of baryte may have provided a common original substrate to these aggregates.

The presence of generally smaller pseudomorphs after marcasite on the 'reverse' side of dome-like crusts, noted at several localities, suggests that in these instances further growth of marcasite occurred after the original crusts had become detached from their substrates. If so, it is possible that the mineral substrate of these masses was removed, perhaps by some form of preferential dissolution, early in the evolution of the host deposit. Dissolution of baryte by bacterial reduction of sulphate may perhaps have provided sufficient sulphide for precipitation of further marcasite on the 'reverse' sides of these crusts.

Specimens from Faggersgill mines, in which aggregates of pseudomorphs occur embedded, or partially embedded, within dolomitised and partially limonitised limestone, suggest that, at least locally, aggregates of euhedral marcasite developed during the metasomatism associated with 'flat' formation. The presence of rare casts of shell fossils at Virgin Moss, and of a rugose coral at Beezy, indicates that the original marcasite crusts represented by these specimens must have formed in an environment where replacement of limestone was taking place. It is therefore clear that at least some of the goethite pseudomorphs from the above three locations were derived from 'flat' mineralisation.

Replacement 'flats' were important features of the deposits worked at all of the sites described here and it is possible that the goethite pseudomorphs at all described locations may have been derived mainly, or perhaps wholly, from such deposits. If so, this might offer an explanation for the source of the original marcasite. Metasomatism of the Main, and at Beezy the Little and Red Beds limestones, may have re-mobilised disseminated iron sulphides within these comparatively impure limestones, resulting in the formation of marcasite crystals both as clusters of crystals within the metasomatised limestone and as crustiform layers in cavity linings.

Throughout the Northern Pennine orefield, both in the Askrigg and Alston areas, near surface alteration processes have created a variety of supergene species. In both areas iron minerals, both sulphides and carbonates have typically altered to goethite (Dunham and Wilson, 1985; Dunham, 1990). These authors regard the supergene alteration seen today throughout the northern Pennines orefields as being the result of attack by oxygenated water of meteoric origin, presumably during Pleistocene or more recent times. It is not possible to adduce the precise provenance of the pseudomorphs found at the sites studied in relation to present or likely recent zones of near surface oxidation, although from considerations of the known configuration of the mine workings, it is possible that all may have been derived from within this zone.

## ACKNOWLEDGEMENTS

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## NOTES FOR CONTRIBUTORS

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Authors are encouraged to prepare papers in electronic format using Microsoft Word and to send the file(s) as e-mail attachment(s) to the Editor. Templates for the format of articles and notes are available from the Editor and the Journal Manager. Do not embed figures and tables within the text, but indicate where they should be inserted. At the end of the manuscript provide figure captions and any tables with their captions. All pages should be numbered in the footer. Each paper will normally be reviewed by two referees. Submission of a paper to the Journal is taken to imply that it has not been considered for publication elsewhere. Material accepted for publication can not be published elsewhere in the same form without the consent of the Editor. The submitted material should normally contain original observations or experimental results relating to mineral occurrences in the British Isles, although other suitable topics may be considered. Full articles should include an abstract of up to 250 words summarising the significant points of the paper; notes (up to 1500 words) do not require an abstract. Review articles are welcomed.

### FORMAT AND PRESENTATION

Papers should be submitted in the style and format of the Journal, and divided into appropriate sections and subsections. A recent issue of the Journal should be consulted for examples. Titles of papers should be adequately informative. Authors should present their material with clarity and conciseness. Results and discussion should not normally be intermingled. National Grid References should be given for localities described in the text (the format is, e.g.: ST 4015 7185, ST 401 718, ST 40 71 and enclosed in square brackets where necessary, e.g.: [ST 4015 7185], [ST 401 718], [ST 40 71]). Identification of the less common minerals should be supported by sufficient proof (X-ray diffraction, microchemical analyses, etc.). It may not be necessary to reproduce such data in full in the text, but they should be supplied to the Editor if required by the referees in the course of their assessment. For mineral occurrences of particular note (e.g. new occurrences in the British Isles or at a particular locality) authors are strongly encouraged to record the specimen number and the institution or collection where the specimen is lodged.

### FIGURES

All figures should be numbered with consecutive Arabic numbers, and referred to in the text as Figure 1, etc. Figures must have descriptive captions, and the scale must be indicated either on the photograph or by specifying, e.g., width of view or crystal size in the caption. Line drawings, crystal diagrams, maps, etc., should be of a quality suitable for direct reproduction, with appropriate line thicknesses and letter sizes. The Editor will arrange artwork for authors who do not have access to such facilities. Photographs and drawings (e.g., locality maps) should be submitted initially as low-resolution electronic files (Jpeg format is preferred) or draft quality prints, however high quality prints or high-resolution electronic files will be required for publication. Optical photographs of coloured specimens should be supplied as colour images.

### TABLES

Tables should be numbered consecutively and referred to in the text as Table 1, etc. Each table should have a descriptive title placed beneath. Horizontal lines should mark the top and base of tabulated data; any footnotes should be placed below this.

### TERMINOLOGY

Authors should adhere to the nomenclature and terminology of the International Mineralogical Association. The most recent Fleischer's Glossary of Mineral Species (at present the 10th edition, by Mandarino and Back, 2008) can be used as a guide to mineral nomenclature, but where this conflicts with Hey's Mineral Index (1993) or Mineralogical Magazine and Mineralogical Abstracts usage, the Editor will advise on the preferred nomenclature. Chemical nomenclature should conform to the rules of the International Union of Pure and Applied Chemistry. Crystal structure studies should be reported in the manner outlined by the International Union of Crystallography (*Acta Crystallographica*, (1967), 22, 45).

### ABBREVIATIONS

Except for common non-scientific abbreviations and those for standard units of measurement, abbreviations should be spelt out in full at their first mention in the article, e.g. platinum group mineral (PGM). If used, 'nd.' in tables must be defined (to 'not determined' or 'not detected'). The following abbreviations may be used without explanation:

XRD	= X-ray diffraction analysis
XRF	= X-ray fluorescence analysis
EPMA	= electron probe microanalysis (electron microscopy analysis)
EDX	= energy dispersive analysis (same as EDA, EDAX, EDS)
SEM	= scanning electron microscope or microscopy
TEM	= transmission electron microscope or microscopy
IR	= infrared
UV	= ultraviolet

### REFERENCES

References should be indicated in the text thus: (Brown, 1967) or 'as stated by Brown (1967)'; (Green and Brown, 1985) for two authors; (Green *et al.*, 1986) for three or more authors. If two or more references would give rise to identical citations in the text, they may be distinguished by appending 'a', 'b', etc. to the publication year.

A list of references in alphabetical order should form the last section of each paper. Some examples of the style used are given below; note that journal names are given in full. Papers in press may be included provided they have been accepted for publication and the journal name is given.

Personal communications and unpublished work (except MSc and PhD theses), should not be included here but can be cited in the text, thus: (A. Brown, *personal communication* or *personal communication*, 1992), (B.C. Green, unpublished work). Likewise, references to Newsletters and similar publications will normally be cited in the text but not included in the reference list.

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