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The journal of British Isles topographical mineralogy

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FRONT COVER:

A group of colourless, transparent baryte crystals (6×2 mm) with overgrowing rhombohedral dolomite from Hickleton Colliery, Thurnscoe, South Yorkshire. Specimen 149 in the Steve Uttley Collection; photo John Chapman.

BACK COVER:

A group of white, translucent, prismatic calcite crystals (34 mm across) from the Whin Sill at Barrasford Quarry, Gunnerton, Northumberland. Peter Briscoe Collection; photo David Green.

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EDITORIAL

TOPOGRAPHIC MINERALOGY

Is mineralogical publication 'in the pink'? Volume 1 part 1 of the journal dropped onto doormats in March 1982. The late Bob King, our first journal editor, noted that:

> "... the need for such a journal has long been felt where accomplished amateur mineralogists might present scientifically important observations, both on systematical and topographical mineralogy ... which might be unacceptable to the current professionally orientated scientific journals".

The key phrase here is 'topographic mineralogy'. Since its inception, the journal has recorded mineralisation at localities in the British Isles. In so doing, many rare and unusual species have been reported, their relationship to the local geology recorded, theories on how they may have formed offered and collections described. And after thirty-six years of publication there is still no shortage of important localities to describe!

Information in mineralogy, as in many other scientific subjects, is organised in hierarchies. Individual specimens and their labels are the foundation on which everything else is built. The value of gluing a small label with locality details to every important specimen is emphasised in a recent newsletter article by Tom Cotterell. Specimens are organised into collections, and if these are assembled thoughtfully, the whole (which may have an accompanying field notebook, photographic archive, catalogue or database) is much more than the sum of the parts.

The information contained in collections provides data for articles. Late-stage hydrothermal mineralisation associated with the Whin Sill of northern England is described in a geological context in an account which includes images of specimens, mostly in the Brian Young Collection, photographed by Andy Hopkirk in the first article of this journal. Tom Cotterell and Roy Starkey have contributed an account, of millerite from Gorsley Common. Rediscovered after more than a century, in an area not known for its minerals, the value of careful detective work is shown. Skarn mineralisation containing euhedral andradite, reported seventy years ago by G. P. L. Walker near Portmuck in County Antrim, is described by Norman Moles. The article includes several excellent photos of specimens from Norman's collection by a new Society member John Chapman. John Mason and colleagues emphasise the geological context of mineralisation in Wales, in two articles, one of which includes a note on the 'magnificent uralite porphyry', an intriguing rock, which like the Gorsley Common millerite, has been rediscovered after many years of obscurity.

The importance of collections and careful specimen curation is shown by Richard Bateman and colleagues in a discussion of the minerals of the South Yorkshire Coalfield. An attempt is made to provide a holistic description of the mineralogy of a relatively large area, in a study which is based on a small collection, a few published articles, and the data in two privately printed manuscripts assembled by the late Steve Uttley.

In mineralogy, the top of the information pyramid is occupied by topographic books, grand syntheses of published data which describe large regions. When volume 1 part 1 of the journal came through members' letterboxes in 1982, British topographic mineralogy was anchored in the nineteenth century. The standard topographic work was the *Manual of the Mineralogy of Great Britain and Ireland* (Greg and Lettsom, 1858). This has since been replaced by *Minerals of Britain and Ireland* (Tindle, 2008) and augmented by a number of well illustrated volumes which deal with the mineralogy of smaller regions.

This year sees the publication *Minerals of the English Midlands*. Roy Starkey's work will need little introduction to most members of the Society, but for those who are unfamiliar with it, a short review is provided on pages 124–126. Thirty-seven articles in the *Journal of the Russell Society* are referenced, and there are numerous photos of specimens found on field trips. Three such specimens, all found since the first part of the journal was produced in 1982, are shown on the facing page. A reminder that interesting specimens remain to be collected and documented across the British Isles.

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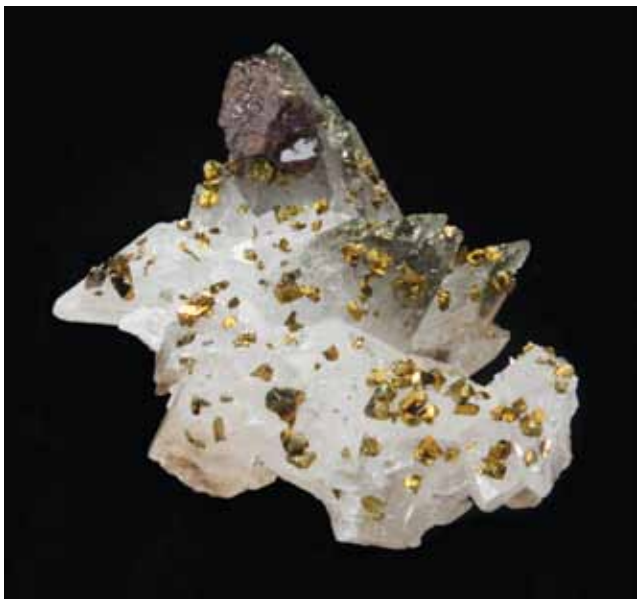
David Green and Malcolm Southwood,

Journal Editors

ERRATUM

Ince, F. (2017). A review of the minerals associated with the igneous rocks of southwest Leicestershire. *Journal of the Russell Society*, **20**, 3–29. On page 25, the final sentence of the quotation describing the Miller Indices for some quartz crystals should read: "Of 52 crystals examined, 43 showed the development of the left trigonal pyramid $\{2\bar{1}\bar{1}1\}$, and rarely the left trigonal trapezohedron $\{6\bar{1}\bar{5}1\}$.", (not $6\bar{1}\bar{1}1$).



Above: A brown sphalerite crystal (7 mm across) on calcite with chalcopyrite; Level G, West Face, Cloud Hill Quarry, Breedon on the Hill, Leicestershire; 35×30×15 mm; Frank Ince Collection (FI-2447). Figure 495, *Minerals of the English Minerals*, p. 207.

Right: Intergrown white to pink, tubular, pseudostalactitic masses of baryte (the enclosing brown calcite matrix has been removed using dilute hydrochloric acid); Hollandtwine Mine, Dirtlow Rake, Castleton Derbyshire; 90×50×40 mm; Frank Ince Collection (FI-1644), formerly in the collection of the late Malcolm Woodward (1058), previously in the collection of the late John Cooper (90/103). Figure 260, *Minerals of the English Minerals,* p. 122.

Below: Colourless to white, bipyramidal crystals of edingtonite (to 15 mm) on prehnite: Squilver Quarry, Disgwylfa Hill, Moreswood, Shropshire; 110×60×40 mm; Allan Mortimer Collection (51-1-19). Figure 738, *Minerals of the English Minerals,* p. 297.

Images: © Roy Starkey (reproduced with permission).

LATE-STAGE HYDROTHERMAL MINERALISATION OF THE WHIN SILL: A REVIEW

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Previous records of the varied suite of minerals which coat joints and locally fill vesicles within the dolerite of the Permo-Carboniferous Whin Sill of northeast England are reviewed and some are illustrated: a handful of hitherto unrecorded occurrences are also reported. All were formed by late-stage hydrothermal processes during the final cooling of the intrusion. Brief speculative comments are offered on the possible genetic significance of the distribution of several of these. This mineralisation is genetically separate from the widespread mineralisation of the Northern Pennine Orefield, many deposits of which are hosted within Whin Sill wall-rocks.

GEOLOGY OF THE WHIN SILL

Since recognition of the Whin Sill's intrusive igneous origin in the nineteenth century (Sedgwick, 1827; Tate, 1870), which established it as the 'type', or original, 'sill' of geological science, it has been the focus of a voluminous research literature, comprehensive references to which are cited in major summaries by Dunham (1970), Dunham and Strasser-King (1982), Francis (1982), Dunham (1990), Randall (1995), Johnson and Dunham (2001), Stephenson *et al*. (2003) and Stone *et al*. (2010). Radiometric dates obtained from the Whin Sill intrusions range from 301 ± 6 Ma to 294 ± 2 Ma. (Fitch and Miller, 1964; Dunham *et al.*, 1968; Stephenson *et al*., 2003; Stone *et al*., 2010). The associated contact rocks have attracted much less attention, though descriptions of these include Hutchings (1895; 1898), Wager (1928), Robinson (1970; 1971) and Randall (1995): more recently Young (2017) has described a suite of magnetite-rich skarns within the sill's metamorphosed contact rocks in Upper Teesdale.

The Whin Sill comprises a suite of four separate, though closely related, sills and associated ENE–WSW trending dykes of Permo-Carboniferous age which underlie at least 4500 km^2 of northeast England. All consist predominantly of fine- to medium-grained dark grey quartz dolerite, associated locally with small bodies of coarse-grained dolerite pegmatite and rarer pink granophyric rocks. The sill complex is thickest, at up to around 90 m, beneath Weardale in the North Pennines, but thins progressively towards its northern, western and southern limits. All parts of the complex are emplaced in Carboniferous sedimentary rocks, which range in age from Viséan to Westphalian, within two major structural settings. North of the Stublick – Ninety Fathom Fault System, the outcrop of which mainly lies a few kilometres south of the course of Hadrian's Wall, the intrusions lie within rocks of the Northumberland–Solway Trough; south of this line they occur within rocks of the Alston Block (Fig. 1).

Within the Northumberland–Solway Trough the sill is commonly present as two or more leaves, in which large xenolithic rafts of metamorphosed Carboniferous country rocks are locally present. Belts of vesicles are common near the top of individual parts of the intrusions at numerous localities, including the area around Bamburgh and Lindisfarne where flattened vesicles with ropey flow structures (pahoehoe; see Fig. 5, p. 10) on their lower surfaces are locally conspicuous (Smythe, 1930; Stephenson *et al*., 2003; Stone *et al*., 2010).

South of the Stublick – Ninety Fathom Fault System, in the Alston Block, the sill occurs almost exclusively as a single leaf, attaining its maximum known thickness of around 90 m at Blackdene Mine in Weardale. At Copthill in Weardale the sill forms an isolated phacolithic body within the zone of structural complexity known as the Burtreeford Disturbance (Dunham, 1990; Johnson and Dunham, 2001). Only in a limited area between Rookhope and Stanhope in Weardale is a second leaf known. This, the Little Whin Sill, is up to 13 m thick, and lies approximately 120 m above the main body of the intrusion (Dunham *et al.*, 1965; Dunham and Kaye, 1965). In contrast to the area to the north of the Stublick Fault, xenolithic rafts are unknown save for a raft of metamorphosed mudstone and sandstone exposed in the banks of the River Tees at Bowlees in Teesdale [NY 9050 2778] and a slab of similar metamorphosed rocks formerly seen near Force Garth Quarry [NY 873 282], but subsequently removed by quarrying (Burgess *et al.*, 1979). Vesicles are generally extremely uncommon in the sill within the Alston Block.

Some of these differences, notably the distribution of vesicles, may be accounted for by the depth of cover rocks overlying the sill at the time of its emplacement: areas rich in vesicles may have been closer to the contemporaneous land surface than those areas in which they are absent.

MINERALISATION OF THE WHIN SILL

Wager (1929) described two phases of joint formation within the Whin Sill, an early phase during its final phases of crystallisation characterised by localised chloritisation, and a later phase in which a suite of hydrothermal minerals were deposited both as joint coatings and vesicle fillings. Numerous authors have made reference to these. Notable amongst these are Holmes and Harwood (1928), Tomkieff (1929) and Smythe (1924a; 1930) all of whom who referred to the common occurrence of pectolite, quartz and calcite in such settings. In addition, local occurrences of prehnite have been recorded by Wager (1929) and Young *et al.* (1991); datolite by Randall (1959); apophyllite and analcime by Randall (1959) and Young *et al.* (1991); stevensite by Randall (1959) and Young and Schofield (1990); and chabazite and stilbite by Young *et al.* (1991).

Most of these reports offer little more than brief references to the presence of the mineral or minerals, very few illustrations of any of them have published, and no comprehensive review of the suite of minerals found in

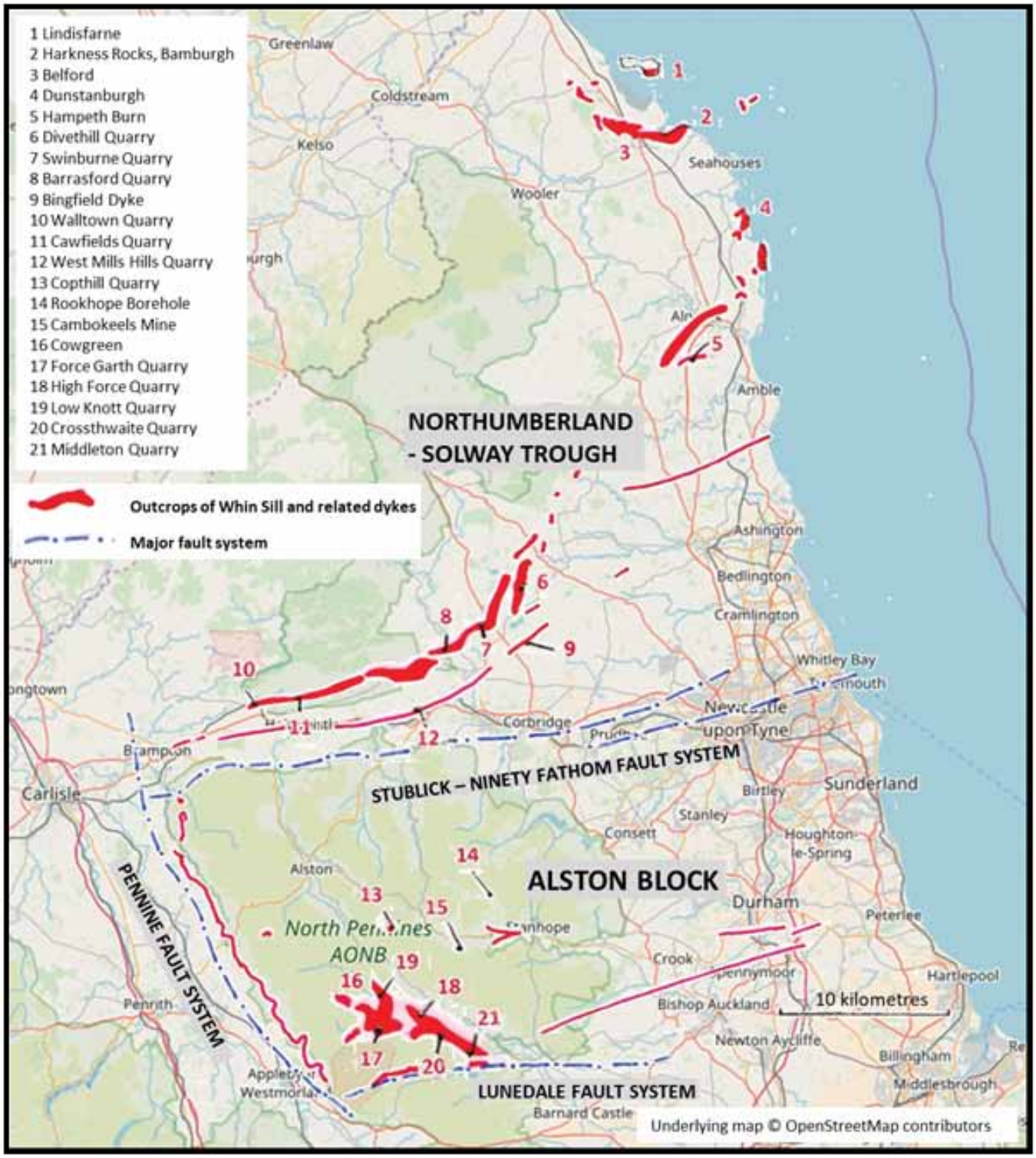

Figure 1. Outcrops of the Whin Sill and its related dykes showing the locations of minerals described in this paper.

these late stage veins has so far been compiled. Based on a review of the published literature, together with original and hitherto unpublished field observations, a review of the varied suite of minerals known within this paragenesis is presented.

Although the Whin Sill is cut by numerous mineralised veins within the Northern Pennine Orefield and parts of the Tyne Valley, where it formed an important wall-rock for several commercial fluorspar, barytes and witherite orebodies, the suite of minerals reviewed here is unrelated to the main North Pennine fluorite-baryte base-metal mineralisation.

MINERALS

ANALCIME, $NaAlSi_2O_6 \cdot H_2O$

The first published record of analcime from the Whin Sill is that of Young *et al.* (1991) who reported it from three locations.

Specimens of analcime, comprising crusts of colourless trapezohedral crystals on dolerite from the Whin Sill at Copthill Quarry, near Cowshill in Weardale [NY 8510 4085] are in the Russell Collection at the Natural History Museum, though the occurrence had not hitherto been published. This quarry is now flooded, its working faces are now inaccessible and the remaining spoil heaps almost completely vegetated.

At Cambokeels Mine, Weardale [NY 935 383] the Whin Sill lies beneath the Jew Limestone. At this location, Young *et al.* (1991) reported analcime coating surfaces of dolerite within a roughly 3 m thick horizontal belt of closely jointed dolerite about 25 m above the base of the sill exposed in the engine chamber at the head of the 320 level decline, and in the walls of the adjacent mine roadways. The mineral occurred here in some abundance as crusts up to 30 cm across composed of colourless trapezohedral crystals typically up to 2 mm across, though a few isolated crystals up to 6 mm across, were encountered (Fig. 2). In many specimens the analcime was accompanied, and locally overgrown by, small colourless prismatic crystals of apophyllite (see below) and in a few specimens was also accompanied by colourless rhombohedral crystals of calcite up to 2 mm across. Examination of thin sections of the dolerite adjacent to these veins showed no evidence of alteration except for a very thin (≤1 mm) film of an unidentified chlorite-group mineral immediately beneath the layers of analcime and apophyllite. Cambokeels Mine has since been abandoned and its underground workings are now flooded.

Young *et al.* (1991) also reported analcime from the long-abandoned High Force Quarry [NY 878 290] in Upper Teesdale. The richest examples were found as crusts up to 12 cm across composed of colourless trapezohedral crystals up to 1 mm across coating joint surfaces of dolerite pegmatite, in fallen blocks derived from the main face of the quarry (Fig. 3). In some examples the analcime was accompanied by a few small (≤2 mm) rhombohedral crystals of white to colourless chabazite. Exactly similar small colourless analcime crystals were also noted *in situ* in narrow stilbite-bearing veins in slightly chloritised dolerite pegmatite then exposed in the northern face of the quarry (see below). Since publication of these descriptions the faces of this quarry have become overgrown by shrubs making detailed observations difficult.

ANATASE, TiO_2

Wager (1929) made very brief reference to "… aggregates of anatase …" associated with chlorite in altered dolerite adjacent to early joints within the sill, although offered no further information on localities or descriptions of the mineral.

APOPHYLLITE GROUP

FLUORAPOPHYLLITE-(K), $KCa_4Si_8O_{20}(F,OH) \cdot 8H_2O$;
HYDROXYAPOPHYLLITE-(K), $KCa_4Si_8O_{20}(OH,F) \cdot 8H_2O$

As noted above, Randall (1959) made passing reference to the presence of apophyllite at Copt Hill Quarry, Cowshill, Weardale [NY 8510 4085], though without any descriptions

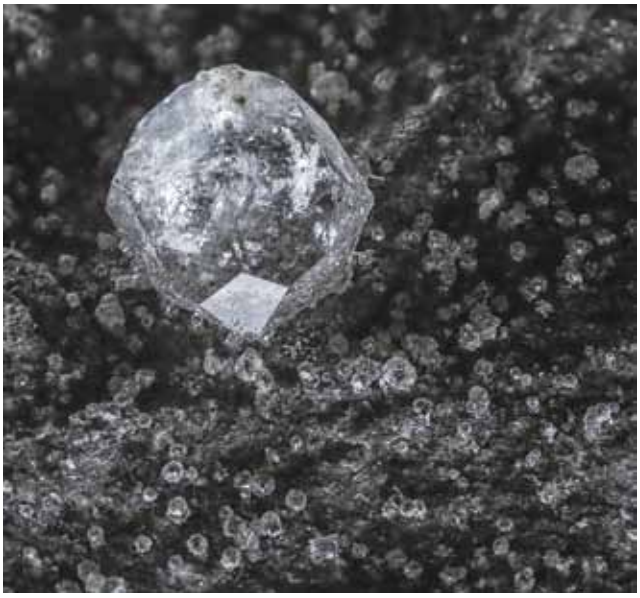

Figure 2. Isolated colourless trapezohedral crystal of analcime on dolerite from Cambokeels Mine, Weardale, Durham. Brian Young Specimen No. BY3711. Field of view approximately 1 cm. Photo Andy Hopkirk.

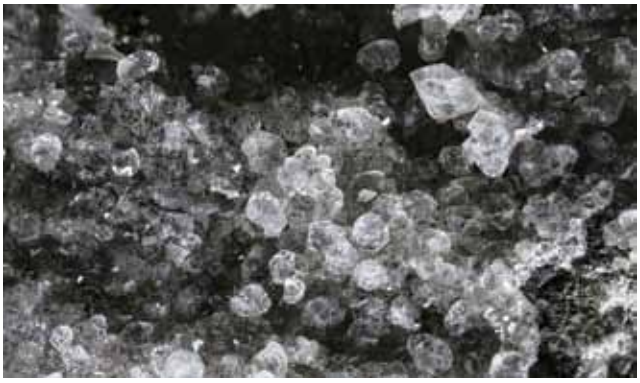

Figure 3. Crust of colourless analcime crystals on dolerite from High Force Quarry, Teesdale, Durham. Brian Young Specimen No. BY4787. Field of view approximately 1.6 cm. Photo Andy Hopkirk.

of the mineral's, appearance, associations or composition. Symes and Young (2008, p. 14) illustrated a specimen of apophyllite from here, accompanied by radiating fibrous pectolite, presented to the British Museum (now the Natural History Museum) in 1911 by the then operators of the quarry. In their 1991 paper Young *et al*. noted that specimens from this site typically exhibit lustrous colourless prismatic crystals up to about 5 mm long with well-marked pyramidal terminations.

At Cambokeels Mine, Weardale [NY 935 383], apophyllite was found in abundance in the 320 level engine chamber in the same area of closely jointed Whin Sill dolerite that yielded the abundant analcime specimens described above (Young *et al.*, 1991). The mineral here typically occurred as stout, colourless, clear to slightly turbid white prisms in which the most prominent forms are {100} and {001}, with the latter commonly displaying rather rough or uneven surfaces, modified by small pyramid {111} forms (Fig. 4). Whereas most of the apophyllite crystals were up to 4 mm long, a few crystals up to 7 mm were also found. The apophyllite is typically accompanied by analcime crystals, though the relationships of these minerals one to another is not clear. In a few specimens the apophyllite was seen to be overgrown by white silky fibrous pectolite. Young *et al.* (1991) noted the presence of a second belt of closely fractured dolerite up to around 2 m thick, approximately 10 m vertically below the engine chamber, in which exactly similar apophyllite was also abundant.

Thermogravimetric analyses of the apophyllite-group minerals from Copt Hill and Cambokeels reported by Young *et al.* (1991) revealed that the Copt Hill mineral is hydroxyapophyllite-(K) whereas that from Cambokeels Mine is fluorapophyllite-(K).

Pale brown crudely radiating subhedral prismatic crystals up to 1 cm long embedded in calcite, collected from a 2 cm wide calcite-quartz vein in dolerite at Low Knott Quarry, Forest in Teesdale [NY 8714 2916], were identified as a mineral of the apophyllite group (David Green, *personal communication*, 2006), though its precise composition was not determined.

Figure 4. Colourless prismatic crystals of fluorapophyllite on dolerite from Cambokeels Mine, Weardale, Durham. Brian Young Specimen No. BY3710. Field of view approximately 4 cm. Photo Andy Hopkirk.

BARYTE, $BaSO_4$

The presence of baryte in quartz-calcite veins in the Whin Sill at Barrasford Quarry was noted without description by Dunham and Walkden (1968). Stephenson *et al.* (2003) made brief reference to baryte, accompanied by a little pyrite, in thin veins within a belt of ENE-trending fractures within the Whin Sill approximately 100 m west of Harkess Rocks, near Bamburgh [NU 1755 3590], though no descriptions of these minerals were given.

CALCITE, $CaCO_3$

Calcite is a common, perhaps ubiquitous, constituent of joint and amygdale fillings within the Whin Sill, though at many locations it is usually present only in subordinate amounts. It is most commonly seen as coarsely crystalline white cleavage surfaces up to 4 mm across coating joint surfaces, and is especially conspicuous in most of the Northumberland quarries. Randall (1959) noted small amounts of calcite in association with both datolite and pectolite within vesicles at Barrasford Quarry, Northumberland [NY 916 748].

At Harkess Rocks, near Bamburgh [NU 1770 3585] white to pale cream coarsely crystalline calcite, together with a little quartz, fills flattened vesicles up to 30 cm across and up to 10 mm deep within the uppermost few metres of the intrusion. Weathering and leaching of the calcite has left these vesicles as open voids which are remarkable for the spectacular development of ropey or pahoehoe structures on their lower surface (Smythe, 1930; Stephenson *et al.*, 2003; Stone *et al.*, 2010) (Fig. 5). Similar vesicles, also close to the top contact of the intrusion, were described by Stephenson *et al.* (2003) from St Cuthbert's Isle, Lindisfarne [NU 123 416] where they also noted the presence of amethystine quartz.

A specimen in the Durham University mineral collection (Durham University Registration No. 7648), collected from Copt Hill Quarry, Weardale [NY 8510 4085] shows calcite pseudomorphing radiating fibrous pectolite. Within this specimen cleavage surfaces of pale cream calcite up to 3 cm across clearly exhibit residual traces of the radiating crystalline fabric of the original pectolite. The pseudomorphous masses are enclosed in coarsely

Figure 5. Pahoehoe surface on lower face of a vesicle from which the calcite filling has been leached. Harkess Rocks, Bamburgh, Northumberland. Photo Brian Young.

crystalline colourless calcite in which cleavage surfaces up to 10 mm across are conspicuous (Fig. 6).

CHABAZITE, $CaAl_2Si_4O_{12}\cdot 6H_2O$

Undifferentiated minerals of the chabazite series were first reported from the Whin Sill by Young *et al.* (1991) from three locations in the Northern Pennines.

In the 320 level engine chamber at Cambokeels Mine, Weardale [NY 935 383] white interpenetrant rhombohedra of chabazite up to 3 mm across were found as rare associates of analcime and apophyllite. A few specimens composed of crusts of colourless crystalline chabazite on dolerite, unaccompanied by any other mineral, were noted by Young *et al.* (1991) from the mine spoil heaps. Whereas the source of these specimens within the underground workings could not be determined, it seems probable that the 320 Engine Chamber was the source as, at the time of this investigation, no other occurrences of zeolite minerals were identified within the Whin Sill at any other exposures in the mine.

Young *et al.* (1991) also reported chabazite as crusts of ill-formed rhombohedra up to 0.5 mm on joint surfaces on blocks of unaltered dolerite at Force Garth Quarry, Teesdale [NY 873 282] and as crusts of similar crystals up to 0.75 mm across on a handful of specimens collected from the main face of High Force Quarry [NY 878 290].

CHALCOPYRITE, $CuFeS_2$

A few small patches (>1 mm across) of bright yellow metallic massive chalcopyrite have been found within masses of dark brown sphalerite within calcite veins at Barrasford Quarry, Northumberland [NY 916 748].

CHLORITE GROUP, $[(Mg,Fe)_5Al](AlSi_3)O_{10}(OH)_8$

In descriptions of chloritisation of dolerite adjacent to early joints within the sill, Wager (1929) suggested that at least some of the chlorite may be diabantite, an obsolete term for iron-rich clinochlore.

Very dark green chlorite was found as listric coatings on joint surfaces within the uppermost few metres of the sill at a depth of around 225 m in the Rookhope Borehole [NY 9374 4278] (Dunham *et al.*, 1965: Figure 8). However, as with other references to chlorite in such joint fillings, the precise identity of the chlorite-group mineral was not specified.

Flakes of dark green chlorite, or chloritised dolerite, are locally common within many of the pectolite veins present in upper Teesdale (see below).

Randall (1959) noted the presence of very small spots of an unidentified chlorite-group mineral within radiating crystalline masses of pectolite in vesicles in the Whin Sill at Barrasford Quarry, Northumberland [NY 916 748].

DATOLITE, $CaBSiO_4(OH)$

From the Whin Sill at Barrasford Quarry, Northumberland [NY 916 748], Randall (1959) recorded datolite both as a partial filling of pectolite- and stevensite-bearing vesicles, and as a constituent of small concentrations of pale pink pegmatitic dolerite beneath these vesicles where it comprised up to 3% of the pegmatite. No more detailed descriptions of the datolite were given.

Figure 6. Masses of pale buff calcite pseudomorphs after pectolite in which faint traces of original fibrous crystalline texture can be detected, enclosed in later white calcite. Copt Hill Quarry, Cowshill, Weardale, Durham. Durham University Specimen No. 7648. Field of view approximately 6 cm. Photo Andy Hopkirk.

A single specimen (NEWHM: 2004.H.2101)[1], collected by Randall in the 1950s, and preserved at the Great North Museum (Hancock) exhibits very pale cream to colourless anhedral crystals of glassy datolite up to about 5 mm across, forming the lining of a vesicle over 5 cm across (Fig. 7). The datolite overgrows a few colourless pyramidal quartz crystals and is overgrown by pale buff radiating clusters of crystalline pectolite up to 20 mm long.

No further specimens of datolite are known to have been encountered at Barrasford Quarry since Randall's record and the site remains the sole location at which this mineral has been identified within the Whin Sill.

Figure 7. Colourless glassy datolite lining a vesicle in dolerite, overgrown by pale buff radiating crystalline pectolite. Note the narrow pale pink feldspathic dolerite selvage immediately beneath the datolite crust. Barrasford Quarry, Hexham, Northumberland. Great North Museum (Hancock) Specimen NEWHM: 2004. H2101. Field of view approximately 3 cm. Photo Andy Hopkirk.

[1] Great North Museum accession number

GALENA, PbS

At Barrasford Quarry, Northumberland [NY 916 748], small anhedral masses of galena up to about 20 mm across, locally accompanied by similarly sized masses of dark brown sphalerite, have been encountered in quartz–calcite veins within the sill (Dunham and Walkden, 1968): small amounts of pyrite, pyrrhotite and traces of chalcopyrite have also been seen in these veins. Elsewhere in central Northumberland, Smythe (1923) suggested that small localised concentrations of galena within veins in Carboniferous rocks adjacent or very close to contacts of both the sill and its associated dykes at Grottington [NY 9645 8082], Great Bavington [NY 983 803], and ill-defined locations near Hartley, Shilbottle, Rothbury, Beadnell and Holy Island, may be genetically related to the sill's late-stage hydrothermal mineralisation.

At Divethill Quarry, Little Bavington, Northumberland [NY 978 789] euhedral cuboctahedral galena crystals up to 10 mm across were seen by one of us (BY) in 1994 in a narrow (>30 mm wide) vein of coarse-grained white calcite in the lowermost few metres of the sill.

Whereas the Whin Sill forms the host rock to numerous galena-bearing veins within the Northern Pennine Orefield, these may readily be differentiated from the veins described in this paper, as will be discussed below.

PECTOLITE, $NaCa_2Si_3O_8(OH)$

Pectolite has long been known as a conspicuous constituent of veins and joint fillings within the Whin Sill (e.g. Wager, 1929; Smythe, 1924a), particularly from its many exposures in Teesdale and at Copthill in Weardale.

In Teesdale, pectolite typically occurs as thin (>4 mm) coatings of white to pale buff mutually interfering aggregates of radiating crystals up to 100 mm across coating joint surfaces. Striking examples of this form were for many years a conspicuous feature of the abandoned High Force Quarry in Teesdale [NY 878 290] (Fig. 8) though the quarry faces are today much weathered and partially overgrown. Exactly similar joint coatings are present in most of the abandoned quarries in the Whin Sill in Teesdale and veins composed of radiating masses of white, pale buff to pale pink pectolite up to 70 mm wide are also known from several locations within the dale. The Whin Sill exposed in the bed of the River Tees between the foot of Cowgreen Dam and the head of the Cauldron Snout waterfall [NY 8140 2870] carries veins up to 35 mm wide composed of pectolite, locally with lenses of coarsely crystalline calcite, forming radiating crystalline bands parallel to the vein walls. Within central voids, up to 10 mm wide, the pectolite exhibits rounded surfaces composed of tiny terminated crystals (>0.5 mm long) (Fig. 9). Clusters of radiating white crystals up to 10 mm across were found coating joints in the Whin Sill exposed in the quarry opened a short distance upstream from Cowgreen Dam to extract dolerite aggregate for the dam's construction [NY 815 294] during the 1960s. The quarry is now submerged beneath the reservoir. Similar pectolite veins up to 70 mm across have long been known from Force Garth Quarry, upstream from High Force [NY 873 282] (Fig. 10) and discontinuous veins of white pectolite are also comparatively common in the abandoned quarries at Low Knott [NY 8714 2916], Crossthwaite [NY 925 255] and Middleton [NY 948 246]. Angular clasts of partially chloritised dolerite up to 30 mm long are present in most examples of these wide pectolite veins. Slickensided surfaces of pectolite seen at Low Knott Quarry, indicate post-mineralisation movement.

In Weardale, the isolated outcrop of Whin Sill formerly worked at Copthill Quarry [NY 8510 4085] yielded fine specimens of typical radiating joint coatings of white pectolite: Symes and Young (2008: pp 165–166) illustrate a good example. In addition, Randall (1995) noted the presence here of pectolite in vesicles up to 0.3 m in diameter near the top of the intrusion. Specimens from this location in the Durham University mineral collection include pectolite pseudomorphed by both calcite and quartz (Figs 6 and 19). The working faces and spoil heaps of this flooded quarry are now inaccessible.

Figure 8. Crust of radiating crystalline pectolite on dolerite from High Force Quarry, Teesdale, Durham. Brian Young Specimen No. BY233. Field of view approximately 5.5 cm. Photo Andy Hopkirk.

Figure 9. Radiating crystalline pectolite with freely grown rounded surfaces in cavity in centre of vein near the River Tees beneath Cow Green Dam, Teesdale. Brian Young Specimen No. BY4822. Field of view approximately 5 cm. Photo Andy Hopkirk.

Figure 10. Pale pinkish buff radiating crystalline pectolite with band of dark green chlorite from Force Garth Quarry in Teesdale, Durham. Brian Young Specimen No. BY232. Field of view approximately 6 cm. Photo Andy Hopkirk.

Although Young *et al.* (1991) did not include pectolite in their descriptions of zeolite-type minerals from the Whin Sill at Cambokeels Mine, Weardale [NY 935 383], it has been found here as thin pure white silky radiating crystalline coatings on dolerite from the same part of the workings that yielded analcime and apophyllite.

Pectolite has not been reported from the Little Whin Sill of Weardale.

Whereas Stephenson *et al.* (2003) suggested that pectolite is abundant within the Whin Sill exposed in the vicinity of Hadrian's Wall, this does not accord with the present authors' observations. Our experience of the sill in the extensive natural exposures and abandoned quarries in this area is that pectolite is rather uncommon here. However, thin (>2 mm) coatings of colourless to very pale grey radiating spherules of pectolite up to 10 mm across have been observed by one of us (BY) at Cawfields Quarry [NY 715 666] which we assume to be the site referred to (though without grid references) by Randall (1995) as Caw Burn, where he reported pectolite in large vesicles near the top of the sill. These are no longer visible here. Elsewhere in the Hadrian's Wall area joint coatings and veins typically consist of coarsely crystalline white calcite and quartz, with small amounts of pyrite and locally pyrrhotite.

Pectolite seems to have a very restricted and localised occurrence elsewhere in central and northern Northumberland. Its presence within vesicles at Barrasford Quarry [NY 916 748] was described by Randall (1959) who noted that much of it had been pseudomorphed by stevensite. One of Randall's specimens, now in the collections of the Great North Museum (Hancock), exhibits pale cream to white compact masses of radiating crystalline pectolite, partially pseudomorphed by stevensite, filling a flattened ovoid vesicle up to 5 cm across (Fig. 11). This specimen

Figure 11. Off white radiating crystalline pectolite lining a flattened ovoid vesicle in dolerite. The pectolite in the centre of the vesicle is much altered to stevensite. Note the layer of pale pink feldspathic dolerite pegmatite beneath the vesicle. Barrasford Quarry, Hexham, Northumberland. Great North Museum (Hancock) Specimen NEWHM: 2018.H67. Field of view approximately 6.5 cm. Photo Andy Hopkirk.

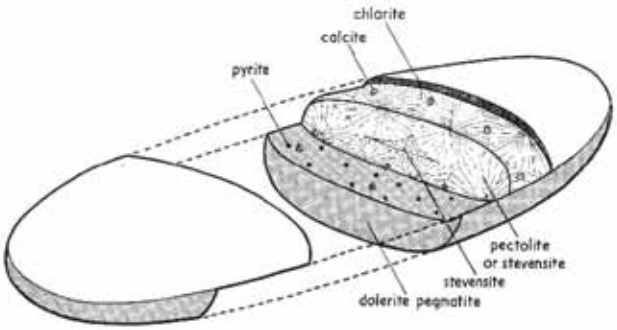

Figure 12. A diagram of the relationship between the pectolite and stevensite vesicle filling and the adjoining pegmatitic dolerite, based on the specimen illustrated as Figure 11; reproduced from Randall (1959) with permission from the Mineralogical Society of Great Britain & Ireland.

(NEWHM: 2018.H67) is plainly the specimen upon which Randall's diagram published in his 1959 report of stevensite is based (Fig. 12, see p.14).

The present authors are unaware of any finds of pectolite or stevensite at this location in recent years, though a single specimen of white radiating pectolite forming interfering spherules up to 6 mm across on a joint surface of dolerite was recovered from the nearby Swinburne Quarry [NY 949 767] in 2005 (Fig. 13). The only other pectolite occurrence in northern Northumberland, known to the writers, is from the east wall of a road cutting on the A1 road, east of Belford [NU 115 347]. The mineral was found here as pale pinkish buff radiating fibrous crystals up to 30 mm long orientated parallel with the walls of a >10 mm wide vein of coarsely crystalline white calcite.

Stevensite pseudomorphs after pectolite are described below from Barrasford [NY 916 748] (Fig. 11); Force Garth [NY 873 282]; High Force [NY 879 290] (Fig. 21); and Middleton [NY 948 246] quarries (Young and Schofield, 1990).

PREHNITE $Ca_2Al_2Si_3O_{10}(OH)_2$

The first published report of prehnite from the Whin Sill is that of Wager (1929: p. 323) who noted its presence, accompanied by calcite and quartz, filling a joint in the dolerite at Copthill Quarry, Cowshill, Weardale [NY 8510 4085], though the whereabouts of his specimens is unknown. Robinson (1973) subsequently recorded prehnite as a constituent of contact metamorphosed calcareous shales and impure limestones at unspecified locations in Teesdale. Young *et al.* (1991: p. 205) described prehnite from joint fillings in the sill at Force Garth Quarry, near High Force, Teesdale [NY 873 282] where it occurred as compact coarsely crystalline pale green lenses up to 5 mm wide and over 5 cm long in the centre of veins of pale pinkish-buff radiating pectolite (Fig. 14). Similar coloured radiating pectolite was also seen forming a band >0.5 mm wide within the centre of one such prehnite lens. Thin (>5 mm) layers of white compact crystalline prehnite coating pale buff radiating pectolite, were collected from the nearby abandoned High Force Quarry [NY 878 290] in 1987 (Neil Hubbard, *personal communication*, 1987).

PYRITE, FeS_2

Pyrite is commonly present in very small amounts, usually as scattered crystals, mainly >1 mm across, in many of the late-stage quartz-, calcite- and pectolite-bearing veins.

PYRRHOTITE, Fe_7S_8

Smythe (1924b) noted the occurrence of small plate-like crystals of pyrrhotite within joints in the Whin Sill at Snook Point, north of Dunstanburgh [NU 246 262].

Similar anhedral pyrrhotite crystals up to about 2 mm across have been seen by one of us (BY) associated with galena and sphalerite in quartz-calcite veins at Barrasford Quarry [NY 916 748] (see above), and unaccompanied by other minerals on joint faces of the sill at Walltown Quarry, near Greenhead [NY 670 660].

QUARTZ, SiO_2

Although quartz is a common mineral coating joints within the Whin Sill, it appears to be significantly more abundant north of Hadrian's Wall in central and northern Northumberland where it is locally the most abundant mineral in this setting. In this same area it is also abundant within vesicles which are locally common, particularly in the upper levels of the intrusion: vesicles are rare or absent from the main body of the sill within the North Pennines. In most of its occurrences quartz occurs as colourless or white translucent joint coatings or fillings, typically associated with coarsely crystalline white calcite and dark green chlorite. Quartz pseudomorphs after pectolite have been found at Copthill Quarry in Weardale (see below). The coloured varieties, amethyst, rose quartz and smoky quartz, are known from several locations, though descriptions of specimens of these, or of their occurrence, are few. The following notes highlight those known to the authors

Figure 13. Off white radiating crystalline pectolite on dolerite from Swinburne Quarry, Northumberland. Brian Young Specimen No. BY7823. Field of view approximately 4 cm. Photo Andy Hopkirk.

Figure 14. Very pale green crystalline prehnite associated with pale buff radiating crystalline pectolite in vein in dolerite from Force Garth Quarry, Teesdale. Durham. Brian Young Specimen No. BY5890. Field of view approximately 4 cm. Photo Andy Hopkirk.

Amethyst

Carruthers *et al.* (1930) noted that at Rumble Churn, near Dunstanburgh Castle [NU 258 221], vesicles in the sill close to its lower contact commonly contain amethystine quartz. Stephenson *et al.* (2003) commented on the presence of radiating crystals of quartz, including amethyst, within vesicles in the sill in the Dunstanburgh area of the Northumberland coast [NU 257 220] and also reported the presence of amethystine quartz in vesicles in the uppermost part of the intrusion at St Cuthbert's Isle, Lindisfarne [NU 130 416].

At Barrasford Quarry, Northumberland [NY 916 748] veins of coarsely crystalline white calcite up to 10 mm wide within the Whin Sill locally contain concentrations of very pale purple, turbid, amethyst. The amethyst typically occurs as roughly radiating elongated prismatic crystals up to 25 mm long and 5 mm wide, some of which have small pyramidal terminations, lying parallel to the vein walls (Fig. 15).

A small roadstone quarry at West Mill Hills, Haydon Bridge [NY 850 650] formerly worked dolerite from the Haydon Bridge Dyke, one of the wide dykes of the Whin Sill swarm of intrusions within the Tyne Valley. Veins and vesicles within the dyke yielded good specimens of bright pale purple amethyst (Smythe, 1927). Whereas much of this material known to the writers was massive or coarsely crystalline, rare examples of euhedral terminated pyramidal crystals up to 5 mm across were occasionally found (Figs 16 and 17). Coarsely crystalline white calcite, together with smaller amounts of dark green chlorite, were common associates of the amethystine quartz at this location. No contemporary descriptions of the quarry survive and nothing is known of the nature of the amethyst occurrences or of the abundance of the mineral here. The present authors never saw the exposures as the quarry was filled and the site restored to agriculture in the early 1980s. However, at a late stage in the restoration work one of us (BY) noted the rather common occurrence of amethyst fragments within the quarry spoil, it seems probable that the mineral may

Figure 15. Elongated crystals of very pale amethyst embedded in white calcite on joint surface of dolerite from Barrasford Quarry, Hexham, Northumberland. Brian Young Specimen No. BY5904. Field of view approximately 7.5 cm. Photo Andy Hopkirk.

Figure 17. Crystalline amethyst with white quartz and calcite in a vesicle in dolerite from West Mill Hills Quarry, Haydon Bridge, Northumberland. Brian Young Specimen No. BY3145. Field of view approximately 6 cm. Photo Andy Hopkirk.

Figure 16. Pale purple pyramidal crystals of amethyst from West Mill Hills Quarry, Haydon Bridge, Northumberland. Brian Young Specimen No. BY3146. Field of view approximately 5 cm. Photo Andy Hopkirk.

Figure 18. Very pale purple crystalline amethyst on dark brown altered dolerite from a now submerged locality at Cow Green Quarry, Teesdale, Durham. Brian Young Specimen No. BY234. Field of view approximately 4.5 cm. Photo Andy Hopkirk.

have been relatively common here. In view of the quality of the material seen at that time, it is perhaps surprising that so few specimens of this material are known in collections.

During the building of Cowgreen Dam, in Upper Teesdale in the 1960s, a substantial quarry was opened a short distance upstream from the dam site to extract Whin Sill dolerite for the construction project [NY 815 294]. The presence of typical examples of pectolite here has been noted above. In addition, a narrow quartz vein (>2 mm wide) within dark brown deeply weathered chloritised dolerite, yielded specimens of coarsely crystalline quartz of a pale, but distinctly purple, amethystine tint (Fig. 18). The quarry was submerged beneath the reservoir and has, to the authors' knowledge, only been re-exposed on one subsequent occasion during a period of exceptionally low water levels during the summer of 1995. The amethyst-bearing vein was not seen at that time.

Chalcedony

The presence of "… pockets of chalcedony …" within the Bingfield Dyke, was mentioned by Smythe (1927) though no descriptions of the mineral or details of locations were offered.

Quartz Pseudomorphs after Pectolite

Specimens in both the Durham University mineral collection (Durham University Registration No. 5061) and the collection of one of the authors (BY), collected from Copt Hill Quarry, Weardale [NY 8510 4085] show typical aggregates of white radiating pectolite crystals up to 20 mm across which exhibit partial or complete replacement by fine-grained white or colourless quartz in which residual traces of the radiating crystalline fabric of the original pectolite remain clearly visible (Fig. 19).

Rock Crystal and Smoky Quartz

Vesicles within the upper parts of the sill at Barrasford [NY 916 748] and Swinburne [NY 949 767] quarries, Northumberland, are commonly partially lined with pyramidal or occasionally bipyramidal crystals of clear quartz which varies from colourless to mid-brown (Fig. 20). The smoky brown tint is commonly concentrated near the extreme ends of the pyramidal terminations. White calcite is a common associated of quartz in these vesicles. Randall (1959) commented on the presence of amygdales partially filled with smoky quartz and calcite within layers of dolerite pegmatite at this location.

Colourless, water-clear quartz crystals found in veins and vesicles near the base of the Whin Sill in the neighbourhood of Dunstanburgh, Northumberland [NU 257 220] have long been known locally as Dunstanburgh Diamonds. Smythe (1927) recalls that, although "… so rarely found … the late vicar of Embleton [a nearby village], on letting his tithes, jokingly said that he reserved only to himself the tithe of the diamonds …".

Rose Quartz

Smythe (1927) made reference to the presence of quartz "… of a beautiful rose colour …" within the Hampeth Dyke, a member of the Whin Sill suite, at Hampeth Burn, southwest of Shilbottle, Northumberland, though offered no further descriptions of the mineral. No reference to this mineral is made by Carruthers *et al.* (1930) in their brief description of the small quarries [NU 170 074] formerly worked in this dyke and we have been unable to find specimens of this material.

SAPONITE, $(Ca,Na)_{0.3}(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2 \cdot 4H_2O$

Described as 'bowlingite', saponite was noted by Wager (1929) as one of the alteration products seen in dolerite adjacent to early joints in the sill, though without references to any locations.

Figure 19. Radiating crystalline pectolite pseudomorphed by quartz from Copt Hill Quarry, Cowshill, Weardale, Durham. Durham University Specimen No. 5061. Field of view approximately 10 cm. Photo Andy Hopkirk.

Figure 20. Pyramidal crystal of smoky quartz, with calcite, in a vesicle in dolerite from Barrasford Quarry, Hexham, Northumberland. Brian Young Specimen No. BY6792. Field of view approximately 3 cm. Photo Andy Hopkirk.

SPHALERITE, ZnS

Within the Whin Sill at Barrasford Quarry, Northumberland [NY 916 748] veins of coarsely crystalline white calcite up to 10 mm wide locally contain abundant scattered anhedral masses of very dark brown sphalerite up to 20 mm across. These are locally accompanied by similar sized patches of galena and more rarely with chalcopyrite and pyrrhotite (see above).

At Divethill Quarry, Little Bavington, Northumberland [NY 978 789] small concentrations of rather rounded subhedral crystals of very dark brown sphalerite up to >1 mm across were found in the narrow galena-bearing vein described above.

STEVENSITE, $(Ca,Na)_xMg_{3-y}Si_4O_{10}(OH)_2$

Stevensite was first recorded in Britain from the Whin Sill of Barrasford Quarry, Northumberland [NY 916 748] by Randall (1959) who described two forms of the mineral found within large vesicles, though of unspecified size, from the uppermost parts of the sill. Randall's 'Type I' stevensite comprised pseudomorphous masses after original pectolite in which the original radiating fibrous texture was clearly retained (Figs 11 and 12). This form of the mineral varied in colour from cream to green, brown and black, and exhibited an earthy lustre. 'Type II' stevensite was found as amorphous masses typically with a bluish-white colour and dull lustre. As far as the authors are aware, no specimens of either stevensite or pectolite have been found at this location for many years.

Young and Schofield (1990) subsequently described stevensite from the Whin Sill at High Force Quarry, Teesdale [NY 878 290] where it was found within the centre of quartz-calcite-chlorite joint fillings as waxy pale cream coloured masses up to 3 cm across, also with a clear residual radiating fibrous texture pseudomorphous after pectolite (Fig. 21). Similar specimens have since been collected from both the nearby Force Garth Quarry [NY 873 282] and the long-abandoned Middleton Quarry at Middleton-in-Teesdale [NY 948 246], though their identity as stevensite has not been confirmed[2].

In his discussion of the mineral from Barrasford Quarry, Randall (1959) noted that, as the X-ray powder pattern of the stevensite bore similarities to heat-treated pectolite, it was likely that the alteration of pectolite to stevensite had occurred before the sill had fully cooled. The paragenesis of the stevensite in its Teesdale occurrences is also consistent with its origin as an early hydrothermal alteration of primary pectolite.

STILBITE $(Ca_{0.5},K,Na)_9(Al_9Si_{27})O_{72}\cdot 28H_2O$

The sole record of a mineral of the stilbite series from the Whin Sill is that of Young *et al.* (1991: p. 205) who described colourless lustrous, tabular prismatic crystals, mostly >1 mm long, lining closely spaced open fissures up to 3 mm wide in chloritised dolerite pegmatite exposed in the north face of High Force Quarry, Teesdale [NY 878 290] (Fig. 22). The stilbite is locally accompanied by small (up to 1.5 mm) crystals of colourless analcime and chabazite. As noted above this part of the quarry is today much weathered and overgrown.

DISCUSSION

The suite of minerals discussed in this review are characteristic of a paragenesis long recognised by numerous authors (e.g. Holmes and Harwood, 1928; Tomkieff, 1929; Wager, 1929; Randall, 1959; Stephenson *et al.*, 2003) as having formed by hydrothermal activity during the final cooling stages of the Whin Sill and its related dykes in late Carboniferous – early Permian times. The common occurrence of pectolite, chlorite and a limited range of zeolite minerals within this assemblage serves to distinguish this mineralisation from the widespread metalliferous mineralisation of the Northern Pennine Orefield where, in the southern half of its outcrop, the Whin Sill formed the wall-rocks for several formerly commercial lead, fluorspar, barytes and witherite orebodies. The generally accepted Hercynian age for this latter mineralisation (Dunham, 1990) implies that it was emplaced very soon after the intrusion of the Whin Sill, and there is evidence for a local interaction between early North Pennine mineralising fluids and Whin Sill contact rocks whilst still at high temperatures (Young *et al.*, 1985; Searle *et al.*, 2016). However, the field relations of the North Pennine deposits and late-stage mineralisation of the Whin Sill are plainly the products of two separate mineralising events, though closely spaced in their time of emplacement. The presence of small amounts of chalcopyrite, galena and sphalerite within joint fillings of the Whin Sill in a few Northumberland locations distant from the North Pennines, is unlikely to be related to that mineralisation. Their occurrence within the Whin Sill here may reflect either small localised concentrations of these metals within the sill and its wall-rocks, or may be an expression of the widely scattered occurrences of these minerals across much of central and northern Northumberland which appear to be unrelated to any clearly defined mineralising event.

Figure 21. Pale buff stevensite pseudomorphing fibrous pectolite on dolerite from High Force Quarry, Teesdale, Durham. Brian Young Specimen No. BY3964. Field of view approximately 6 cm. Photo Andy Hopkirk.

[2] Stevensite is currently regarded as a questionable species by the International Mineralogical Association.

Figure 22. Colourless flat prismatic crystals of stilbite in joint filling in dolerite from High Force Quarry, Teesdale, Durham. Brian Young Specimen No. BY4526. Field of view approximately 1.5 cm. Photo Andy Hopkirk.

A feature of note, and perhaps genetic significance, within the Whin Sill mineralisation is the distribution of certain minerals. Quartz, calcite and chlorite appear to be virtually ubiquitous across the sill's outcrop, although they appear to be most abundant in central and northern Northumberland. However, pectolite, which is particularly abundant within the North Pennine outcrops, appears to be much less common and very restricted in its distribution north of the Stublick Fault Zone in central and northern Northumberland. Analcime, apophyllite, chabazite, and stilbite are known only from the Pennine outcrops in Weardale and Teesdale.

The localised occurrence of these minerals may reflect higher temperature late-stage hydrothermal activity in the thicker portions of the intrusion within the Alston Block where, in addition, a thicker cover of sedimentary country rocks resulted in comparatively slower cooling of the intrusions. In this context it may be significant that the pahoehoe structures, seen at Harkess Rocks and on Lindisfarne have been interpreted as evidence for emplacement of the intrusion here at shallow depths (Stephenson *et al.*, 2003) where cooling of the sill would almost certainly have been more rapid, effectively limiting the potential for the formation of zeolites and related minerals.

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MILLERITE FROM LINTON QUARRY, GORSLEY COMMON, HEREFORDSHIRE

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Millerite occurs in cavities surrounding fossil brachiopod shells in dolomitic Lower Siltstones of the Ludlow Series a few tens of centimetres above the Gorsley Limestone at Linton Quarry, Gorsley Common, Herefordshire. The occurrence was briefly noted in the late nineteenth century by William Symonds, but subsequently lost. No contemporary millerite specimens have survived in museum collections. Recent fieldwork has provided sufficient material to confirm the presence of millerite as acicular crystals up to 5 mm in length in dolomite-lined cavities surrounding fossil brachiopods, and in thin calcite-lined fractures. Some of the millerite crystals are coated or replaced by an amorphous nickel-green supergene phase with a composition which suggests it is a precursor to jamborite.

INTRODUCTION

Herefordshire is a county not generally noted for its mineralogical interest, but an unsubstantiated report of the nickel sulphide millerite, from long-disused limestone quarries near Gorsley Common, attracted the attention of one of us (RES) as part of the research for a book on the minerals of the English Midlands (Starkey, 2018).

The occurrence was first noted by the Rev. W. S. Symonds[1] (Symonds, 1872: p. 207):

> "A thin impure limestone, worked at Gorseley [*sic*] common, north of May Hill, is the representative of the Aymestry beds, and affords specimens of Pentamerus galeatus. The workmen call these fossils "*gold nuts*", as in some instances this shell, when broken, contained in the septa the needle-like spiculæ of sulphuret of nickel".

The stratigraphy and palaeontology of the rocks was reviewed by James Lawson (1954), who commented:

> "Many of the brachiopod shells have been partially or completely replaced by crystalline dolomite, and radiating aggregates of acicular pyrites [*sic*] are not uncommon in some of the cavities".

In a review of the mineralogy of the area around Newent in Gloucestershire, Bick (1986) cited Symonds (1872), but lamented that no millerite specimens were known. He remarked that Lawson (1954) had mentioned neither the brachiopod *Pentamerus galeatus* nor millerite in his description of the area, but does not appear to have considered the possibility that Lawson's 'acicular pyrites' may have been a misidentification of millerite.

In a summary of the minerals of Gloucestershire, which includes the localities around Gorsley Common in nearby Herefordshire, King (2008) noted: "An exhaustive search in museum collections has failed to locate any specimens". An appeal for information using the Geological Curators' Group JISC mailing list, as part of this research, generated no response. Enquiries at Worcester Museum, where the Symonds Collection is preserved, and an inspection of James Lawson's research collection at the Lapworth Museum (University of Birmingham), also failed to identify any material from 'Gorsley Quarry'.

SITE INVESTIGATION

An examination of early Ordnance Survey maps, and a reconnaissance of the area around the village of Gorsley Common, suggested Linton Quarry [SO 6774 2569] as a locality for field investigation. The quarry was abandoned in the early part of the twentieth century and the site is heavily overgrown. Most of the rock faces are obscured by moss and other vegetation (Fig. 1), however they are the most accessible and best documented exposures of the Silurian rocks of the Gorsley Inlier (Aldridge *et al*., 2000). As a result, Linton Quarry is notified as a Site of Special Scientific Interest (Natural England, 1990).

The nodular Gorsley Limestone, which forms the base of the succession at the quarry, has been variously regarded as the lateral equivalent of the Wenlock Limestone, or the younger Aymestrey Limestone (Gorstian Stage), of mid-Ludlow age (Upper Silurian). Opinion is still somewhat divided, but the consensus appears to be that it belongs to the Wenlock Series, and it is listed as such by the British Geological Survey in their lexicon of named rock units (British Geological Survey, 2018).

[1] William Samuel Symonds (1818–1887) was a clergyman with wide interests in natural history. He was born in Hereford, and educated in Cheltenham and at Christ's College, Cambridge. He married Hyacinth Kent in 1840, and was appointed Rector of the village of Pendock, in the southeastern corner of Worcestershire, in 1845. Symonds was a committed Darwinian and an active member of many local scientific societies (Oldroyd, 2004). His extensive contributions to geology are summarised by Woodward (1887), who notes that "He was never so happy as when conducting the members of his own Naturalists' Field-clubs over some classical region in "Siluria", with every spot of which he was familiar".

A succession of Ludlow deposits, which is very condensed in comparison with the nearby inliers at Woolhope and May Hill, overlies the Gorsley Limestone. This 6 m thick sequence includes the Lower and Upper Siltstones, the Přídolí Upper Phosphatic Pebble Bed and Clifford's Mesne Sandstone, and provides evidence that the area was a depositional high (the Gorsley Axis), or an area of active uplift, during Ludlow times. The presence of unconformities between the sedimentary units provides further support for this interpretation (Natural England, 1990).

A preliminary examination of the quarry faces and associated loose material was undertaken with the consent of Natural England and the landowner. A slab of compact, grey, calcareous rock, containing a number of small (*c*. 1 cm) brachiopod fossils, was removed for detailed examination. Inspection at low magnification under a stereomicroscope showed that the brachiopod shells were coated by minute, lustrous, colourless, euhedral dolomite crystals. The whole rock showed signs of dolomitisation, with small crystal-lined cavities surrounding many of the brachiopod fossils.

Tiny (sub-millimetre) acicular brassy metallic crystals were found in one cavity and tentatively identified as millerite. Other crystals with a dull lustre were overgrown by a distinctive pale nickel-green alteration product. Careful examination revealed further sulphide minerals: a minute metallic dark blue-grey galena cube, and tiny sphenoidal brassy chalcopyrite crystals, were found in cavities surrounding partly dolomitised brachiopods.

As a result of the success of the first visit, additional consent was sought, and arrangements made for further field investigation. Digging in the undergrowth and soil below the south face of the quarry yielded a number of pieces of rock containing fossil brachiopods, and these were collected for more detailed study. Further cavities containing microscopic brassy metallic needles, some coated by or completely altered to a nickel-green oxidation product (Fig. 2), were found.

A final visit to Linton Quarry was made in an attempt to identify the horizon from which the nickel-bearing material had come. A small amount of *in situ* material was carefully removed from the quarry face (in compliance with the consent documentation; Fig. 3), and a thin dolomite-lined fracture, containing needles of partly oxidised millerite up to 3 mm in length, was collected (Fig. 4).

The millerite-bearing horizon is in the Lower Siltstones of the Ludlow Series, approximately 40 cm above the unconformity with the underlying Gorsley Limestone. Although the millerite was found in a vertical fracture,

Figure 1. Linton Quarry SSSI, Gorsley Common, Herefordshire. Photo Roy Starkey.

Figure 2. A nickel-green phase, pseudomorphous after acicular millerite, with silvery-grey metallic galena from Linton Quarry. The crystal spray is 3 mm long. Roy Starkey Collection, Reg. No. RES 1722-055. Photo Roy Starkey.

Figure 3. Sampling position (arrowed) on the south face of Linton Quarry (the hammer is 30 cm long). Photo Roy Starkey.

Figure 4. Millerite collected *in situ* at Linton Quarry. The crystal spray is 2.5 mm long. Roy Starkey collection, Reg. No. RES 1722-054. Photo Roy Starkey.

Figure 5. A nickel-green phase, partially pseudomorphous after acicular millerite, within a dolomite-lined cavity collected *in situ* at Linton Quarry. Amgueddfa Cymru – National Museum Wales specimen no. NMW 2018.21G.M.1a. Photo Tom Cotterell.

fossil brachiopod shells associated with small dolomite-lined cavities, which are identical to those described in the foregoing text, are present at the base of the bed.

ANALYSIS

A highly altered millerite crystal with a nickel-green coating was selected for analysis by X-ray diffraction (XRD) at Amgueddfa Cymru – National Museum Wales (AC–NMW); specimen number NMW 2018.21G.M.1b (the other half of this specimen is shown in Fig. 5). The results produced an excellent match for millerite (NMW X-3595), with a small additional unmatched peak at a *d*-spacing of 3.141 Å. The high background intensity is characteristic of 'amorphous scatter', and almost certainly produced by the green alteration product, which is not sufficiently well crystallised to produce a diffraction pattern.

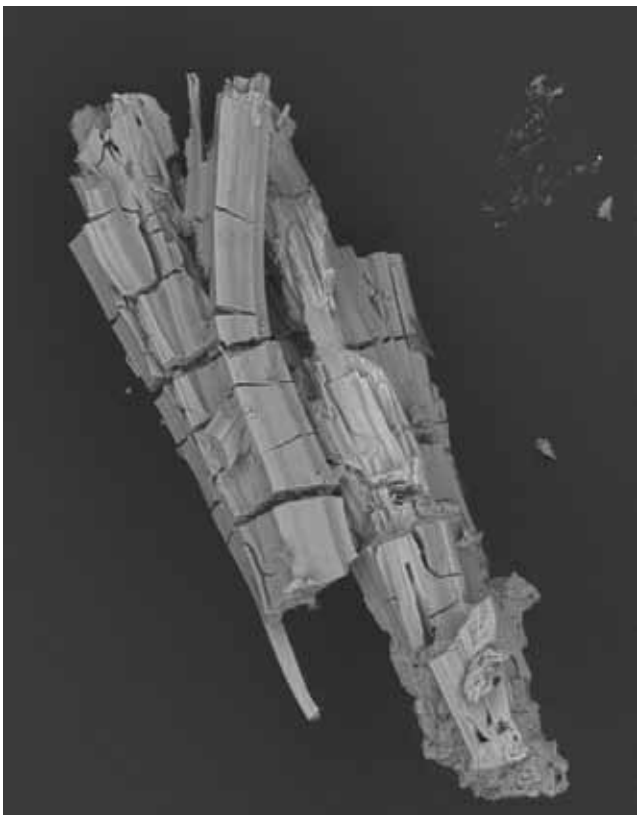

Figure 6. Scanning electron micrograph of a fragment of altered millerite taken from specimen NMW 2018.21G.M.1b. Note the fracturing, which is indicative of dehydration, of the material under vacuum within the SEM chamber. In this example the alteration product has completely replaced prismatic millerite.

The white rhombic crystals lining cavities and coating brachiopod shells have been identified by XRD as dolomite (NMW X-3599), confirming Lawson (1954).

Representative fragments of the nickel-green alteration product were examined by energy-dispersive spectrometry on a scanning electron microscope at Cardiff University. Eight analyses of three carbon-coated fragments (Fig. 6) revealed the presence of 32–57 wt% nickel. The sulphur content was 1.4–1.8 wt% and the cobalt content 2.4–5.9 wt%. Analyses of oxygen are particularly sensitive to specimens morphology (Newbury and Ritchie, 2013) and are not quoted. No iron was detected in any of the specimens.

DISCUSSION

After 146 years, William Symonds' record of millerite from Herefordshire has been established beyond reasonable doubt. It may be present in more of the geological units at Linton Quarry, but the Lower Siltstones of the Ludlow Series are the only horizon at which it was collected *in situ*. The fact that the millerite-bearing fossils acquired a local name, 'gold nuts', while the quarry was being worked, suggests that they were common and conspicuous. However, active operations ceased in the early twentieth century, and the exposures are now so weathered and obscured by vegetation, that it is hard to find any trace of mineralisation.

Surprisingly, no contemporary millerite specimens have been located in museums. A number of the specimens that were found in this research have been accessioned into the

mineral collection at AC–NMW (accession numbers NMW 2018.21G.M.1–4) and will provide a useful resource for future investigation.

The nickel-green alteration product on the millerite at Linton Quarry is X-ray amorphous. It has a high water content, and fractures due to dehydration when examined under vacuum in a scanning electron microscope (Fig. 6). Its composition (Table 1) is consistent with jamborite, which is the only mineral currently approved by the International Mineralogical Association that contains nickel, cobalt and sulphur, together with oxygen and hydrogen, and nothing else. The green material that commonly occurs as a recent supergene coating on millerite needles usually contains more iron than cobalt and is typically an amorphous precursor to honessite or hydrohonessite (Bindi *et al*., 2015).

Standardless analyses of three-dinensional specimens by SEM/EDS are at best semi-quantitative (Newbury and Ritchie, 2013). However, the presence of nickel, cobalt and sulphur in the correct proportions, and the absence of iron, suggests the nickel-green alteration product might be a precursor to jamborite. In a re-examination of jamborite from the type localities in Italy, Bindi *et al*. (2015) found that much of the nickel-green material replacing millerite was X-ray amorphous, and that analytical totals, even for crystalline material, could be low and variable.

Millerite is widespread but uncommon in Palaeozoic and Mesozoic sedimentary sequences. The occurrence in fossil shells is interesting. The only comparable British locality known to the authors is in Scotland. Millerite was reported in fossil shells in limestone at Dockra, near Beith, by Coutts (1878). Coutts' locality is near the modern workings of Trearne Quarry [NS 372 533], where millerite occurs with baryte, calcite, fluorite, pyrite and strontianite in fossil brachiopod shells in Lower Carboniferous limestone (Todd, 1989).

ACKNOWLEDGEMENTS

Thanks are due to Mary Berry of Natural England for granting permission for us to undertake the work, and to collect material from the Linton Quarry SSSI, and to Elizabeth Malcolm and Max Gough of Linton Parish Council for access to the site. Rosemary Roden is thanked for checking specimens in the Symonds Collection at Worcester Museum, and Jon Clatworthy for permitting access to James Lawson's research material in the Lapworth Museum (University of Birmingham). The reviewers, David Green and Neil Hubbard, are thanked for their comments on the manuscript.

Element	Linton Quarry	Ideal Formula
Ni	32–57	45.2
Co	2.4–5.9	5.0
O (and H)		47.0
S	1.4–1.8	2.7

Table 1. A comparison of the composition (wt%) of the unidentified green mineral from Linton Quarry, determined by energy-dispersive spectrometry at Cardiff University, with jamborite: $Ni^{2+}_{1-x}Co^{3+}_{x}(OH)_{2-x}(SO_4)_x \cdot nH_2O$, with $x = 0.1$ and $n = 0.9$.

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ANDRADITE AND MAGNETITE IN CONTACT-METAMORPHOSED CHALK NEAR PORTMUCK, ISLANDMAGEE, COUNTY ANTRIM

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Skarn mineralisation was first reported 70 years ago by the mineralogist G. P. L. Walker at several coastal localities near Portmuck on the Islandmagee peninsula in eastern County Antrim. Described here is mineralisation associated with a 4 m wide Palaeogene dolerite dyke intruded through Cretaceous chalk. Along the dyke margin is a decimetre-thick, dull-grey band of massive magnetite-calcite rock which, in thin section, has a clustered granular texture. In nearby marble, 2–3 mm diameter brown euhedral crystals of andradite garnet occur in close association with nodules of flint that have been metamorphosed to micro-crystalline quartz. Analyses by EDX indicate that the andradite is close to the ideal end-member, $Ca_3Fe_2(SiO_4)_3$, with minor substitution of Mg and Al. Flint is likely to be the source of silica for the crystallisation of andradite, whereas iron was probably introduced by hydrothermal fluids derived from the basaltic magma that formed the nearby sill-dyke complex.

INTRODUCTION

'Skarn' is a generic term for mineralisation formed by the metasomatic alteration of carbonate-rich rocks by the infiltration of hydrothermal fluids, or by diffusion of constituents from adjacent compositionally distinct rock bodies. Skarns are commonly formed by intrusion of magma into carbonate-rich sedimentary rocks, but can also be associated with regional metamorphism.

In the previous volume of this journal, Brian Young described hitherto unreported occurrences of magnetite mineralisation in contact metamorphosed sedimentary rocks adjoining the Whin Sill swarm in Teesdale in the northern Pennines (Young, 2017). He speculated that this mineralisation formed during sill intrusion in a process of 'iron metasomatism' involving the expulsion from the magma of iron-rich magmatic fluids which interacted with the country rocks. Young *et al*. (1985) had earlier described nickeline-magnetite mineralisation from former mines in the region, and attributed this to reactions between the mineralising brines and the still-hot contact metamorphosed rocks soon after sill emplacement.

The current article describes similar iron metasomatism associated with the intrusion of Palaeogene dolerite sills and dykes into Cretaceous chalk near Larne in County Antrim. Previous reports of magnetite occurrences in this area are summarised by Tindle (2008: p. 327) who refers to skarn mineralisation at Scawt Hill and Carneal, and to magnetite-bearing metasomatised basalt at various localities including Islandmagee and the nearby Isle of Muck (not to be confused with the Scottish island of the same name). Tindle (2008) also reports some occurrences of skarn andradite, including a xenolithic chalk block within the Central Ring Complex of Arran. He does not mention the Islandmagee localities, as hitherto the garnet has not been characterised to species level. This also applies to garnet from Scawt Hill, as noted by Tindle, who mentions that the garnet-like species at Carneal (in a similar geological context to Scawt Hill) is hibschite. Hibschite, which is commonly also described as 'hydrogrossular', is a variety of grossular garnet in which some of the silicate is replaced by hydroxide. Hydrogrossular (hibschite) is also reported by Young *et al*. (1985) from garnet-rich selvedges between magnetite- and calcite-rocks at Harwood Beck, Teesdale.

In the period from the end of the Second World War until the mid-1960s, the Ulster geologist George P. L. Walker published his mineralogical investigations of the Antrim basalts, dyke intrusions and associated zeolites. One of his first publications, in 1948, was a 'preliminary note' on the contact metamorphic rocks and minerals of the Portmuck area, near the northern end of the Islandmagee peninsula (Fig. 1). Walker mapped in detail the igneous features along this rocky coastline, including vents, composite lava flows and various dykes intruding the lava flows and the underlying chalk (currently designated the Ulster White Limestone). In the note, Walker describes skarn-like minerals developed in the contact metamorphosed margins of dykes. These minerals include andradite garnet, magnetite, ilmenite, apatite, 'soda diopside' and 'sphene' (now titanite). Walker's geological map of the coastal region is reproduced as Figure 2.

Walker provides a detailed account of a specific dolerite dyke intruded through chalk "about a quarter of a mile southeast of Portmuck harbour", a locality labelled on his map as 'Garnetiferous chalk'. His excellent description (Walker, 1948: p. 166) is repeated here:

> The northern margin of the dyke is vertical and very regular, and the chalk along some fifty feet of the exposed contact and for a distance of several inches from the margin of the dyke has been partially replaced by magnetite. The typical black rock that has been produced consists of approximately equal proportions of calcite and magnetite. Flint nodules occurring in this band are unaffected by this alteration. The remarkably sharp junction, simulating an intrusive junction, between the rock rich in magnetite and the altered chalk, free from magnetite is worthy of note. The black magnetite rock is easily distinguished from the brown weathered dolerite of the dyke. The southern margin of the dyke is extremely irregular, with numerous offshoots and enclosed masses of chalk. The chalk has been recrystallised to a coarse-grained calcite rock, calcite

grains up to three inches in diameter being observed. Locally the chalk contains chalcedony, garnet, magnetite and other minerals, in varying amount.

Pebbles and boulders of a variety of skarn rocks found on the bar (tombolo) are described including "Garnet-diopside rocks of various types" and "flinty rocks, usually packed with garnet, or sometimes rich in sulphides (pyrite and pyrrhotite)" (Walker, 1948: pp. 166 and 167). Walker also records abundant magnetite on joint planes in dolerite along the northern shore of the Isle of Muck, and large pink apatite crystals and well-formed ilmenite in veins in basalt adjacent to a dyke exposed at the southeast end of the island (Fig. 2). The author has not examined these occurrences due to the very considerable hazard of crossing the tombolo, which consists of rounded boulders coated in slippery seaweed and is only exposed at low tide, and because the Isle of Muck is a nature reserve and important bird nesting site with access requiring permission from the Ulster Wildlife Trust. Along the Islandmagree coast south from the tombolo is Two Mouthed Cave where zeolites (especially gmelinite-Na) are particularly well developed in vesicular basalt, however potential visitors are warned that access is challenging as this coastline is dangerously tidal.

LOCATION

The specimens described here are from Walker's 'Garnetiferous chalk' locality which is adjacent to a 4 m wide dolerite dyke on the mainland opposite the Isle of Muck. The dyke is exposed on the rocky shore in the intertidal zone at the southern margin of a storm beach just south of the tombolo which connects the Isle of Muck to the Islandmagee peninsula (Fig. 3). The locality is at Ulster Grid reference D 3463 4021. Access to the site is not easy and requires low tide; it involves following a hazardous path around the rocky shore from Portmuck harbour leading on to the storm beach. No attempt should be made to access the site by crossing fields from Portmuck car park (Fig. 2).

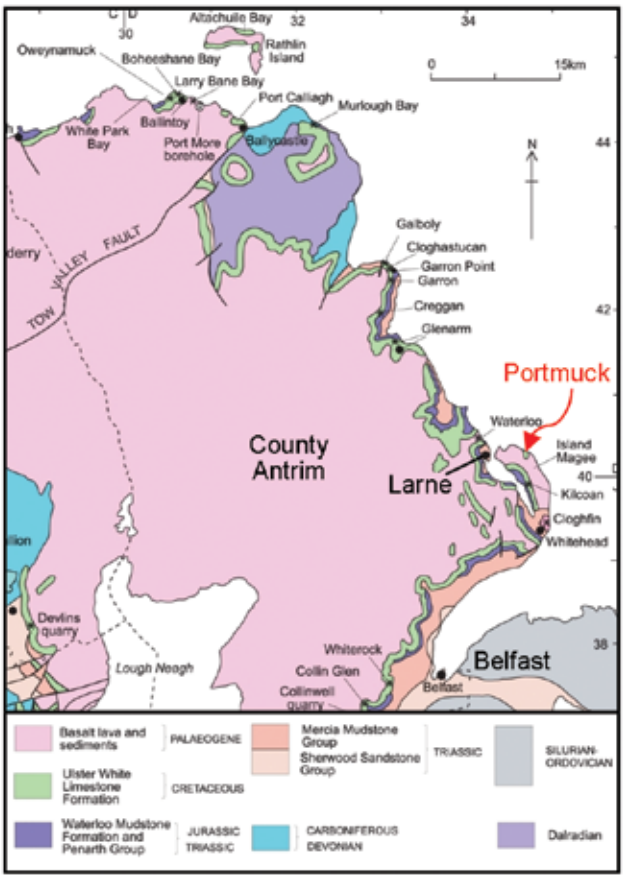

Figure 1. Simplified geological map of County Antrim, highlighting the outcrop of the Ulster White Limestone (from Mitchell, 2004), and indicating the location of Portmuck. Copyright of the Geological Survey of Northern Ireland, image reference number P947855, reproduced with permission.

SKARN MINERALISATION

Magnetite-Calcite Rock and Metamorphosed Flint

The magnetite-rich rock occurs principally at the contact between marble and dolerite, forming a distinctive grey band up to 30 cm wide (Fig. 4). The margins are sharply defined. The magnetite rock – marble contact runs

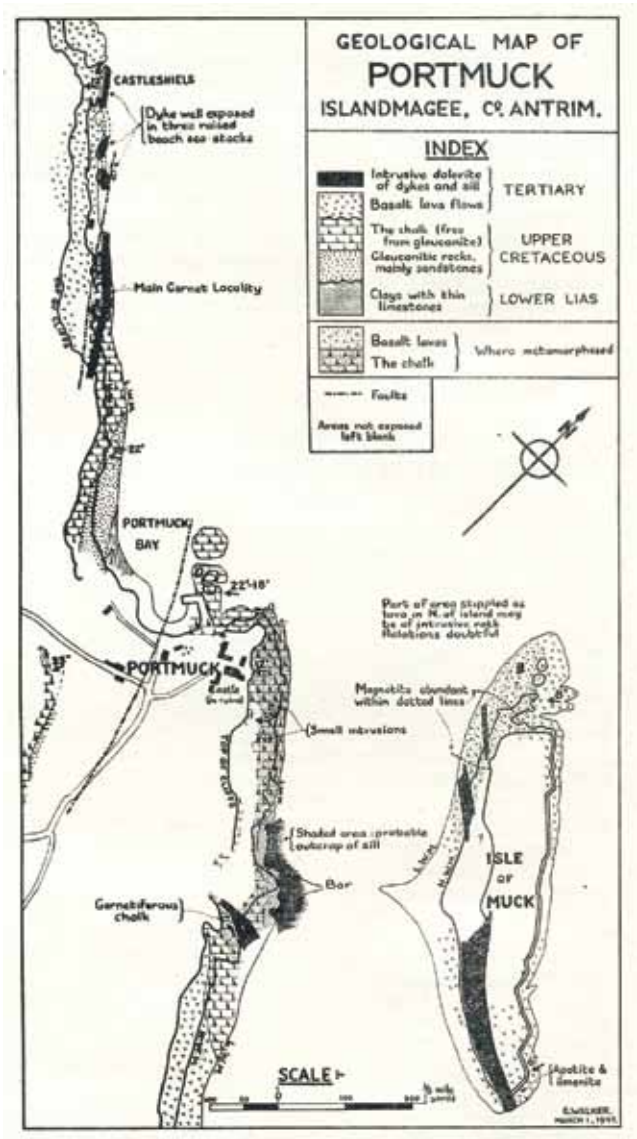

Figure 2. Walker's 1948 geological map of the Portmuck coastline and the Isle of Muck, reprinted with the permission of the Irish Naturalists' Journal Ltd. The locality described here, labelled 'Garnetiferous chalk', is southwest of the bar joining the Isle of Muck to the mainland (Islandmagee).

Figure 3. View northwards of the Islandmagee coastline opposite the Isle of Muck with the bar visible at top right. Rock exposures are of chalk (Ulster White Limestone) with the dark grey–brown dolerite dyke trending east–west in the centre of the view. Magnetite occurs along the northern margin of the dyke.

Figure 4. The northern margin of the dyke showing the dark grey, fine-grained magnetite rock in sharp contact with dolerite (top, south) and marble (bottom, north). Width of view approximately 0.8 m.

parallel to the edge of the dyke. Patches and stringers of magnetite-calcite rock also occur within the proximal marble. The contact between magnetite rock and dolerite is more irregular (Fig. 4). It is not clear whether this irregularity is due to disruption during mineralisation or to faulting post-dating dyke emplacement, or possibly both. In comparison to dolerite from the interior of the dyke, the marginal dolerite is fine-grained and paler in colour. The colour difference may be due to iron depletion, though this was not ascertained.

Hand specimens of the magnetite rock appear finely crystalline in comparison with the nearby marble. At the former Geology Department at Queen's University of Belfast, a thin section was cut from a sample showing the contact between magnetite rock and a metamorphosed flint nodule within the marble. Examination using a polarising microscope (Fig. 5) reveals that the magnetite forms clusters of small crystals that are embedded in a matrix of relatively coarsely crystalline calcite. The clusters are 0.2–0.4 mm in diameter, and consist of individual crystals that are about one tenth of this size. The adjoining metamorphosed flint consists of micro-crystalline quartz that is criss-crossed with numerous veinlets of calcite resulting in a brecciated texture (Fig. 5). Some tiny crystals of magnetite occur within the calcite veinlets.

Garnetiferous Marble

Garnet occurs occasionally within the magnetite-calcite rock, and more prominently surrounding some metamorphosed flint nodules within recrystallised limestone near the dyke. Boulders and pebbles can be found nearby, similar to those described by Walker, of flint nodules encased in magnetite-calcite rock which have a rim of garnet crystals surrounding the metamorphosed nodule (Fig. 6). The garnets are transparent honey-brown (yellow-brown if shattered) and occur as crystals which are typically a combination of trapezohedral and dodecahedral forms (Figs 7–9), usually 1–3 mm across and occasionally up to

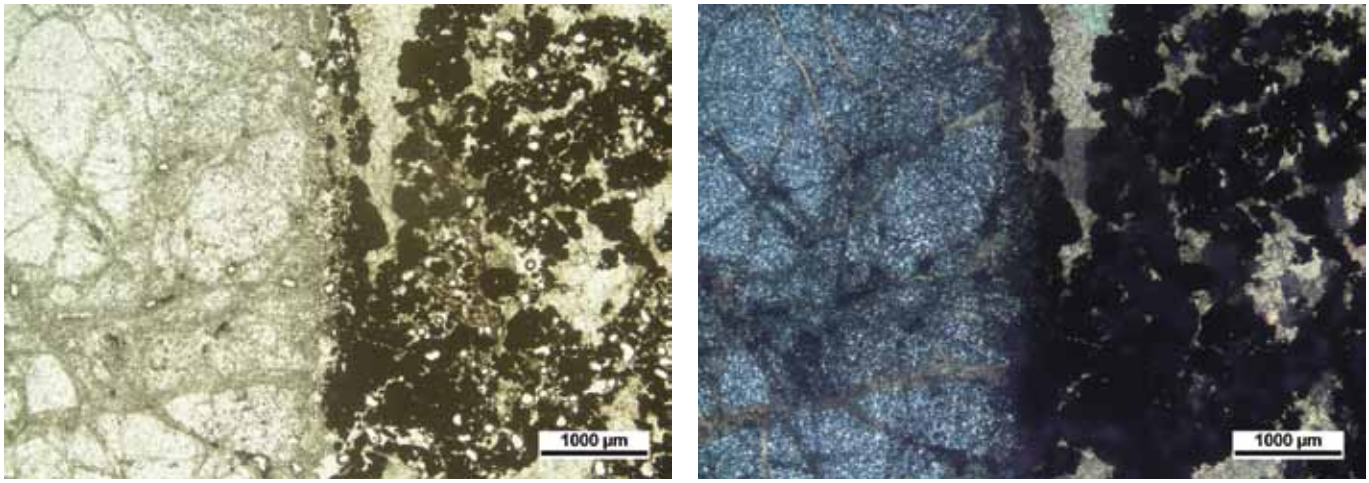

Figure 5. Transmitted light images (left: plane polarised light; right: between crossed polars) of the contact between calcite-veined chalcedony (left) and magnetite rock. Scalebar width 1 mm.

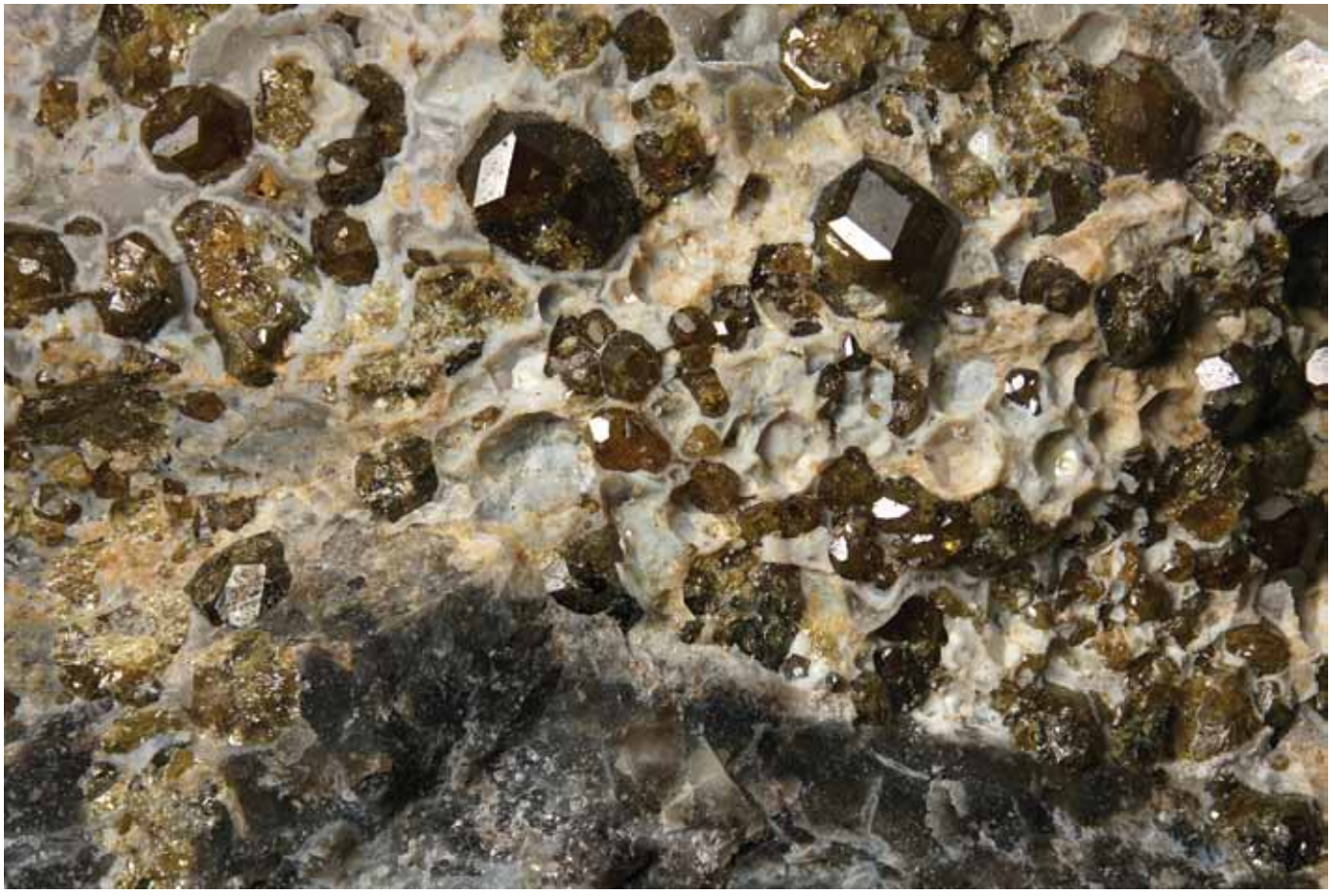

Figure 6. Abundant euhedral brown andradite in recrystallised limestone showing the contact with an altered flint nodule in the lower part of the image. Concentric rims are visible around the crystals at top left. Field width 16.2 mm. Photo John Chapman.

5 mm. If enclosed in marble the associated calcite has a similar crystal size, and can show concentric zonation in transparency similar in appearance to 'fortification' banding in agate (Fig. 6). The flint has been baked to form pale grey and cream-coloured micro-crystalline quartz similar to that described above. The association of garnet with flint nodules, but rarely elsewhere within the marble, suggests that the garnet crystallised only where silica was available during formation of the skarn.

Ten garnet crystals from one sample were glued to an 8 mm diameter plate to obtain semi-quantitative energy-dispersive X-ray analyses using an EVO-SEM in the School of Pharmacy and Biomolecular Sciences, University of Brighton. The analyses confirm that they are rich in calcium and iron with traces of aluminium and magnesium. This indicates compositions close to the andradite end-member, $Ca_3Fe^{3+}_2(SiO_4)_3$, with minor solid solution with grossular and pyrope, respectively. Trace amounts of

Figure 7. Euhedral brown andradite up to 2.5 mm across in recrystallised limestone. Photo John Chapman.

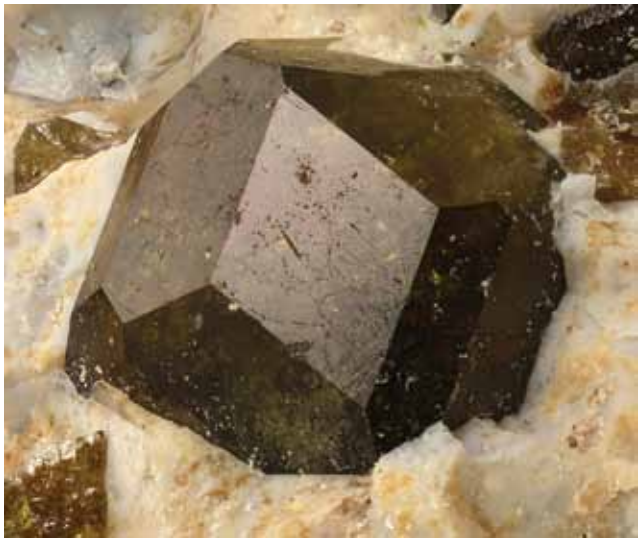

Figure 8. Dark brown andradite, 2 mm across, showing about equal development of two prominent crystal forms. Four-sided diamond-shaped faces of the dodecahedron {110} alternate with six (or seven) sided faces of the trapezohedron {211}. Photo John Chapman.

manganese were detected in some analyses, but no titanium (which occurs in melanite, a Ti-rich variety of andradite). Conversion of the analysed weight% oxide proportions to formula units (mole fractions) based on 12 oxygen atoms shows deficiencies in Ca+Mg of 0.42–0.56 formula units, and excesses in Fe+Al of 0.18–0.31 units and in Si of 0.29–0.39 units, in comparison to the ideal formula $(Ca,Mg)_3(Fe^{3+},Al)_2(SiO_4)_3$. These discrepancies are most probably systematic analytical errors due to non-ideal geometry during analysis [faces not exactly perpendicular to the incident X-ray beam, and other geometric and surface factors (Newbury and Ritchie, 2013)]. They might also possibly be due to cation-site vacancies or the presence of hydroxyl molecules within the andradite similar to the relationship between grossular and 'hydrogrossular' (hibschite).

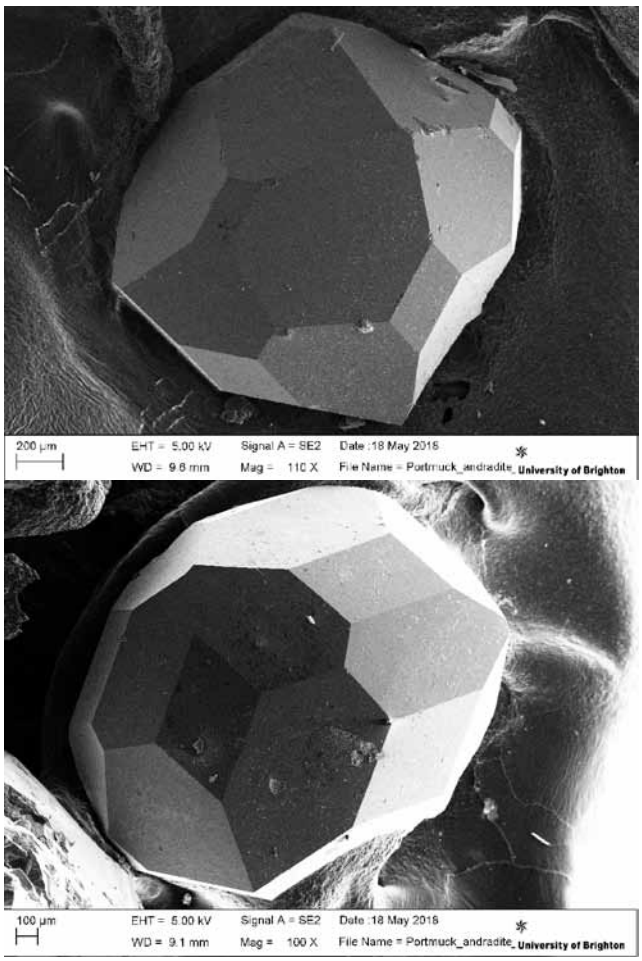

Figure 9. Scanning electron microscope images of two andradite crystals showing typical crystal habits. The prominent six-sided faces, best shown in the upper image, belong to the trapezohedron {211}; they are modified by four-sided diamond-shaped faces of the dodecahedron {110}, which are prominent in the lower image.

Analyses by XRD of three samples confirm the identification of andradite, magnetite and the associated minerals calcite and quartz. Wollastonite and diopside were sought but not detected in the small number of samples examined.

DISCUSSION

The extensive outcrop of metamorphosed chalk along the coastal section southeast of Portmuck, as noted by Walker (1948) and indicated by the shaded brick symbol on his map (Fig. 2), and of metamorphosed basalt on the Isle of Muck, suggests the presence of one or more concealed dolerite sills in addition to the exposed dykes. At the 'Garnetiferous chalk' dolerite dyke locality, the magnetite-rich selvedge suggests a prolonged metasomatic process rather than a 'flash' injection of magma into a fissure. Both features support the idea that the sill-dyke complex may have been a magma reservoir feeding overlying lava flows that have since been removed by erosion.

The presence of the assemblage andradite+quartz+calcite+magnetite, and absence (at least within the samples studied) of wollastonite and other calc-silicate

minerals, places some constraints on the physico-chemical conditions during skarn formation. The reaction of calcite and quartz to form wollastonite requires temperatures of more than 535°C, and low partial pressures of CO_2 (expressed as pCO_2); larnite formation requires even higher temperatures, some researchers have suggested in the order of ~750°C, and/or extremely low pCO_2 (Bowman, 1998). The generation of such low pCO_2 in carbonate-rich rocks requires the infiltration of large amounts of water-rich fluids to dilute the CO_2 generated by the breakdown of calcite and formation of calc-silicate minerals. Bowman (1998) explains that andradite is stable over a wider range of pCO_2 than grossular, shifting the wollastonite-forming reaction to higher temperatures. Andradite is also stable over a wider range of oxidation states (represented by the oxygen fugacity, fO_2). Unless the fO_2 is extremely low, wollastonite formation requires temperatures considerably in excess of 500°C. The assemblage andradite+quartz+magnetite is restricted to relatively oxidising environments, whereas lower fO_2 (and higher temperature) is needed to stabilise pyroxene-bearing skarn assemblages (diopside, hedenbergite). At high pressures (50 MPa), the coexistence of andradite with quartz+calcite+magnetite constrains log fO_2 values to >–25 at temperatures around 400°C (Gustafson, 1974). However the sub-volcanic system envisaged at Portmuck would involve lower pressures and probably a hydrostatic regime.

Development of the magnetite and skarn mineralisation was probably promoted by an abundance of watery fluid available in the chalk aquifer. Intrusions of basaltic magma supplied the heat for the hydrothermal system as well as for contact metamorphism. The hydrothermal fluids circulated through the chilled margins of the dykes (and probably sills) causing metasomatic alteration and extracting iron into solution. This iron then precipitated as magnetite under oxidising conditions at the dyke margin, and iron-rich watery fluids interacted with silica in flint nodules to form andradite. The marginal dyke rock and adjoining marble and altered flints were fragmented and veined, a process that can be attributed to hydraulic brecciation as the superheated watery fluid boiled in the low pressure regime. Porosity reduction and compaction as chalk was converted to marble may have helped to generate space for further injections of magma.

Walker's reports of 'soda diopside' and of pyrite and pyrrhotite in skarn rocks found in pebbles and boulders in the nearby tombolo, indicate that more reducing conditions prevailed elsewhere in the hydrothermal system. Reducing conditions were probably associated with basaltic magma intrusions into the Jurassic Waterloo Mudstone Formation that underlies the Ulster White Limestone. The mudstones are typically rich in organic matter and iron sulphides.

Further studies of the mineralogy and mineral chemistry of skarn mineralisation in the Portmuck area are warranted, particularly to ascertain if hibschite or similar hydrated garnets are present. Also of interest in the vicinity are the contact metamorphosed basalts which have not been considered here. The author hopes that this short article may inspire others to undertake considerate sampling and more detailed analysis, and to report findings in a subsequent publication: preferably less than 70 years hence.

ACKNOWLEDGEMENTS

Many thanks to Bryan Burke and Neil McVeigh for taking the locality photographs, and to John Chapman for the garnet photos. Thanks to Jon Salvage and Mike Helias at the Image Analysis Unit, the School of Pharmacy and Biomolecular Sciences at the University of Brighton, for assistance with SEM imaging and EDX analyses. Thanks to Nigel Monaghan for providing a copy of Walker's 1948 article and to the trustees of the *Irish Naturalists' Journal* for permission to reproduce Walker's geological map of Portmuck.

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MINERALISATION IN THE COAL MEASURES OF YORKSHIRE AND ADJOINING AREAS

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In memory of Steve Uttley (1957–2016)

Despite a long history of geological research, little has been recorded of the mineralisation found in faults and fractures in the rocks of the Yorkshire Coal Measures. The descriptions herein are based on information collated by the late Steve Uttley (1957–2016), who worked as a coal-mine geologist in south Yorkshire in the 1980s. Two distinct assemblages are widespread and common. Dolomite and chalcopyrite, with rare baryte, occur in the Lower and Middle Coal Measures at many collieries in south Yorkshire. A number of specimens show that the dolomite-chalcopyrite veins are separated by a period of faulting and gentle brecciation from later calcite with minor pyrite. The calcite-pyrite vein assemblage is widespread throughout the Coal Measures. The mineralogical differences between the two assemblages are interpreted in terms of a temporal gap, during which the composition of basinal fluids changed.

In addition to the widespread fracture mineralisation, other more localised assemblages have been identified. Massive hematite with minor quartz, associated with the South Don Fault at Denaby Colliery, probably represents deep penetration of oxidising fluids migrating from the reddened rocks at the Carboniferous–Permian unconformity. Peloidal kaolinite ironstone with sphalerite from Smithy Wood Opencast is likely to be an ancient lake-bed deposit. Recent supergene and post-mining minerals include halite, which was commonly reported from brine seepages in coal mines; aragonite and rhodochrosite, which have been identified in flowstone crusts; and gypsum, jarosite and melanterite, which crystallise in the acid solutions produced by the oxidation of iron sulphides. A catalogue of coalfield minerals, including the early authigenic phases, coal cleat minerals, and the species found in syneresis cracks in clay-ironstone nodules, is provided.

INTRODUCTION

Remarkable mineral specimens have been collected at a number of Coal Measures localities in the British Isles. The collieries of south Wales are famous for some of the world's finest millerite (Bevins, 1994). Exceptional witherite specimens were found in Pennine-type veins in the Durham Coalfield (Symes and Young, 2008). A variety of species are known from coalfield localities in the Midlands (Burch, 1998; Starkey, 2018) and northern England (Anderson and Smythe, 1942; Dearman and Jones, 1967; Young and Nancarrow, 1988; Dunham, 1990). The South Yorkshire Coalfield is, however, surprisingly blank on the mineralogical map. There was no tradition of mineral collecting among the miners, and specimens of any sort are exceedingly rare. The only notable discovery known to the authors was at Manvers Main Colliery, Wath-upon-Dearne, where a large cavity containing euhedral baryte crystals was found. It is described in a short note by Cornelius Finn (1930) and in more detail by Arthur Russell (1934). The scarcity of specimens from an area that produced much of Britain's coal gives a scientific and cultural importance to the few that survive.

This account is based on the observations recorded in Uttley (1993), and on specimens from collieries in south Yorkshire and Nottinghamshire in the collection of the late Steve Uttley. The Uttley Collection contained twenty specimens, representing 11 species from 14 different localities in the coalfield, when it came into the authors' care in 2016. Documentation and field notes, referring to specimens that were no longer present, were also found. These data are supplemented by information obtained from borehole logs (British Geological Survey, 2017); by a search of the literature on the history of coal mining and the geology of the Coal Measures; and by a survey of specimens in collections.

A coalfield is an area in which coal mining is, or was, economic. There is no generally agreed definition; some authors divide the coal-rich areas of Britain into dozens of small coalfields, whereas others aggregate them into a few larger ones. The 'South Yorkshire Coalfield' is used herein to maintain consistency with Uttley (1993). It reflects boundaries used by the National Coal Board (NCB) and is a purely administrative construct used to delineate the economic Coal Measures that lie beneath the pre-1974 county of Yorkshire. The East Pennine Coalfield, which commonly features in recent studies, is a more geologically defensible unit and a few localities in the East Pennine Coalfield, in Nottinghamshire and Derbyshire, are included in this account. The topography of the area, major settlements, roads, rivers and current county boundaries are shown in Figure 1.

BIOGRAPHY

Stephen Uttley (1 June 1957 – 6 March 2016), known to friends and family as Steve, was born in Mexborough, South Yorkshire. He became interested in geology and mining during family holidays to Cornwall, and on day trips to the Derbyshire dales. After leaving school, at the age of 16, he trained as a draughtsman at the National Coal Board (NCB) offices in Wath-upon-Dearne.

Steve joined the NCB's geological team in 1979, a privileged position which allowed underground access to local coal mines. He developed good relationships with other team members and the staff at some of the pits and would often ask if any interesting mineralisation had been encountered. He recorded he minerals that were found, and occasionally acquired specimens for his personal collection.

An enthusiastic mineral collector and long-time member of his local mineral society, the Doncaster Mines Research Group (DMRG), Steve used his draughting skills to produce the society's location maps and mine plans, and contributed articles to its journal (Uttley, 1983; 1985a; Moore and Uttley, 1984). His first article describes the minerals of south Yorkshire (Uttley, 1983). He organized field trips to the Lake District (Fig. 2), the northern Pennines and the Peak District where he forged good relationships with the tributers and quarry operators around Castleton and Matlock (Moore and Uttley, 1984; Anon., 1985, McCallum, 1985). As a founder member of the team that produced the *UK Journal of Mines & Minerals*, Steve used his skills to generate the sketches, plans and crystal drawings required by authors; he contributed articles to many of the early issues (Uttley, 1985b; 1986; 1987; 1988b; 1989), some of which describe minerals from the collieries of south Yorkshire.

The contraction of the coal mining industry in the late 1980s resulted in redundancy in 1990. By this time the NCB had been replaced by British Coal and the industry was being readied for privatisation. Steve set up in business as a graphic designer (using the name 'Untouchable Graphics') and later worked as Media Manager for Doncaster Rovers Football Club. Despite a busy work schedule, which restricted his contributions to mineralogy, he found the time to revise a guide to the minerals of the South Yorkshire Coalfield, which he had begun as a member of the geological team at British Coal (Uttley, 1988a). The extended manuscript, *Coalfield Minerals of South Yorkshire*, provides a unique description of the fault and fracture minerals of the area (Fig. 3); it was privately printed in 1993.

In the fourteen years that he worked at Doncaster Rovers, Steve collaborated on a number of popular accounts of the club and its history (e.g. Bluff and Uttley, 2009; Uttley, 2010). His dedication and enthusiasm earned him the affectionate title 'Mr Doncaster Rovers'. He travelled, camera in hand, to exotic destinations (Fig. 4) and became well known for the quality of his photographic work. He decided to go freelance in 2014, working with local newspapers and Mansfield Town Football Club. He also ran a wedding and event photography business and, returning to his coal-mining roots, had started working with the Pleasley Pit Trust, assisting with their public relations.

Steve died unexpectedly in March 2016, leaving two daughters, Lisa and Suzanne, and a son, Alan. He is survived by his sister, Ann, and partner, Carol Smith.

THE UTTLEY COLLECTION

In the summer of 2016, some months after his death, family members uncovered Steve's mineral collection. The cardboard flats, which had been kept in an outbuilding, were in poor condition, but the specimens were relatively undamaged. They were transferred into new flats and the family agreed to a period in which research could be undertaken before the collection was dispersed.

Most of the specimens were accompanied by handwritten labels (Figs 5 and 6) and some had catalogue numbers written in black ink on a white paint spot on an inconspicuous area of matrix. Unfortunately, the catalogue could not be located, and the accession numbers, which were written on most of the labels, were present on fewer than half of the specimens. They were absent from all but one of the pieces from the South Yorkshire Coalfield. In total, about 250 specimens were found, less than half of the original number (the highest catalogue number noted was 643). Notable material included a fine suite of specimens from Taffs Well Quarry near Cardiff, a collection of lead minerals from Whitwell Quarry in Derbyshire, and two flats of specimens from the coal mines of south Yorkshire and Nottinghamshire. This last collection was acquired by two of the authors (PJB and DIG) in 2017, and forms the basis of this article. More than half of the specimens are from localities from which there is no published record of fracture mineralisation. Indeed, almost all of the references to fracture mineralisation in the South Yorkshire Coalfield cited in Tindle (2008), the most comprehensive review of the minerals of the British Isles, refer to articles by Steve Uttley.

The coalfield specimens were in generally good condition, with little decay or damage. The principal concern for the security of the collection was the potential for labels to become separated from specimens. If this happened it would not be possible to provenance them, and their value would be lost. In almost all cases, the only link

Figure 1. Sketch map of south Yorkshire and adjoining areas of Nottinghamshire and Derbyshire, showing the topography, principal roads, major rivers, cities, towns and a few of the smaller settlements described in the text. Drawn by Peter Briscoe.

between specimens and labels was their presence in the same card tray; only one specimen had a catalogue number which could be associated with a label. For added security, small typed labels with catalogue numbers and locality details were glued onto each specimen. The specimens were brushed to remove dirt and dust and the old boxes replaced.

Although the collection catalogue could not be located, a considerable amount of information relating to the specimens was found in the text of *Coalfield Minerals of South Yorkshire* (Uttley, 1993). In many cases this manuscript records precise locality details, useful geological data and the name of the collector. This information was abstracted and included on typed labels in the trays with the specimens.

HISTORY

Across the South Yorkshire Coalfield, little now remains as a reminder of the influence that mining once had on the landscape and the lives of local people (Fig. 7). Although coal mining came to dominate in the twentieth century, other extractive businesses also made valuable contributions to the economy. Iron mining was of particular importance from the last quarter of the seventeenth century until the last quarter of the nineteenth century, and industries which required raw materials such as ganister, fireclay, pottery clay, and even pyrite, were of local importance at different times.

Figure 2. Steve Uttley on a collecting trip with the Doncaster Mines Research Group in the early 1980s to the well-known stibnite location at Robin Hood Mine near Bassenthwaite, Cumbria.

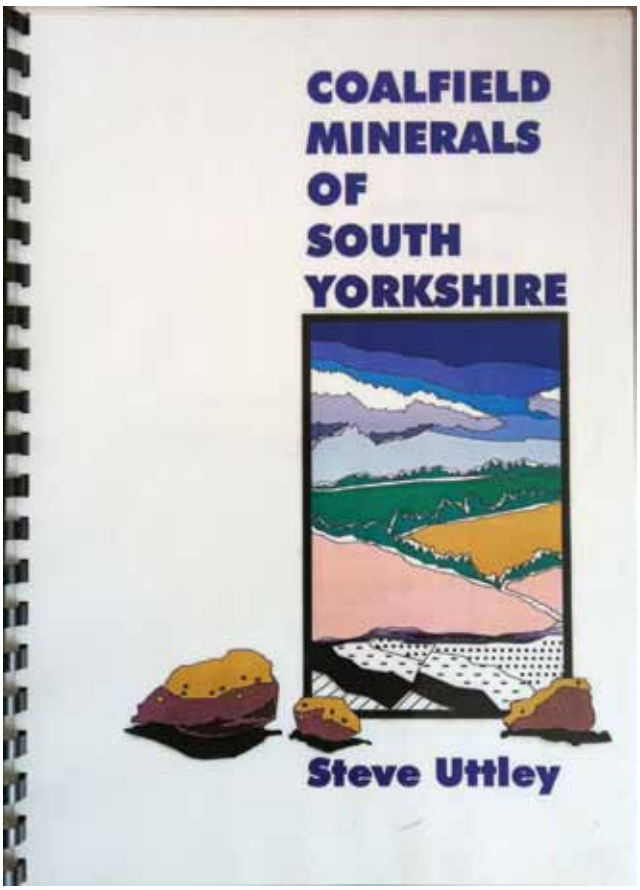

Figure 3. The front cover of *Coalfield Minerals of South Yorkshire*, a sixteen page manuscript designed and privately printed by Steve Uttley in 1993, and distributed to a few friends. Copy in the Max Freier library.

Figure 4. Steve Uttley in 2011 with camera and backpack on the Inca trail in Peru. This trip, with players from Doncaster Rovers, raised money for the NSPCC. Photo courtesy of Suzanne Uttley.

Most of the minerals described herein are from coal mines. The scale of the industry in south Yorkshire was such that it is only feasible to offer a general outline of its history and development. An authoritative guide to the history of coal mining until the mid nineteenth century is provided in Galloway (1898) and the monumental five-volume *History of the British Coal Industry* is the definitive modern scholarly account (Hatcher, 1993; Flinn and Stoker, 1984; Church *et al*., 1986; Supple, 1988; Ashworth and Pegg, 1986). A history of the 123 Yorkshire pits that were nationalised in 1947, and the 13 that were developed subsequently by the NCB, is provided in Downes (2016). The collieries of north Derbyshire are described in Bridgewater (2009). The social and economic history of coal mining in the region is described in Hill (2002; 2012). Many works describing specific mines or groups of mines, social and political history, and aspects of coal mining technology, continue to be produced; the reader is referred to the excellent library at The National Coal Mining Museum for England, for up-to-date information. The *Gazetteer of British Coal Mines*, compiled by the Northern Mine Research Society, records more than 1200 coal, clay and iron mines in Yorkshire from 1854 onward; an appreciation of the density of mining in the region can be obtained from their interactive coalfield maps (Northern Mine Research Society, 2018).

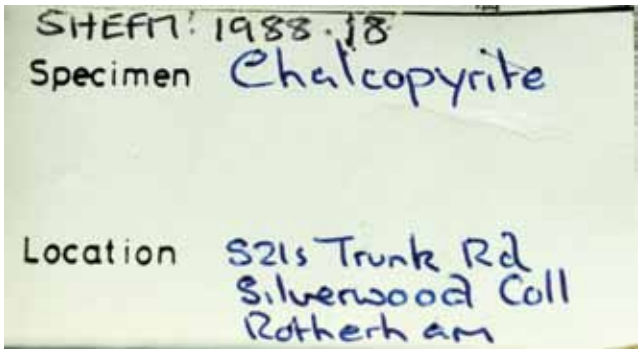

Figure 5. A hand-written label, showing Steve's distinctive style (in blue), for a chalcopyrite specimen which he donated to Sheffield Museum in 1988, the accession number [SHEFM: 1988.18] has been added by the curator. Steve designed a simple template which could be printed onto card; many members of the Doncaster Mines Research Group used it to label their collections in the 1980s.

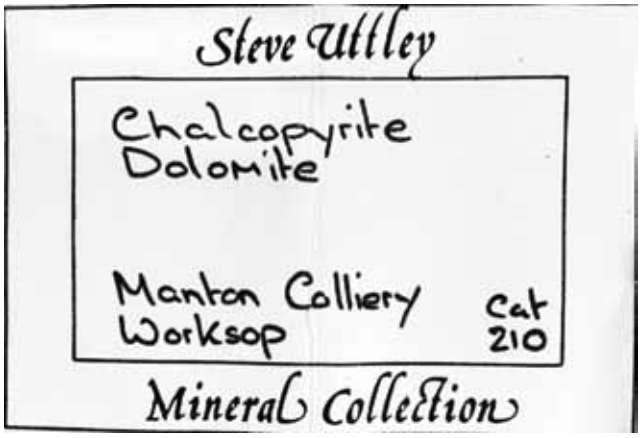

Figure 6. A typical 'large label', for a coalfield specimen from Manton Colliery, showing Steve's distinctive handwriting.

In its heyday, from the 1850s to the 1980s, coal mining had an enormous impact on the landscape. In that time, south Yorkshire acquired a reputation as a grim industrial enclave. This was not always so. Thomas Walford, who wrote a guide for the 'scientific tourist', listing features of archaeological, geological and botanical interest, considered Doncaster to be "one of the most beautiful towns in England" (Walford, 1818). With the demise of coal mining and its associated heavy industry, the landscape is changing once again. It has some way to go before it recaptures former glories, but there has already been remarkable regeneration. In this, the region's mining heritage is playing a part. The National Coal Mining Museum for England, at Caphouse Colliery, which is located between the cities of Leeds and Sheffield, provides an excellent day out for anyone with an interest in mining history.

Coal and Iron

The history of coal and iron mining is sufficiently entangled that the two are considered together. In any

Figure 7. Hickleton Colliery in the village of Thurnscoe in the 1980s showing the degree to which coal mining dominated the landscape. Steve Uttley found baryte here in November 1987 and described the crystals in an article in the *UK Journal of Mines & Minerals* published in the following year (Uttley, 1988b).

historical account it is as well to begin at the beginning, but research dating as far back as the nineteenth century (e.g. Galloway, 1898) has shown that many claims of ancient mining are unfounded. Archaeological evidence of the extraction of iron ore from small openworks in Britain pre-dates the Roman occupation. Iron Age cultures began to develop in Britain in the seventh century BCE and objects containing the metal are found with increasing frequency in the following centuries (Tylecote, 1986). Iron production was well established in the Weald of Kent and the Forest of Dean by the time of the Roman occupation (Cleere, 1981). The Middle Iron Age 'Arras Culture' of east Yorkshire worked and smelted deposits of limonitic ore in east Yorkshire from around 300 BCE (Halkon and Millet, 1999).

In south Yorkshire, there is good evidence of Roman iron smelting and coal use at Templeborough [historically Templebrough] near Orgreave (Bromehead, 1948b; Tylecote, 1986). Archaeological excavations in the early twentieth century revealed bloomery furnaces which used iron ore from the local area. Iron ore may also have been smelted at the Roman industrial settlement of Cantley near Doncaster (Cleere, 1981), and was worked at Bradfield near Sheffield (Bromehead, 1948a). Roman coins found among 'cinders' (i.e. iron slag) left by the smelting of iron in the Bradford area are recorded in Dunham (1960).

Coal was in common use in Roman Britain (Smith, 1997; Travis, 2008) and some archaeological samples can be traced to local seams. Coal from Garforth in West Yorkshire, for example, was used at Roman crematoria in York (Goodchild, 2000). Surprisingly however, there are no credible reports of ancient coal workings in Yorkshire. Most potential sites have been obliterated by later mining or industrial development (Chadwick, 2009).

In the Roman period, extraction involved opencast working on exposed coal seams and ironstone deposits. Underground mining for valuable metals such as copper and gold was well established at the time, but coal and iron ore were too abundant to make such a costly extractive technique worthwhile. Most coal was mined for local use, but a trade developed along the east coast of England (Smith, 1997), foreshadowing the medieval trade that would be centred on Newcastle-upon-Tyne.

Coal and iron mining continued after the Roman occupation, but records from the period are sparse. At some time, probably in the late medieval period, the surface deposits became exhausted and the seams and nodule bands began to be followed underground via bell pits. Iron mining in Yorkshire begins to be described in documents in the twelfth century. Medieval iron workings were small and numerous (Vellacott, 1912). They relied on charcoal from the forests, which was used to smelt the ore in bloomeries.

Accounts of coal mining around Leeds, Wakefield and Sheffield appear in documents in the thirteenth century (Goodchild, 2000). Coal was used in metal working, particularly by blacksmiths, if wood or charcoal provided insufficient heat. It was also used in the production of ceramics, and as a fuel for lime-burning. Workings were widespread but small. In 1535, the historian and antiquary John Leland noted that: "Though here be plenti of wood, yet the people burne much yearth cole by cawse hit is plentifull and sold good chepe [*sic*]" (Tew, 1882). In his travels, Leland also noted "There be plenty of veines of se cole in the quarters about Wakefeld [*sic*]" (Smith, 1907: p. 42). "Se cole" refers to 'sea coal' a common term in early accounts, which appears to have its origins in the fact that coal was gathered from beaches in the northeast of England (Galloway, 1898).

By the mid sixteenth century, diminishing supplies of wood and charcoal, and innovations in housing design, particularly the introduction of fireplaces with separate chimneys, had increased demand for coal; yet as late as 1598 the output of the South Yorkshire Coalfield was only about 2000 tons per annum. Production began to increase in the seventeenth century as industries such as glassmaking and brewing, which required high temperatures, switched from charcoal to coke as a fuel. Various patents were granted in the 1620s and 1630s for coking [literally cooking] coal to free it from smoke and sulphur; coke was better suited for use in houses and for many industrial applications. Coke was well established as a substitute for charcoal in the brewing industry by the middle of the seventeenth century. Attempts were made to use coal and coke in iron smelting from the late sixteenth century onward[1] , notably in Staffordshire (Dudley, 1665), but they were not wholly successful. Abraham Darby was almost certainly familiar with these experiments and came up with the first practical method for the use of coke in iron smelting in the early eighteenth century. However, iron remained expensive until the 1780s, when a method of producing bar iron from pig iron without the use of charcoal, came into general use.

As demand increased, many coal mines began to use variations of the 'longwall' system of working (Farey, 1811): long galleries were driven in seams, and the coal cut out sideways in one operation. This made extraction easier as the miners could work with natural fractures in the rock. It produced a pattern in the workings which the poet Thomas Dalton (1709–1763) likened to a "City of subterraneous streets".

Dewatering the workings had been a problem from the late medieval period and as the mines became larger and deeper mechanical pumping became essential. Thomas Newcomen (1664–1729) installed the first successful steam-driven pumping engine in a coal mine at Tipton in Staffordshire in 1712. Steam engines had the great advantage that they could make use of the 'small coal' from the pits which otherwise had little value. They revolutionised mining.

Effective transport was the key to further development of the inland coalfields. Engineering work, completed in about 1704, which made the River Aire navigable as far as

[1] The earliest recorded attempts to smelt iron using coal in England appear to have been in Yorkshire: in 1589, Queen Elizabeth granted a patent to Thomas Proctor in the County of York to "make iron steel or leade, by using of earthe coal, sea coale, turffe, peate, or some of them" (Galloway, 1898).

Leeds and the River Calder as far as Wakefield, stimulated coal mining in the Aire Valley. Canalisation made the Don navigable as far as Rotherham in about 1740, and later as far as Tinsley near Sheffield, increasing production in that area.

As coal mines became larger and deeper, collapses, fires and explosions resulted in more injury and loss of life. Efforts were made to improve ventilation, and in 1815 safety lamps, which could be used in flammable atmospheres, were introduced. Regardless of the improvements, underground conditions remained appalling; many accidents and disasters were preventable, but in the absence of legislation, mine owners were unwilling to take measures that would reduce short-term profit. Public outcry was such that a Royal Commission was set up in 1840 to investigate the mining industry. In 1842 an Act of Parliament prohibited all women and girls, and boys younger than ten, from underground work.

In 1812, the first successful steam-driven railway engines were installed at Middleton Colliery near Leeds. Built by Matthew Murray (1765–1826), the locomotives, Prince Regent and Salamanca, began the synergy between coal mining and rail transport that extended until the last pit closed in 2015. Rail transport was the key to expansion, but it was several decades before it had a major impact in south Yorkshire. The Leeds & Selby Railway, the first modern line in the West Riding, opened in 1834. Sheffield and Rotherham were linked in 1838. However, as late as 1846, the Reverend William Thorp, secretary of the Geological and Polytechnic Society of the West Riding of Yorkshire[2] , observed that:

> "... the Coal-field of Yorkshire is one of the largest ... in Great Britain. The towns of Sheffield, Bradford, Leeds, Halifax, Huddersfield, and Barnsley owe their existence to [it]. About 4,000,000 tons are annually raised, and owing to the want of a cheap and quick communication to the sea, on the one hand, only comparatively few tons are annually exported, while Northumberland and Durham export 7,000,000 tons; and, on the other, without any connection with any main trunk lines of railway of the country, as the Sheffield and Manchester, or Midland, the Coal-field from Wakefield to near Sheffield is completely cut off from all cheap and quick modes of transit".

As the rail network expanded in the 1850s, transport problems eased and colliery owners stepped up production, which more than doubled in the ten years following Thorp's account (Hunt, 1859). In south Yorkshire, the most important target was the Barnsley Seam, which was worked by deeper and deeper shafts as it dipped to the east. In this direction the Coal Measures are unconformably overlain by younger Permian and Triassic rocks. The first colliery to sink through the Permian cover to exploit the concealed coalfield was at Shireoaks near Worksop; it reached the Clowne Seam in July 1858 and began mining the Barnsley (Top Hard) Seam in 1859, at a depth of 1530ft. Local pride was such that the coal was paraded through the streets of Worksop in horse-drawn carts (Downes, 2016; p. 507).

Iron ore was of great economic importance in south Yorkshire from the late medieval period, but it was not until the 1780s, when coke supplanted charcoal in iron production, that it was mined on an industrial scale (Dunham, 1960; Hemingway, 1974)[3]. The importance of Coal Measures ironstone is emphasised by Phillips (1824), who, in an analysis of ironstone from Bradford, notes that "the immense quantity of iron yielded by the mines of this kingdom is obtained from what is called argillaceous iron ore". In a review of the iron ores of Great Britain, Smyth *et al*. (1856: p. 31) note that the Low Moor, Bierley and Bowling ironworks near Bradford were "celebrated for the production of the best irons made in Britain".

The third quarter of the nineteenth century saw a peak in the production of iron ore from Yorkshire's clay ironstones. Beneficiation was a labour-intensive process; the ore, which occurs as concretions in shale and mudstone, was freed from the surrounding rock by repeatedly turning the nodules as they weathered and scraping off any adherent shale; the nodules were calcined before smelting, great care being taken at every stage to remove impurities (Smyth *et al*., 1856: p. 32; Green *et al*., 1878: p. 155).

The first half of the twentieth century saw the complete demise of iron mining in the Coal Measures. Coal Measures ironstone could not compete with bedded ironstone from the Cleveland Ironstone Formation of North Yorkshire or the rich hematite ore from Lancashire and Cumberland. Baines (1929) notes that ironstone nodules were collected and sold at Robin Hood Quarry in the 1920s, but made little profit. The last Coal Measures iron mine in England, at Racecourse Colliery near Hanley in north Staffordshire, closed in the early 1940s (Trueman, 1954: p. 224).

Coal production rose in the last half of the nineteenth century and during the years leading up to the First World War. By the beginning of the twentieth century much of the world depended on British coal. Coal mining was the largest industrial occupation in Edwardian Britain and it generated huge wealth for the nation.

In his presidential address to The Yorkshire Geological and Polytechnic Society in 1905, Walter Rowley observed:

> "it will, I think, not be without interest to glance at the tremendous strides made in the science and

[2] The forerunner of the Yorkshire Geological Society, the word 'Polytechnic' was included as a reflection of the coal mining and other practical interests of many of the founding members. The West Riding of Yorkshire included all the principal coal mining towns in the south of the county.

[3] The history of iron mining in south Yorkshire is surprisingly obscure: Smyth *et al*. (1856) provide probably the best geological account of mining in its heyday; Willies (1997) provides a fragmentary history of iron mining from the Coal Measures of Derbyshire; Kendall and Wroot (1924: pp. 192–203) devote some text to iron-mining in the Coal Measures; Meade (1882: pp. 317–414) describes the principal clay-ironstone mines and provides useful tabulations of their chemical composition, and ore and metal production; and Hopkinson (1961) describes the development of the industry around Sheffield.

art of mining in recent years. In the year 1870, the production of coal from the collieries of Great Britain was 110 million tons, while the output of 1903 was, roughly, 230 million tons, or more than double; but while the output has doubled, the death rate from accidents has been very greatly reduced, from 1 in 345 of persons employed in 1870, to 1 in 805 in 1902. This remarkable decrease in the number of accidents is undoubtedly due to the rise of greatly improved means of education, which led to the passing of the various Coal Mines Regulation Acts, and the appointment of inspectors of mines".

Despite Rowley's upbeat assessment life was harsh. Pit villages in south Yorkshire were commonly built around the shaft, and the mining company often owned the local shop and pub. Miners and their families occupied rooms in small pithead terraces. At the end of the nineteenth century, Denaby near Rotherham was described as the worst village in England:

"... where religion is forgotten, home life is shattered where immorality and intemperance are rife, where wives are sold like cattle, and children are neglected".

This shocking description, published in *The Christian Budget* (Anon., 1899), should be seen in an evangelical context. However, many companies had little sense of moral responsibility; repeated public investigations revealed lamentable working conditions and lax safety standards. The years following the First World War remained challenging for the mining communities of south Yorkshire and the Great Depression of the early 1930s hit very hard. In some areas unemployment reached 70%. George Orwell painted a shocking picture of conditions in *The Road to Wigan Pier* (Orwell, 1937). His diary records a visit to Grimethorpe Colliery near Barnsley in March 1936. At the time Grimethorpe was one of more mechanised pits in the county, but it still relied on hand labour to break the coal and shovel it onto the conveyors. Orwell's diary entry for 21 March 1936 records that "The place the fillers were working was fearful beyond description".

In 1947, almost all of the privately owned collieries were nationalised. On 1 January 1947, (vesting day) all mines and collieries with more than 30 employees came under the control of the National Coal Board (NCB), which took responsibility for 970 working collieries, 55 coking plants, 85 brickworks, 20 briquette-making plants, a workforce of 796,000 and 141,000 tied houses (Downes, 2016). The NCB divided the UK into eight major areas known as divisions. The South Yorkshire Coalfield was in the North Eastern Division and was initially split into eight administrative areas. Numerous reorganisations followed and in 1967 the divisional structure was removed and the coalfield split into four administrative areas: South Yorkshire, North Yorkshire, Doncaster and Barnsley.

There were many advantages to nationalisation: wages were standardised, safety and welfare reforms introduced, and investments made in new technology. In 1957 the NCB established a geological department. As mechanised mining systems were installed, a detailed understanding of the geology became more critical; from 1974 geologists and technicians gathered detailed coal-face data at almost all British collieries (National Coal Board, 1984).

The 'oil crisis' of 1973 led to a national strategy to reduce the dependency on imported fuel: 'The Plan for Coal'. Exploratory drilling in the Selby area (Jones and Scott, 1979), showed the Barnsley Seam extended a long way to the east. Five new pits, connected to a single processing facility, were planned and the first one, Wistow Mine, came into production in 1983. Production from the Selby Coalfield peaked at 12 million tonnes in 1993; but it did not reach its full potential through a mixture of geological, political and economic problems.

By the early 1970s, the labour force had become militant and their unions wielded considerable power; the strikes of 1972 and 1974 brought about the downfall of the Conservative government led by Edward Heath. Their power was not to last. The year-long miner's strike of 1984–1985, and changes in energy supply policy, sealed the coal industry's fate. By 1986, 73% of the coal produced in south Yorkshire was used for electricity generation; the pits had only one customer (British Coal, 1986).

The NCB became the British Coal Corporation (colloquially British Coal) on 5 March 1987, and sentiment in the industry remained positive (British Coal, 1986). In the early 1990s, 50 pits remained in production, but the privatised electricity-generating industry had begun to switch to imported coal, oil and gas. In October 1992, British Coal announced 31 pit closures. Two years later most of its remaining assets were acquired by RJB Mining. On 30 December 1994, RJB Mining, run by Richard Budge (1947–2016), acquired three of the five core areas run by British Coal (17 of the 19 deep mines and 30 opencast operations) in what the then energy secretary, Cecil Parkinson, described as the 'ultimate privatisation'. It became the largest independent coal producer in Europe. In Yorkshire RJB Mining took control of ten collieries and was already operating Rossington Colliery under licence. The only independents were Hatfield Colliery, which was subject to a management buy-out, and Markham Main, which was run by Coal Investments Ltd. All of British Coal's administrative functions were transferred to the Coal Authority on 31 October 1994 and it was dissolved as an entity in 1997.

Despite job losses, restructuring and modernisation, it was impossible for deep mines in Britain to compete with imported coal from countries such as the USA and Australia with large near-surface reserves. On 14 July 2001 Richard Budge resigned as CEO of RJB Mining and the company re-formed as UK Coal Ltd. The flagship Selby Coalfield, which supplied Britain's largest complex of power stations, was abandoned in 2004. Other nearby mines survived and it was hoped that the development of carbon-capture technology would allow the continued use of coal for electricity generation. In July 2013, an underground fire forced the closure of Daw Mill Colliery in Warwickshire, UK Coal's largest remaining colliery. The company was forced into administration and its Yorkshire sites were

floated as separate entities. Thoresby colliery closed in the summer of 2015. Hatfield Colliery (which was not owned by UK Coal and had struggled for some time), closed at the end of June 2015. Grant aid for developing carbon capture technology was withdrawn, and Kellingley Colliery near Knottingley in North Yorkshire, the last deep coal mine in Britain, closed in December of that year.

In *Old King Coal*, an account of mining in the Don Valley published in 1941, Robert Ward wrote:

> "There is no likelihood of our grandchildren seeing the last lump of the Barnsley or Silkstone Seams being thrown on the fire".

How wrong he was. In 2017, there were many periods when coal-fired power stations supplied no electricity in Britain (Gridwatch, 2017). Complete closure of the UK's coal-fired power stations is planned by 2025. Of the seven current surface mining licences in the UK, two are in south Wales, two in East Ayrshire and three in the northeast of England. Five small private coal mines remain (of these only Eckington Drift Mine in northeast Derbyshire lies within the study area). There are no active underground or opencast sites in Yorkshire (Coryn Reynolds, *personal communication*, 2017) and little likelihood of a return to large-scale extraction in the area. There may, however, be a future for a deep mine for metallurgical coal off the coast of Cumbria, for which West Cumbria Mining has tentative plans.

Other Extractive Industries

There is a long history of quarrying, particularly in Coal Measures sandstones, for aggregate and building stone. Many workings are described in the relevant *Memoirs of the British Geological Survey*. A guide to the building stones is provided by Lott (2012). The fissile sandstones of the Elland Flags, which are much sought after as paving stones, are probably the best known; they are sold under the trade name York Stone (Ensom, 2009).

Some seatearths (fireclay, seatclay and ganister) and mudstones found uses in the manufacture of ceramics. Kaolinite-rich fireclays are refractory; clays with higher proportions of illite and quartz have non-refractory applications. Most of the mines and quarries are now closed, but a siliceous fireclay with a low iron content was worked below the Halifax Hard Bed Coal at a mine in the Shibden Valley near Halifax until very recently. It was used by Parkinson-Spencer Refractories to manufacture specialist products for the glass-making industry.

Numerous workings for ganister and fireclay are described in the relevant *Special Reports on the Mineral Resources of Great Britain* (Geological Survey, 1920a,b); further detail is included in Wray *et al*. (1930); Smith (1974); and Highley (1982). None of these descriptions include much about the mineralogy of individual deposits, beyond an occasional note of the presence of pyrite. Ganister was of particular importance in steelmaking. As the steel industry developed in the nineteenth century, traditional firebricks proved inadequate. More resistant 'silica firebricks' were produced by William Young (1776–1847) in the 1820s for the steelworks in south Wales. Although its refractory qualities were known, ganister only became valuable in the mid 1850s when Sir Henry Bessemer (1813–1898) introduced the steel-making process that bears his name. The highly siliceous firebricks produced from crushed ganister were well suited for use in Bessemer's 'acid converters'. Mines and quarries developed across the region (Holgate, 1871; Kenworthy, 1915; Geological Survey, 1920a; Wray *et al*., 1930), and were worked until the Second World War when ganister was replaced by more modern refractories in furnace linings.

Brick-making clay is a term used to describe any clay or mudstone used in the manufacture of bricks, roof tiles or pipes. Many Coal Measures mudstones have been worked in south Yorkshire and the Pennine Coal Measures remain the principal brick clay resource in northern England (Ridgeway, 1982; McEvoy *et al*., 2006a,b). At least sixteen horizons produced brick clay in the Wakefield area alone (Lake, 1999). The heavy clays used by the industry tend to be relatively illitic in composition (Spears, 2006).

South Yorkshire rivalled north Staffordshire as a centre for the production of porcelain and earthenware in the eighteenth and nineteenth centuries. The most famous potteries were around Leeds, where excellent potter's clay, and the coal required to fire it, were found in close proximity. Grabham (1916) produced an illustrated guide to the major Yorkshire potteries, the most famous being the Leeds Pottery where:

> "in several parts of the neighbourhood beds of clay are found particularly suitable for this purpose, which no doubt have been worked for this class of ware from the British and Roman period".

At nearby Burmantofts Pottery:

> "Both the clay and coal wherewith to bake it, are obtained on the spot, the former lies two feet thick, one hundred yards from the surface, under a fourteen inch seam of the Low Moor Better Bed coal, and covers about one hundred acres".

Further information about the industry and its geological basis is provided in Smith (1974) and references therein.

Pyrite was collected at many collieries for use in the manufacture of iron sulphate (known as copperas or green vitriol), which was used in dyeing and chemical manufacture. From 1820 sulphuric acid (also known as oil of vitriol) was also produced from pyrite (Partington, 1962: p. 561). An early reference to the production of iron sulphate is provided by Thoresby (1715, p. 470), who notes: "*Copperas* very fine, made at Hallifax [*sic*] (where the Pyrites are more plentiful)". James Sowerby (1817: p. 98) records that in the area around Bradford and Halifax "great quantities [of pyrite were] sold for making vitriol". The total production of Yorkshire 'coal brasses', a colloquial term for pyrite, was estimated at 3560 tons in 1857 (Hunt, 1859). By this time it was gathered almost entirely as a by-product of coal mining.

Alum, which was used as a mordant to fix dyes, was of vital importance to the cloth-making industry in Yorkshire. It had been produced from shale dug from the cliffs near

the coastal port of Whitby from about 1604. The key to the process was repeated crystallisation, which produced the pure product that dyers needed. The coastal works were surrounded by such secrecy that no contemporary accounts of the process survive (Rickard, 2015). Their monopoly was broken by Peter Spence (1806–1883) who developed a process based on the digestion of Coal Measures shales. He was granted patents in 1845 and 1850 and set up a successful works (which produced ammonium alum) in Manchester.

Demand was significant, and other manufacturers soon followed Spence's example. The West Yorkshire Alum Works was built near Park Hill Colliery in the 1860s. It produced alum, sulphuric acid and ammonium sulphate (Downes, 2016: p. 417). Several collieries near Rotherham and Barnsley produced alum shale at the beginning of the twentieth century (Strahan *et al*., 1917). It was calcined, oxidising the iron sulphides to form sulphates of iron and aluminium, steeped in shallow pits, treated with potassium chloride and evaporated to produce potash alum. Alum shale was mined at Park Hill Colliery near Wakefield until the middle of the twentieth century. It was produced from a shale band, about 30 cm thick, in the Stanley Main Coal (Edwards *et al*., 1940; Lake, 1999).

Other economic products of the Coal Measures include grindstones, which were produced at Ackworth until in the 1970s (Lewis and Rees, 1926; Smith, 1974); glass-making sand, which was produced from Coal Measures sandstone near Bolsterstone, Sheffield (Kenworthy, 1914); and crude oil and a number of heavier hydrocarbon waxes and oils, which were distilled from 'oil shale' at the West Ardsley Collieries near Leeds between 1867 and 1873.

Finally, mention must be made of the finely divided variety of hematite known as 'raddle', which was mined near the hamlet of Micklebring, and used in paint making and for polishing lenses. It is described in more detail under hematite.

GEOLOGY

The Coal Measures were deposited in a gently subsiding basin which covered most of northern England and extended to the east across the North Sea into Germany and Poland, and to the west across Ireland and into North America, in late Carboniferous (Westphalian) times. The climate was warm and humid, and the landscape dominated by shallow freshwater lakes and low-lying swampy forests cut by fluvial channels (Rayner and Hemingway, 1974; National Coal Board, 1984: pp. 55–122; Cope *et al*., 1992; Woodcock and Strachan, 2000; Aitkenhead *et al*., 2002; Waters and Davies, 2006; Sheffield Area Geology Trust, 2017).

Coal mining was the most important industrial activity in south Yorkshire for most of the nineteenth and twentieth centuries, and many geological studies were published. Wilcockson and Goossens (1958) summarise research until the late 1950s, which concentrates on structure and stratigraphy, matters that were of particular concern to the mine owners. In the heyday of mining, entire journals were devoted to the physical and chemical properties of coal, such was its economic importance. Coal Measures lithologies were described in increasing detail as the study of sedimentary basins was refined in the twentieth century. The South Yorkshire Coalfield has become one of the most studied geological sequences in the world, and its lithologies, patterns of sedimentation and diagenetic pathways are relatively well understood.

Coal Measures Stratigraphy

The Coal Measures have a distinguished stratigraphic history. The term was introduced in a geological sense by the mineral surveyor John Farey (1811) and it was adopted by the 'Father of English Geology', William Smith (1769–1839), who included it on his now-famous maps. Smith divided the Coal Measures rocks into thirteen separate units on his county map of Yorkshire, which was published in 1821. His nephew, John Phillips, described the Coal Measures in the popular *Outlines of the Geology of England and Wales* (Conybeare and Phillips, 1822), and the name became embedded in nineteenth-century literature. The gentlemen of the Geological Survey were well aware of the economic importance of the Yorkshire Coal Measures and the second director, Sir Roderick Impey Murchison, despatched Alexander Henry Green (1832–1896) to survey the area. The resulting memoir (Green *et al*., 1878) was the largest the organisation ever produced.

The Coal Measures rocks of South Yorkshire were divided into three lithological units: the Lower or Ganister Coal Series, the Middle Coal Series, and the Upper Coal Series, by John Phillips (1855). Edward Hull (1860), working in Lancashire, renamed these units the Lower, Middle and Upper Coal Measures in the first of the Memoirs of the Geological Survey to be mapped at a six-inch scale. The terms came to be applied to almost all British coalfields, although initially with local marker horizons. As research progressed, the rocks began to be described as Westphalian, and were divided into Westphalian A, B and C in Yorkshire (and Westphalian D outside the county). The boundaries of the Westphalian A, B and C, which are chronostratigraphic units, do not precisely correspond with those of the Lower, Middle and Upper Coal Measures, which are lithostratigraphic units.

The Coal Measures are divided using 'marine bands', laterally extensive marine mudstones which contain distinctive fossils. The Subcrenatum Marine Band (314.5 Ma), formerly known as the Pot Clay Marine Band, marks the boundary between rocks of the Millstone Grit Group and the Pennine Coal Measures Group, and between the Namurian and Westphalian. The Westphalian, a chronostratigraphic unit, is subdivided into several substages and the first three of these, the Langsettian, Duckmantian and Bolsovian, are of importance in Yorkshire. The bases of the Langsettian, Duckmantian and Bolsovian substages are defined by the Subcrenatum, Vanderbeckei and Aegiranum marine bands, respectively. The bases of the Lower, Middle and Upper Coal Measures, which are lithostratigraphic units, are defined by the Subcrenatum, Vanderbeckei and Cambriense marine bands, respectively. The Pennine Upper Coal Measures extend into the Asturian Substage outside the study area. They are overlain by rocks of the Warwickshire Group in

a few places, but the boundary is strongly diachronous and there are no important exposures in south Yorkshire.

The nomenclature which describes the Carboniferous succession in Europe has been revised extensively in recent years and much entrenched terminology has been either abandoned or redefined (Heckel and Clayton, 2006). A summary of the changes relevant to the Carboniferous in Britain is provided by Waters *et al*. (2009; 2011). Recent revisions of international stratigraphic nomenclature have redefined the 'Westphalian Period' as a local stage. The Langsettian, Duckmantian and Bolsovian, which were formerly defined as stages, have been redefined as local substages. Boundaries in the Pennine Coal Measures do not correspond to global geological markers and the Carboniferous of Yorkshire no longer holds the central position it once did in stratigraphic nomenclature. Modern terminology is used only if practical in this account; it is difficult to integrate the old but regionally useful terms into the new paradigm.

Regional Setting

The South Yorkshire Coalfield, as it appears on modern geological maps (Fig. 8), is an eroded and faulted fragment of a more extensive sedimentary basin. By the early Carboniferous, the landmass that would become England had accreted onto the southeastern edge of the Laurussian plate to form the Avalonian section of the large northern continent of Laurussia. The microcontinents of Amorica and Iberia, which lay in the Theic Ocean between Gondwana to the south and Laurussia to the north were separated from Avalonia by a narrow seaway floored by oceanic crust. Northward directed subduction of the Theic Oceanic Plate beneath the southern edges of Iberia and Armorica, early in the Carboniferous, resulted in back-arc extension, which produced a north–south extensional stress, thinning the crust to the north.

Sedimentary basins developed along the Laurussian margin in this extensional regime. Global sea levels were relatively high and a 'basin and block' topography developed in the epicontinental sea that covered most of northern England. The Alston and Askrigg blocks, which lay on buoyant and competent Caledonian plutons, and the Peak District of Derbyshire, were isolated as topographic highs, and a series of basins developed in the surrounding areas (Pharoah *et al*., 2011).

At a regional level, the sedimentary sequences that were deposited in the early Carboniferous were governed by the interplay between basinal subsidence and sea-level change. Sea-level oscillations of up to about 160 m, with major periodicities calculated at approximately 100,000 and 400,000 years (Collier *et al*., 1990), were generated by the advance and retreat of ice sheets which covered large areas of the southern continent of Gondwana. In common with modern ice ages, the Carboniferous glaciations were brought about by orbital 'wobbles' (Milankovitch cycles) which altered the amount of solar radiation incident on the Earth's surface. Nineteenth century geologists studying Lower Carboniferous strata in the Yorkshire Dales and elsewhere described the repeating lithologies produced by sea-level change as 'cyclothems'.

In Namurian times, the stress field that had generated the early Carboniferous basin and block topography reduced and gentle thermal subsidence became the dominant tectonic process in northern England. Rivers with a northerly source deposited rocks of the Millstone Grit Group in delta fans, which gradually filled pre-existing basins. By the end of the Namurian, southward-prograding delta fans had filled the rift basins across northern England. The complex system of basins and platforms that characterised the early Carboniferous had been replaced by a large shallow basin with little internal relief. The northern and southern limits of this basin are well established. It extended from the Wales–Brabant High to the Southern Uplands High. The greatest subsidence (averaging about 0.35 mm per year) was in the area around modern-day Manchester, which is described as the local depocentre. The extent of the basin to the east and west is not well constrained. To the west, it appears to have stretched across Ireland, where little evidence is preserved, and into interlinked basins which (due to subsequent continental rifting) are now in north America. The eastern extension ran across the North Sea into similar basins in Germany and Poland, and possibly as far as the Ukraine.

Sedimentation Patterns

By the beginning of the Westphalian, low-lying terrestrial environments had become the norm. The marine transgressions, which had had a profound influence on earlier Carboniferous lithologies, were infrequent and the thick marine limestones that characterise Lower Carboniferous successions are absent in the Coal Measures. Cyclical patterns of sedimentation remain in Westphalian sequences, but their lateral extent, vertical scale and lithologies differ from the Lower Carboniferous cyclothems. Westphalian sedimentary cycles are thinner and more numerous, and the principal control on cyclicity appears to have been the interplay between deposition and subsidence (e.g. Pharoah *et al*., 2011; p. 73).

Despite these differences, Coal Measures sedimentary cycles are commonly described as 'cyclothems', especially in mid-twentieth century guides. The term should be treated with caution as the lithologies, periodicities, patterns of deposition and geological drivers differ from Lower Carboniferous cyclothems. The vestiges of Lower Carboniferous periodicity, produced by glacially driven sea-level change generated by orbital wobbles, are represented in the Coal Measures by occasional marine bands, deposited at times when the global sea-level was unusually high.

The more general term cycle is used in this discussion to describe the somewhat cyclical nature of sedimentation. At the base of a typical Coal Measures sedimentary cycle, grey, well-bedded, lacustrine mudstone rests on the top of the underlying sediment. The clastic rocks are typically upward-coarsening, passing from mudstone into bioturbated siltstone and pale grey sandstone. A cycle is capped by fossilised soil, which is commonly described using the term seatearth, and may be overlain by coal (Duff and Walton,

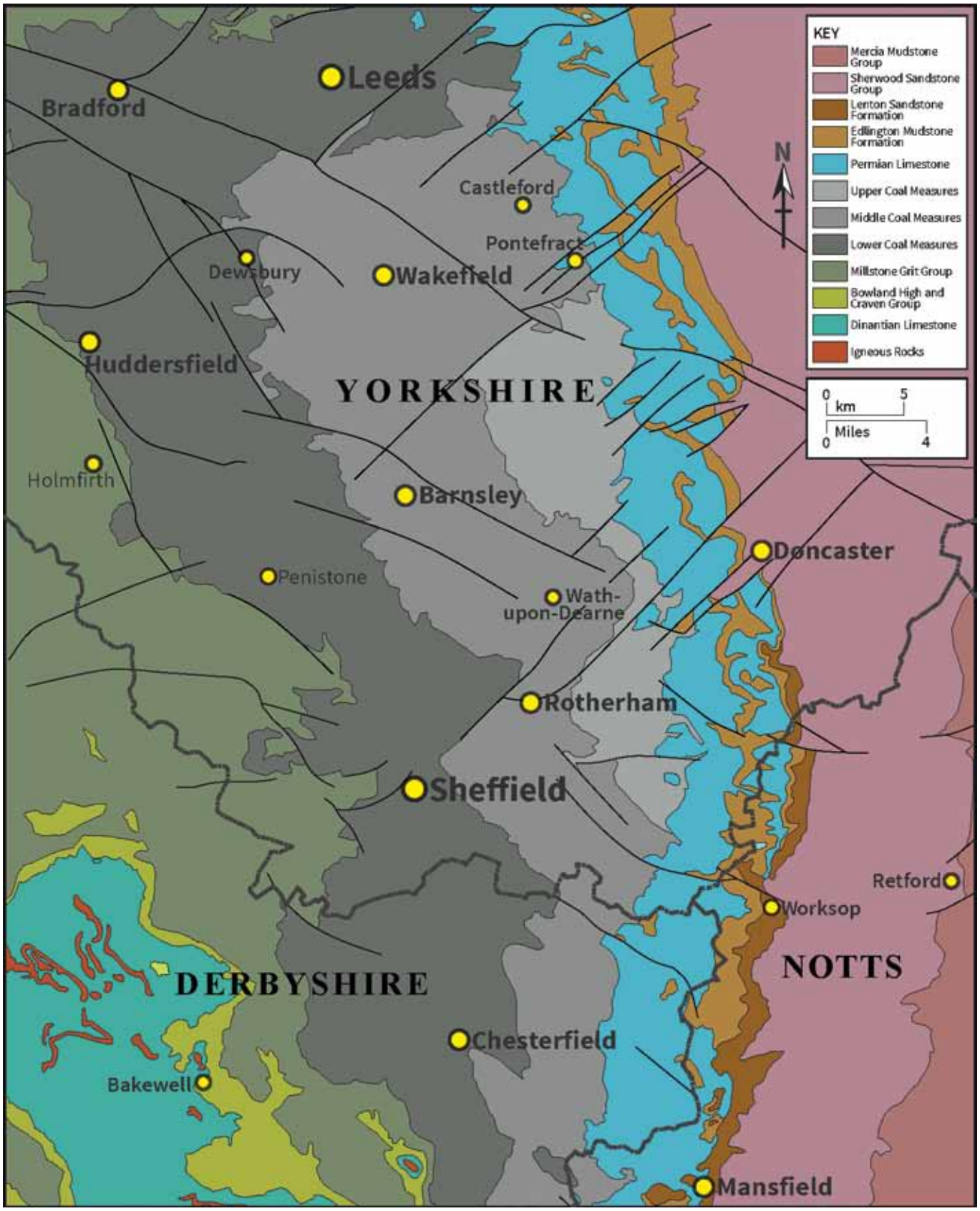

Figure 8. Simplified geological map showing the Coal Measures and surrounding lithologies. Drawn by Peter Briscoe. Contains British Geological Survey materials © NERC [2018].

1962). Many Coal Measures cycles differ from this ideal sequence. Although the siliciclastic rocks in most cycles are upward coarsening, some are upward fining. At the top of a cycle there may be several seatearths interbedded with seams of coal; coal interbedded with fine-grained mudstone; or no coal at all.

The interplay between deposition and subsidence appears to have been the principal control on cyclicity. The coal-forming ecosystems excluded sediment (as is clear by its relative absence in coal seams) and in this situation, the rate of subsidence, small though it was, exceeded the rate of accumulation. The swampy coal forests were eventually overwhelmed by floods and replaced by shallow lakes with muddy bottoms. Sedimentation rates in the lakes exceeded rates of subsidence and they gradually silted up, producing emergent surfaces which plants could colonise, forming soils and coal forests, and beginning the 'cycle' once again. At the southern edge of the Pennine Basin, where the rate of subsidence was much smaller, the sequences are different. Thicker layers of vegetation accumulated, allowing the formation of rock units such as the Warwickshire Thick Coal over a long period in a stable environment (Fulton, 1987).

The levees which formed the banks of rivers flowing through the coal forests were typically about 7 m high, reducing somewhat in lacustrine deltas, where they were 3 to 5 m above the surrounding flood plains. Levee height seems to have been the principal control on the thickness of the crevasse-splay sediments deposited during times of flood. The presence of duplicated coal seams beside ancient river channels, produced when rafts of peat were displaced by flooding, and deposited intact on top of nearby vegetation, indicates some of the floods were more than 7 m deep (Elliott, 1985).

Although the cyclic model is widely used to introduce Coal Measures geology, a more realistic interpretation is provided by sequence stratigraphy, which looks at individual sediment bodies in detail, and takes account of erosion surfaces. It generates a more complex picture in which ribbons of coarse fluvial sandstone, up to a few tens of kilometres wide, associated with ancient river channels and delta fans, are surrounded by sedimentary sequences dominated by fine-grained lithologies, but including crevasse-splay sandstone, seatearth and coal. The stratigraphic complexity of the Coal Measures in the relatively large area under study is such that it is impossible to provide a meaningful diagrammatic summary. A discussion with a diagram which shows the principal sand bodies and the way in which the major coal seams split (and their various local names) is provided in Sheppard (2005: p. 13).

Coal Measures Lithologies

The Yorkshire Coal Measures are dominated by fine-grained clastic sedimentary rocks, which were deposited in shallow lakes and on flood plains. Coarse-grained sandstones are common and the more competent units form prominent scarps in the landscape. Marine mudstones are well known to geologists as marker horizons, but only constitute a tiny part of the sequence. Fossil soils, described using the terms seatearth and ganister, are widespread. Coal, which gives its name to the rocks, is well known but makes up less than 2% of the total sequence.

Sandstone

Sandstones make up about 20% of the Coal Measures in south Yorkshire. Coal Measures sandstones are typically grey when fresh, and weather to a pale brown as iron-bearing minerals oxidise. Hematite-bearing sandstones, reddened by ancient oxidation in Permian desert environments, are present below the Carboniferous–Permian unconformity.

Coal Measures sandstones are typically dominated by subangular to subrounded quartz grains and most contain some detrital feldspar. Mica-group minerals, particularly muscovite, may make up more than 5% of the rock by volume, they are conspicuous on bedding planes, especially in Lower Coal Measures sandstones (Fig. 9). Fine-grained phyllosilicate minerals, including kaolinite, illite, illite-smectite and rarely chlorite, typically make up 10–15% of Coal Measures sandstones. Diagenetic cements include early siderite, quartz, kaolinite, illite, chlorite, low temperature feldspars, and late calcite and dolomite (Huggett, 1984).

Analyses of heavy mineral suites and palaeocurrent directions have shown that three river systems transported the sediments that form Coal Measures sandstones. At the beginning of the Westphalian, rivers transported a garnet- and monazite-rich heavy mineral suite from mountainous areas to the north. It was replaced in the Langsettian by a garnet- and monazite-poor mineral suite with variable amounts of chrome spinel, which originated in the west. As Variscan uplift raised land to the south in the late Duckmantian, the western source was replaced by sediment from the east and southeast, which is characterised by a garnet-rich heavy mineral suite containing monazite and chrome spinel (Hallsworth and Chisholm, 2000).

Figure 9. Micaceous Lower Coal Measures sandstone forming an external mould of the trunk of a species of *Lepidodendron*, a tree-like lycopod which was abundant in the coal swamps. Specimens such as this found by miners in the eighteenth century were described as 'fossil serpents', on account of their scaly appearance. Accessioned as BRFMS: BMT08343 at Cliffe Castle Museum, Keighley. Photo John Chapman.

Dense minerals (most of which are detrital), that have been separated from Coal Measures sandstones, include the titanium dioxides anatase and rutile; chromium-rich spinel (and rarely the zinc-bearing spinel gahnite); chloritoid; garnet-group minerals; minerals of the monazite series; zircon; epidote; staurolite; calcium-bearing apatite-group minerals; and tourmaline-group minerals.

The sandstones that accumulated in river channels typically have a well-defined erosional base and may be complex multi-storey bodies many tens of metres in thickness. The sandstone bodies left by Coal Measures river systems were of particular interest to NCB geologists and are categorised in *Procedures in Coal Mining Geology* (National Coal Board, 1984: p. 79) as follows:

> "Various river forms have been identified and the geometries of their deposits are of special importance to the mapping of coal seam roofs and floors:
>
> 1. fairly straight, often multi-storey, sandy ribbons representing main distributaries, with crevasse splays or minor distributary branches from individual storeys;
> 2. complex sandy sheets or broad belts representing the infill of laterally migrating channels...;
> 3. anastomosing sandstone ribbons channelled into a mudstone/siltstone sheet and representing the changing course of a river liable to both branching and reunion;
> 4. sinuous to straight simple channels between sandy or silty levees, usually closely associated with or within a coal seam (the channel may have been filled with peat, the compacted structure then being known as a 'swilley'); and
> 5. sinuous to straight cannel and mud-filled channels within or adjoining coal seams".

Lacustrine and flood-plain sandstones are typically graded crevasse splay deposits which accumulated in the areas surrounding river channels in times of flood. The way they formed means that it is unusual for individual sediment bodies to persist laterally for more than about ten kilometres.

Mudstone and Shale

Fine-grained sedimentary rocks dominate the Coal Measures in South Yorkshire. Mudstones and shales were typically deposited in low-energy environments in the shallow freshwater lakes, lagoons and coal swamps that surrounded river channels. They are generally grey to black when fresh and weather to produce a stiff clay. Where pyrite-rich shales are exposed to weathering, pyrite decay causes chemical disintegration and gypsum and jarosite may form on bedding planes (Fig. 10).

Coal Measures sandstones grade laterally and vertically into siltstones, mudstones and shales, and all of these lithologies contain similar minerals. Detrital quartz is ubiquitous, decreasing in abundance with decreasing grain size (Spears, 1980). Phyllosilicate minerals increase in abundance as the grain size decreases; the most important phases in freshwater Coal Measures shale and mudstone are kaolinite, illite, mixed-layer illite-smectite[4] and chlorite-vermiculite (Spears, 2006). Kaolinite is concentrated in the fine-grained lithologies relative to illite and illite-smectite (Pearson, 1979) and it also increases in more mature shale and mudstone, in which chlorite-vermiculite is generally absent (Spears, 2006). Authigenic siderite is common in disseminated form, as sphaerosiderite, and in clay-ironstone nodules.

The Carboniferous Basin in northwest Europe was subject to continual gentle subsidence and at times some terrestrial environments may have been below sea level. Glacio-eustatic sea-level rises generated extensive, shallow, epicontinental seas, in which fine-grained mud accumulated, for a few relatively short periods in the Westphalian (Collier *et al*., 1990). A survey of Namurian to Westphalian marine bands, which identifies four environments of deposition, each with its own characteristic lithology, is provided by O'Mara and Turner (1997). Marine band mudrocks

Figure 10. Transparent monoclinic gypsum crystals up to 10 mm long, with yellow jarosite, on a bedding plane in shale from the Coal Measures near Idle, north of Bradford. Specimen 1006 in the collection of Joseph Dawson, now preserved at Cliffe Castle, Keighley. Dawson's label describes "Crystallized Gypsum as it lies in Shale". The acid sulphate-rich pore fluids produced in coal and shale by the oxidation of iron sulphides dissolves calcium-bearing minerals and the solutions commonly become sufficiently concentrated for gypsum to crystallise, particularly in impermeable shale bands. Photo John Chapman.

[4] The alteration of smectite clays to illite is a well-known reaction in fine-grained sediment during burial diagenesis. It produces material described as illite-smectite (commonly abbreviated I-S) (Lanson *et al*., 2009). The term describes an interstratification of illite (a potassium deficient variety of muscovite) with a clay mineral of the smectite group (commonly montmorillonite–beidellite).

typically consist of detrital quartz, kaolinite, muscovite, illite, mixed-layer illite-smectite, and chlorite, plus early authigenic siderite and pyrite (Ashby and Pearson, 1979). Marine band mudrocks typically contain less kaolinite and more illite and illite-smectite than comparable non-marine mudrocks (Spears, 2006). They are usually found above a coal or seatearth, and vary from a few centimetres up to about ten metres in thickness.

Seatearth

Seatearths are fossil soils characterised by poor stratification and an abundance of rootlets. They are commonly found beneath coal seams and represent a change from shallow lacustrine environments to swamps in which waterlogged soils developed. Muddy argillaceous soils form fine-grained seatearths which are commonly described as fireclay (some authors prefer the term seatclay[5]). Seatclays typically contain kaolinite, illite, mixed layer illite-smectite and chlorite. Sandy arenaceous soils form ganister. Hard ganisters, composed of uniform angular quartz grains with interstitial kaolinite, in which feldspars and other unstable detrital minerals have been removed by pedogenic processes, were used in the production of furnace bricks. They are so common in Yorkshire that the Lower Coal Measures were described by early geologists as the Ganister Beds.

Coal

Coal seams represent thick layers of peaty organic matter which accumulated in swampy conditions. They are numerous, extend over large areas of the Pennine Coal Measures, vary laterally in quality and thickness, and may split, be 'washed out' by river channels, or die out completely (National Coal Board, 1984).

Although coal makes up less than 2% of the total thickness of Coal Measures sediments in Yorkshire, the peat from which it formed probably took more than half of the duration of the Westphalian to accumulate (Rippon, 1998). An account of the formation of coal, through loading by overlying organic matter to form peat; compaction by sediment with the resultant collapse of plant cells and gelification of organic material; and coalification by heat and pressure during burial; is provided by Elliott (1985), who estimated compaction ratios for Yorkshire coal of between 15 and 20. Although it appears homogeneous in hand specimens, coal is made up of components known as macerals (Taylor *et al*., 1998). These can be made visible under the polarising microscope, which reveals a rich and complex structure (Fig. 11). The abundant presence of fusinite in many seams shows that fires were common in the oxygen-rich Carboniferous atmosphere.

Thick coal seams commonly contain mudstone partings, deposited in times of flood. The individual 'leaves' of coal, between the partings, are known as plies. The mudstone between coal plies is finer than in typical lacustrine deposits, due to the filtering effect of the coal-forest ecosystem (Larsen *et al*., 2007).

Ironstone

Ironstone nodules, ranging from a few millimetres to more than half a metre across, are present in most mudstones. They are typically concentrated at definite horizons, and probably nucleated around decaying organic matter at shallow redox boundaries in the sediment. The term 'ironstone' is embedded in the geological literature, but it is used to describe such a wide variety of lithologies that it is of little value without qualification. In the Yorkshire coalfield, ironstone originally described those mudstone and shale bands (typically found above coal seams) which contained enough clay-ironstone nodules to be of use as iron ore (Dunham, 1960). Some geological studies reserved the term for the nodules themselves, which typically contain siderite and about 30% clay minerals; others used it to describe the entire nodule band including the surrounding shale and mudstone.

An attempt to extend the definition to include 'spherulitic ironstones' was made by Deans (1934) who argued that the abundance of authigenic siderite (described by the petrographic term sphaerosiderite) in some Coal Measures rocks required a suitable descriptive expression. Sphaerosiderite can occur in almost any Coal Measures lithology; it is particular common at the base of seatclays and in the strata that lie directly below them.

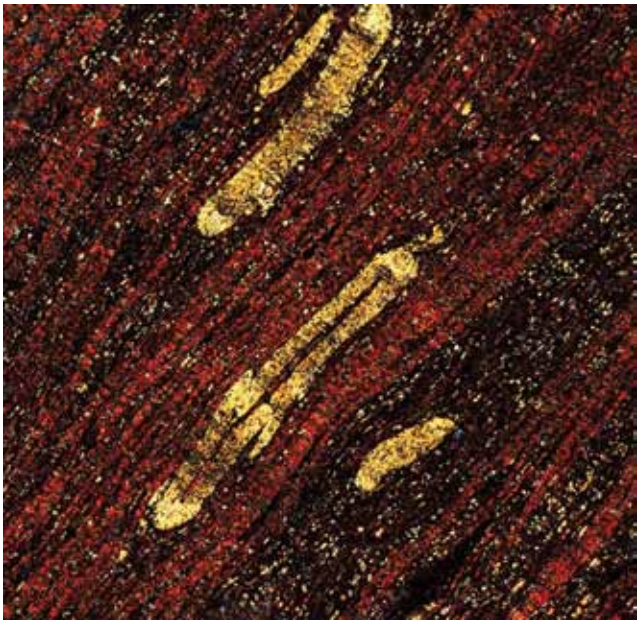

Figure 11. Seemingly homogeneous coal reveals complex relationships between macerals when viewed in thin section between crossed polarisers. Microstructures were commonly used to characterise specimens as in this microscope slide, which is from the former British Coal laboratories at Wath-upon-Dearne. The yellow oval structures are fossilised spores. Field of view is 1.2×1.2 mm; John Chapman collection and photo.

[5] Many recent publications use the term fireclay to describe any type of argillaceous seatearth (e.g. Addison *et al*., 2005) and such usage was almost universal until the latter part of the twentieth century. However, in clay mineralogy, the term fireclay has come to be associated with a particular type of reworked fossil soil, associated with marine bands, in which diagenetic alteration has produced abundant kaolinite, and all traces of the soil structure have been lost (Highley, 1982; Spears, 2012).

In a subsequent paper, Deans (1936) introduced the term 'oolitic ironstone' to describe a lithology commonly found just above coal seams and seatclays which contains an abundance of kaolinite ooliths. Neither of these terms has survived into modern usage. The so-called spherulitic ironstones are generally described as siderite-rich variants of more common lithologies, such as seatclay, mudstone and sandstone, and there has been little further study of the 'oolitic ironstone' from the Coal Measures. Deans detailed studies of Yorkshire 'ironstones' revealed considerable mineralogical and petrographic variability and they remain as useful descriptions of these forgotten lithologies.

Limestone

Carbonate rocks other than ironstone are rare in the Coal Measures; carbonate-rich mudstone, colloquially known as 'cank'[6], is associated with some marine bands (particularly the Aegiranum Marine Band) and muddy dolomitic limestone is recorded in a few boreholes, notably the Lindholme borehole 16 km ENE of Doncaster and in the sub-Clowne Carbonate Bed in northeast Derbyshire.

Tonstein

The only igneous rocks in the East Pennine Coalfield are found in concealed rocks to the south and east of a line joining Nottingham to Lincoln. They were intersected in deep boreholes drilled in the search for oil (Burgess, 1982). Extrusive activity culminated in the Langsettian, with outpourings of alkaline basalt, tuff and hyaloclastite. A mafic intrusive suite appears to represent a slightly later stage of igneous activity, associated with Bolsovian tectonism. These rocks lie beyond the boundary of the study area, but ash-fall deposits are present across the South Yorkshire Coalfield.

Ash-fall deposits that have altered to kaolinite, known as tonsteins, are present at many horizons in the Pennine Coal Measures in Yorkshire (Spears, 2012). They are commonly monomineralic, but may include high-temperature β-quartz, sanidine, dark micas and a diagnostic assemblage of heavy minerals, including zircon, apatite, magnetite and ilmenite. In common with marine bands, tonsteins can be traced over wide areas and they make valuable marker horizons. Two chemically and mineralogically distinct groups have been identified, one produced by the alteration of ash of basaltic composition from relatively nearby volcanic sources, and the other from ash of rhyolitic composition from more distant and violent eruptions. The mafic tonsteins, which are the most common, typically extend over areas of a few tens of square kilometres; the felsic tonsteins are rarer but may extend over thousands of square kilometres and can be traced across continental Europe (National Coal Board, 1984: p. 80; Rippon and Spears, 1989; Spears, 2006).

[6] The terms 'cank' and 'canky' appear commonly in borehole logs and geological descriptions of the Yorkshire Coal Measures, but they are not well defined, they describe mudstone that is rich in ferroan dolomite, micritic limestone, calcite concretions ('cank balls') and rock containing veins of pale carbonate minerals.

Post-Westphalian Development

The gap in the geological succession at the top of the Coal Measures in south Yorkshire reflects a period of burial and faulting in an extensional regime, followed by compression, uplift and folding initiated by Variscan mountain building further to the south. In the interval (of about 45 million years) between the latest Coal Measures rocks exposed in Yorkshire and the renewal of deposition in the late Permian Zechstein Sea, a fault pattern developed in what, at first, was a gentle extensional regime. The faults were of significant economic interest in Victorian times and they were mapped in detail (Johns, 1905). The principal tectonic faults reflect lines of weakness in the Lower Carboniferous basement (e.g. Addison *et al*., 2005; Kirby *et al*., 2000; Pharoah *et al*., 2011). The smaller fractures, within rhomboidal fault blocks, and the microfractures within coal seams, described as 'cleat', reflect local stress fields (Rippon *et al*., 2006).

The cleat, a system of microfractures which forms at right angles to the bedding in coal, was initiated during burial and diagenesis (e.g. Lake, 1999; p. 81; Ellison, 1997; Rippon *et al*., 2006). In Yorkshire, the cleat direction is affected by contemporary faults, particularly in the Morley–Campsall/Askern–Spital fault zone (Ellison, 1997; Rippon *et al*., 2006). However, it does not usually vary by more than 10° from a regional northwest trend (Kendall and Wroot, 1924).

Variscan earth movements began to have a significant effect on the Yorkshire Coal Measures early in the Permian. Inversion anticlines developed and once-continuous areas of the Northwest European Carboniferous Basin were gradually isolated. The climatic conditions changed from warm and humid to hot and dry, and uplift allowed oxidising solutions to penetrate up to about thirty metres beneath the surface, reddening the rocks as pyrite and siderite oxidised to form hematite. To the north of Leeds and Bradford, uplift and subsequent erosion removed the entire Coal Measures sequence, exposing the underlying Namurian sandstones and shales.

As the Permian progressed, basins began to develop to the east and west of the Pennines, in response to continental rifting. As the rocks subsided, faults were reactivated and in Yorkshire the Coal Measures tilted to the east. To the east, the basin floor fell below sea level and it was flooded in the Late Permian by the Zechstein Sea. The sea was periodically cut off from its ocean source, and dried out, depositing evaporite sequences over a wide area.

Rifting and subsidence continued into the Mesozoic tilting the strata in the Yorkshire coalfield further to the east, with the deposition of successively younger sedimentary sequences. It is widely accepted that Mesozoic rocks covered northern England well beyond the limits of their present-day outcrop (Holliday, 1999). There has been considerable controversy with regard to the depth of burial of the rocks of the Pennine blocks in the Mesozoic. Modern interpretations suggest kilometre-thick cover sequences were removed by uplift and erosion, beginning in the Cenozoic (Green, 2005). Cenozoic erosion removed almost all of the remaining Coal Measures rocks in the Alston

and Askrigg blocks, exposing Lower Carboniferous strata, and isolating the Coal Measures to the east and west of the Pennine Hills to produce the geological pattern we are familiar with today.

MINERALS

This account is based on Uttley Collection specimens, and observations in *Coalfield Minerals of South Yorkshire* (Uttley, 1993). A sketch map showing the localities described in the text is reproduced as Figure 12. A number of public collections provided additional data. These include the collections of Sheffield Museum, which were extensively cited in Uttley (1993); the mineral collection held by Bradford Museums and Galleries at Cliffe Castle in Keighley, which includes the collection and manuscript catalogue of Joseph Dawson[7], manager of the famous Low Moor Ironworks near Bradford (Dawson, 1810–1813; Pacey, 2003); the collection of the Natural History Museum in London, which contains a number of coalfield specimens, including the baryte collected by Sir Arthur Russell at Manvers Main Colliery, Wath-upon-Dearne; and the collection of the National Coal Mining Museum for England. An appeal for information about material in private collections produced information about specimens from Kellingley Colliery in the collection of Jon Evans.

Coal Measures borehole logs, available on the *Geology of Britain viewer* (British Geological Survey, 2017) were also examined. It would be impractical to include every record of common minerals such as 'ankerite', calcite, dolomite, kaolinite, pyrite and siderite (or the variety sphaerosiderite). However, notable borehole and shaft-section reports of calcite, galena and kaolinite are summarised in Tables 1–3 which are included in descriptions of the respective species.

The text has a bias towards crystallised specimens found in open fractures in Coal Measures sandstones (these form the bulk of the specimens in the Uttley Collection and the institutional collections examined in the course of this research). Authigenic minerals and the cleat mineralisation found in the coal (Spears, 2015) are noted as they make an interesting comparison to the fracture mineralisation. Detrital minerals (summarised briefly in the section on Coal Measures lithologies) are omitted. Mineralisation in the ironstones (particularly in syneresis cracks in clay-ironstone nodules) is described, although references are few. Supergene or post-mining assemblages from Coal Measures localities are noted wherever possible. Geological substances such as coal, which were regarded as minerals in many early accounts (e.g. Greg and Lettsom, 1858), but which do not fall within the modern definition of a mineral are excluded. However, some text is given over to hydrocarbons.

Species subtitles in the descriptive section are in uppercase and normal font if there is no doubt about the identification; they are italicised if doubt exists as to the identification or the validity of the species; and listed in lowercase if they are discredited.

ANATASE, TiO_2

Authigenic anatase is widespread in the Yorkshire Coal Measures. It occurs as overgrowths on leucoxene in Coal Measures sandstone. Anatase is reported as a constituent of fireclay at Amber Thorn, Denholme, Elland, Gildersome, Queensbury and Tong in Brindley and Robinson (1947).

ANKERITE, $Ca(Fe^{2+},Mg,Mn^{2+})(CO_3)_2$

The mineral name ankerite is used inconsistently in geology. Dolomite-group minerals have a general formula $CaM^{2+}(CO_3)_2$, in which the M^{2+} cations are commonly Mg^{2+}, Fe^{2+} and Mn^{2+}; modern guidelines produced by the International Mineralogical Association (IMA) define ankerite as the mineral with Fe^{2+} as the dominant cation in the M^{2+} site. However, systems of nomenclature which describe iron-rich dolomite as ankerite are in common use (see Bridges *et al*., 2014 for a detailed discussion). In the absence of quantitative chemical data for specimens from south Yorkshire, the term ankerite is used *sensu lato*. Almost all of the 'ankerite' described in the references quoted herein is Fe^{2+}-rich dolomite.

'Ankerite' is commonly recorded as a minor constituent of Coal Measures rocks in borehole logs (British Geological Survey, 2017). It is, for example, noted in the cleat of the coal at several horizons in the Kirkby Common Borehole, which was sunk from SE 4354 1025, just west of South Kirkby near Wakefield. It is recorded as "discs with radial ornament" in two mudstone bands below the Shafton Coal Seam in the Greavefield Lane No. 7 Borehole, which was sunk from SE 4771 2180, east of Pontefract. It is described in joints in shale just above the Flockton Thin Seam in the New Lodge No. 3 Borehole was sunk from SE 3352 0928 about 2 km NNW of Barnsley. It is present as veins in ironstone in the Woolley Colliery No. 26 Underground Borehole, which was cored in 1968 from SE 3146 1208 at Woolley Colliery between Barnsley and Wakefield.

Ankerite is commonly noted as an impurity in coal (National Coal Board, 1984: p. 66), and is reported in the cleat of the coal in South Yorkshire by Uttley (1993) as follows:

> "Common mineral from within the 'cleat' of coal seams. It is very rare to find any resemblance to crystals, more usually it is found as thin (<1mm) dirty white crystallised coatings. Crystals have only been noted from a cavity at Kiveton Park Colliery and closely resemble dolomite".

In an account of minerals found in the cleat of English Coal offered for sale in London, Crooke (1911) provides analyses of 'ankerite', all of which correspond to Fe^{2+}-rich dolomite. The same applies to the average composition of 17 'ankerite' specimens reported by Spears and Caswell (1986) from Yorkshire Main and Thoresby collieries.

[7] Joseph Dawson (1740–1813) was one of the founders of the Low Moor Ironworks near Bradford. He had wide interests including mineralogy and chemistry, and applied scientific principles to the production of iron. His mineral collection is accompanied by a manuscript catalogue, and includes specimens from the coal and iron mines that supplied the Low Moor Ironworks (Dawson, 1810–1813; Pacey, 2003).

Figure 12. Simplified sketch map showing the locations of the principal mineral localities described in the text. Drawn by Peter Briscoe.

The Mansfield Cank is a carbonate band from which 'ankerite' and siderite are commonly described. It is locally present near the base of the Mansfield Marine Band [now the Aegiranum Marine Band] (Taylor and Spears, 1967; Taylor, 1971; Ramsbottom *et al*., 1974). Analyses in Dunham (1960, p. 238) and Taylor (1971: p. 318) correspond to Fe^{2+}-rich dolomite. The same applies to the 'ankerite' which is the principal component of the Sub-Clowne Carbonate Bed over a significant area of northeast Derbyshire and adjoining areas of Nottinghamshire and south Yorkshire. Rippon and Spears (1989: p. 196) calculate empirical formulae of $Ca_{1.0}(Mg_{0.85},Fe_{0.11}Mn_{0.04})(CO_3)_2$ and $Ca_{1.14}(Mg_{0.51},Fe_{0.30},Mn_{0.05})(CO_3)_2$; in both cases, Mg is the dominant cation at the M^{2+} site; the first analysis contains a relatively small amount of iron and is a typical dolomite, the second is an Fe^{2+}-rich dolomite, but even in this case, Mg is considerably in excess of Fe.

Descriptions of tension cracks in pyrite infilled by 'parankerite' in Taylor (1971: p. 320) do not refer to ankerite in the modern sense, but to dolomite containing about 10% Fe^{2+}.

An occurrence of ankerite in fractures at Kiveton Park Colliery near Rotherham, South Yorkshire, is recorded in Uttley (1993):

> "Crystals similar to dolomite, up to 7 mm of a light brown colour were found associated with calcite crystals and pyrite from a cavity in the sandstone roof of the High Hazel Seam on H01's face".

This description is a good match to a specimen labelled "Calcite, Dolomite" from the "H01s Roof Kiveton Park Colliery" (catalogue number 203 in the Uttley Collection). The only inconsistency is that it is labelled dolomite rather than ankerite. As the specimen labels pre-date publication of *Minerals of South Yorkshire* by some years, it may be that analyses carried out at British Coal's regional scientific laboratories, revealed that the dolomite from this locality was particularly iron-rich and it was decided that it would be better described as ankerite.

A quantitative X-ray fluorescence analysis of handpicked fragments from specimen 203, freed as far as possible from sulphide and calcite, corresponds to the empirical formula $Ca_{1.07}(Fe^{2+}_{0.59},Mg_{0.29},Mn^{2+}_{0.05})(CO_3)_2$ (Clifford Rice, *personal communication*, 2017). A small correction was made for included sulphide (~1%), which could not be fully separated from the sample. The formula lies within the ankerite composition field and appears to be the only record of ankerite *sensu stricto* supported by quantitative data from the Yorkshire Coal Measures. Excess calcium is commonly reported in analyses of dolomite-group minerals; it may, in this case, be due to calcite impurities in the handpicked sample, or to calcite nanodomains in the ankerite structure.

Specimen 203 measures 65×40×40 mm and consists of brown crystals of ankerite up to 5 mm on edge overgrown by calcite (Fig. 13). The ankerite occurs as selvedges which have become detached from the walls of a fracture in medium-grained well-bedded sandstone. Chalcopyrite and pyrite occur as subhedral to euhedral inclusions in the ankerite and as euhedral crystals on exposed surfaces. Pyrite forms minute cubic and cuboctahedral crystals and rare capillary masses. Chalcopyrite occurs as brassy yellow sphenoidal crystals up to 2 mm on edge. The overgrowing calcite occurs as colourless to white, blocky to tabular, nailhead crystals up to 11 mm across with rhombohedral terminations and relatively short prism faces.

APATITE

The term apatite is used herein to describe undifferentiated calcium- and phosphate-bearing members of the apatite group. Phosphate, most of which is likely to be apatite, is commonly reported in analyses of Coal Measures rocks (e.g. Smyth *et al*., 1856; Dunham, 1960: p. 239; Pearson, 1974a). Material described as collophane (a cryptocrystalline colloform variety of apatite) or 'fossilised phosphate', is likely to be carbonate-rich hydroxylapatite (Knowles, 1963; Deans, 1936). The mineral component of the fossil bones and teeth is typically carbonate-rich hydroxylapatite (e.g. Trueman and Tuross, 2002).

Apatite is recorded as yellow-brown cryptocrystalline collophane in the Aegiranum Marine Band at Tinsley Park, Sheffield and occurs as idiomorphic crystals up to about 15 μm across at the same horizon (Taylor, 1971). It is noted as carbonate-apatite and collophane in the Alton Marine Band [now the Listeri Marine Band] by Knowles (1963). Collophane is also recorded in a calcite concretion (bullion) in the Hard Bed Marine Band near Wilsden, Bradford (Stephens *et al*., 1953: p. 116).

Shrinkage cracks in ironstone filled with kaolinite and crystalline apatite, and apatite ooliths in grey siderite, are described by Deans (1936) at Robin Hood Quarry near Thorpe-on-the-Hill, south of Leeds. Analyses show the apatite, which occurs as isolated tabular crystals up to 0.5 mm across and as crystalline aggregates in kaolinite peloids, is carbonate-rich fluorapatite. It was described using the now discredited name francolite; the OH:F ratio is 1:3, and no chlorine is present (Deans, 1938). A specimen is preserved at the Natural History Museum (London) under accession number BM 1978,376. Three other occurrences of "crystalline phosphate" are described by Deans (1936)

Figure 13. Brown rhombs of ankerite up to about 5 mm on edge [with an empirical formula $Ca_{1.07}(Fe^{2+}_{0.59},Mg_{0.29},Mn^{2+}_{0.05})(CO_3)_2$], with minor chalcopyrite, overgrown by later calcite. Specimen 203 in the Uttley Collection from the sandstone roof of the High Hazel Seam at Kiveton Park Colliery, near Rotherham, South Yorkshire. Photo John Chapman.

in the richest, at Bowling near Bradford, apatite makes up almost 10% of the rock in some 'oolitic ironstones'.

In analyses of siderite from ironstone nodules found near the Listeri Marine Band at Hazlehead near Penistone, Pearson (1974b) assumed that all the P_2O_5 was present as hydroxylapatite. He later described an unusually phosphate-rich nodule from the site with an approximate composition "siderite 50%, apatite 25%, clay minerals 14%, and quartz 7%", which contained abundant hydroxyl-rich carbonate fluorapatite, with an OH:F ratio of 1:1.4 (Pearson, 1976).

Small euhedral pyramidal crystals (<1 mm) of chloride and carbonate-rich apatite associated with dickite and siderite occur in fractures in ironstone found in backfill at the defunct Smithy Wood Opencast, Chapeltown, Sheffield. The ironstone is from the 25 m of shale and sandstone overlying the Upper (or Top) Silkstone Seam (Neall, 2004) and is probably part of the Claywood Ironstone (Mitchell *et al*., 1947).

Apatite is abundant in some Coal Measures tonsteins, thin kaolinite-rich beds produced by the alteration of volcanic ash. Euhedral apatite crystals containing fluid inclusions are illustrated in Spears (2012). In some Coal Measures tonsteins, such as the Rowhurst Tonstein in Staffordshire (Wilson *et al*., 1966), and one of the tonsteins exposed at the Oxbow Opencast Site near Swillington, West Yorkshire (Perrin, 1971) the calcium aluminium phosphate crandallite occurs with apatite. Monazite-series minerals have also been identified in the clastic rocks. It is not safe to assume, therefore, that all of the phosphate in chemical analyses of Coal Measures rocks can be assigned to apatite-group minerals. However, apatite is commonly present in the heavy mineral suites isolated from Coal Measures sandstones (Hallsworth and Chisholm, 2000) and is particularly abundant in Langsettian sandstones with a northern source (Chisholm *et al*., 1996).

ARAGONITE, $CaCO_3$

Post-mining aragonite has been reported in recent flowstone in mine levels at Caphouse Colliery near Wakefield (Davies-Vollum *et al*., 2016). It is likely to be common as a recent deposit in similar environments throughout the South Yorkshire Coalfield. Aragonite is stabilised by the presence of Mg^{2+} in solution, which inhibits the formation of calcite, allowing the ion activity product to increase until aragonite can form (Hill and Forti, 1997).

BARYTE, $BaSO_4$

Baryte is widespread in small amounts in Coal Measures rocks. It is recorded "scattered through the ankerite layers in the form of crystalline plates" in the cleat of English coal in Crook (1911) and in the cleat of coal from the Top Hard Seam at Thoresby Colliery in Yorkshire by Spears and Caswell (1986). Veins of baryte are present in ironstone nodules from the Thorncliffe White Mine, Parkgate, south Yorkshire and Thorncliffe or Old Black Mine (Smyth *et al*., 1856). At Civilly Rake in Derbyshire an ironstone nodule band described as the "chance balls...exhibit[s] cracks lined with crystalline barytes of white and pinkish hue" (Smyth *et al*., 1856: p. 44).

Rosettiform baryte occurs in a shale band above the Two-Foot Coal at Borough Colliery, north of Barnsley (Mitchell *et al*., 1947: p. 70). Baryte is noted without description in the Coal Measures above the Wales Seam near Whitwell, Derbyshire (Ineson *et al*., 1972); this observation is supported by the log of the nearby Buskeyfield Lane Borehole, which was sunk from SK 5617 7198, about 0.8 km north of the village of Cuckney, in 1972. The borehole log notes a "large near-vertical mineralised joint with barytes and a little galena" in sandstone at a depth of about 696 ft (32ft above the Wales Seam) (British Geological Survey, 2017). Ineson *et al*. (1972) also note baryte "in one or two veins at the Parkgate horizon near the shafts at Bevercotes Colliery" north of Ollerton in Nottinghamshire. Recent baryte precipitates, comparable to the so-called 'Sunday stones'[8], which are well known from collieries in the northeast of England have also been reported at Bevercotes Colliery, where baryte precipitates accumulated in some of the shaft linings. In addition to these localities, a number of collieries have produced noteworthy specimens.

Hickleton Colliery

Hickleton Colliery is situated in the village of Thurnscoe, between Doncaster and Barnsley, South Yorkshire; it was amalgamated with nearby Goldthorpe Colliery in 1986. Baryte was discovered by John Wilson (the mine geologist for the Goldthorpe/Hickleton complex) and Steve Uttley, in November 1987. The mineralisation was exposed in fractures in a siltstone unit between two faults in a development roadway driven at the Parkgate Seam level.

Baryte was identified by energy-dispersive spectroscopy on a scanning electron microscope at British Coal's regional scientific laboratories and is described by Uttley (1988b) as follows:

> "Rarely found in the South Yorkshire coalfield, this mineral occurs at Hickleton as slender transparent orthorhombic crystals up to 15 mm long often with a coating of dolomite or kaolinite on some of the faces. Many of the crystals are similar to those from Silverwood ... occasionally the crystals show parallel growth with multiple terminations, the largest of these being 7.5 mm in length, ... One fracture contained massive barite with small crystals at the edges, this massive variety shows a slight pinkish tinge caused by iron staining".

A specimen from Hickleton Colliery was donated to the Natural History Museum (London) where it is preserved under accession number BM 1988,107; it has a small colourless baryte prism on creamy dolomite with chalcopyrite and either kaolinite or dickite.

Two specimens were found in the Uttley Collection when it came into the authors' possession. Number 149

[8] Baryte precipitates from coal mines in the northeast of England are described by Smythe (1922). A short discussion of 'Sunday stones' and of the necessity of keeping different aqueous streams separate to prevent pipes becoming blocked by baryte is provided by Bridges and Green (2006: pp. 79–80).

is a small siltstone fragment overgrown by dolomite with a 6.5 mm baryte crystal aggregate made up of two colourless, transparent, prismatic crystals in parallel growth (Fig. 14). The baryte contains minute inclusions of an unidentified sulphide mineral and is overgrown by a few late-stage dolomite rhombs. One side of the crystal group has a stoss-side deposit composed of minute inclusions, possibly of dolomite, just below the crystal surface (Fig. 15).

A large specimen, without a catalogue number, has a planar fracture at a high angle to the bedding in well cemented siltstone. The 200×100 mm fracture surface is coated by millimetre-size buff dolomite rhombs, which form a crust between 1.5 and 2.5 mm in thickness. Tarnished chalcopyrite crystals up to 2 mm on edge are scattered on the dolomite. A number of colourless, transparent, prismatic baryte crystals, up to 5 mm in length, are also present. They typically have a simple prismatic crystal habit (see Figure 3 in Uttley, 1988b).

In common with many other coalfield specimens, baryte crystals from Hickleton Colliery are elongated along the *a*-axis, with prominent prismatic *o* {011}. The faces which make up the complex termination of the crystal on specimen 149 are labelled with form letters in Figure 16, and shown in clinographic projection in Figure 17.

Kellingley Colliery

At Kellingley Colliery to the east of Knottingley in North Yorkshire, a cavity approximately 0.5×1.8 m across and up to 3 m deep, lined with dolomite and chalcopyrite, contained a single baryte crystal very similar in appearance and morphology to those from Hickleton and Silverwood collieries (Jon Evans, *personal communication*, 2016).

Kilnhurst Colliery

Discoloured baryte was reported from a small fault fissure in the Parkgate Seam close to the Don Fault at Kilnhurst Colliery near Rotherham by Forster-Smith (1959).

Manvers Main Colliery

In 1930, a large cavity, which contained euhedral prismatic and tabular baryte crystals up to 70 mm in length associated with chalcopyrite and dolomite, was encountered in the roof of the Parkgate Seam at No. 3 Pit, Manvers Main Colliery, Wath-upon-Dearne, South Yorkshire. The discovery was sufficiently interesting to generate the following request from the curator of Sheffield Museum on 17 February of that year:

> "I have been informed by Dr. Banham, Yarra House, Sheffield, that you have come across a deposit of barium sulphate during the workings in one of your collieries, and he thought that you would be disposed to supply a good museum specimen if I made application to you. I should be very glad indeed to obtain a specimen for our mineralogical collections".

The general manager, Arthur T. Thomson, replied by return on elegant headed notepaper:

> "In reply to yours of the 17th inst, we had a fall in the waste in the Parkgate Seam that brought down some Barium Sulphate crystals. There had evidently been a cavity in which they had been formed and they are speckled with Pyrites. Unfortunately, in the fall, they were rather damaged, but I will endeavour to get you a sample as good as possible for your Museum".

A large cabinet specimen covered in euhedral transparent baryte crystals (accessioned as SHEFM: 1930.1) was delivered to the museum the next day! The curator replied:

> "I thank you for your letter of February 18th in which you kindly offered to find us a good specimen of Barium sulphate crystals from your Parkgate seam. This duly arrived by your messenger this afternoon, and I must express cordial thanks for your kindness in securing so splendid a specimen for the Museum. I shall have pleasure in submitting it to the committee in due course".

The specimen was on display at Sheffield City Museum in the early 1990s (Uttley, 1993) but is now in the museum store (Fig. 18). It consists of transparent prismatic baryte crystals up to 50 mm long covering one side of a large piece of dolomite-encrusted sandstone. Dolomite on the reverse of the specimen and some of the baryte crystals are overgrown or included by small brassy sphenoidal chalcopyrite crystals. The chalcopyrite crystals, which reach about 2 mm on edge, formed at a late stage in the deposition of the baryte, which surrounds and overgrows some of them, indicating contemporaneous precipitation of sulphide and sulphate.

A short descriptive article, including a photograph of a specimen, was written by the company's chemist Cornelius P. Finn[9] (Finn, 1930), who was made aware of the discovery early in the summer of 1930. A more comprehensive account was provided by Sir Arthur Russell (1934), who made several visits to the colliery to collect specimens. Russell notes:

> "... a large cavity lined with exceedingly beautiful crystals of baryte; this being the first occurrence of the kind recorded in the south Yorkshire coalfield. The cavity was quickly more or less completely wrecked by the miners, when fortunately my friend, Mr. C. P. Finn, the Company's chemist, had his attention drawn to the matter, and as a result some brief notes on the occurrence, accompanied by a photograph of a specimen, were published ... Thanks to the efforts of Mr. Finn, and as the result of visits to the colliery, I was able to obtain some very fine and interesting specimens of the mineral".
>
> "The cavity was in a compact grey sandstone, directly overlying the Parkgate Seam, and apparently occupied a small fault. Its dimensions as ascertained

[9] Cornelius Philip Finn (1880–1961) earned a BSc in chemistry in 1901. After a number of positions in research and management, he was appointed manager of the coke-oven, washery and brickworks departments at Manvers Main Colliery where he remained from 1920 until 1934. It was during this period that a cavity lined with outstanding baryte crystals was encountered in No. 3 Pit. A keen amateur photographer, Finn published a photo of a large and impressive "representative" specimen, though he noted that "many more perfect crystals were found" (Finn, 1930).

Figure 14. Colourless transparent baryte crystal group, 6 mm in length, with overgrowing rhombohedral dolomite from Hickleton Colliery, Thurnscoe, South Yorkshire. The faces are labelled with form letters in Figure 16. Specimen 149 in the Uttley Collection; photo John Chapman.

Figure 15. Colourless transparent baryte crystal group, with overgrowing rhombohedral dolomite from Hickleton Colliery, Thurnscoe, South Yorkshire (reverse side of Figure 14 showing prominent prismatic *o* {011} and minute stoss-side dolomite inclusions). Specimen 149 in the Uttley Collection; photo John Chapman.

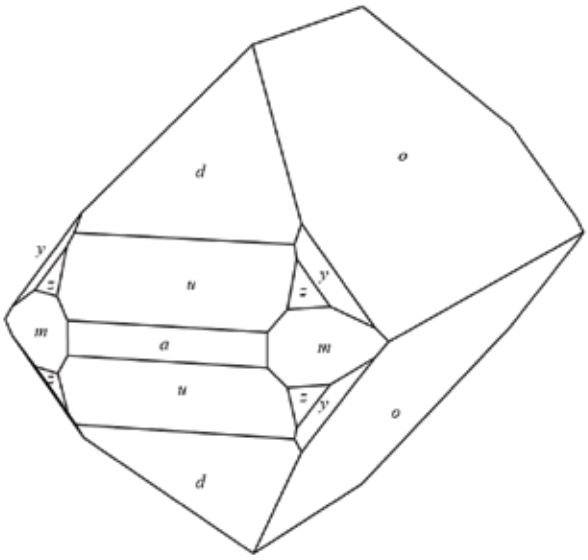

Figure 17. Idealised crystal drawing showing the forms and crystal habit of baryte from Hickleton Colliery, Thurnscoe (and from Sandy Flat Borehole), based on goniometric measurements carried out in this study. Miller indices for the lettered forms are *o* {011}; *d* {101}; *u* {201}; *a* {100}; *m* {210}; *y* {111}; and *z* {211}. The drawing has the c-axis set vertical. Drawing produced using SHAPE software.

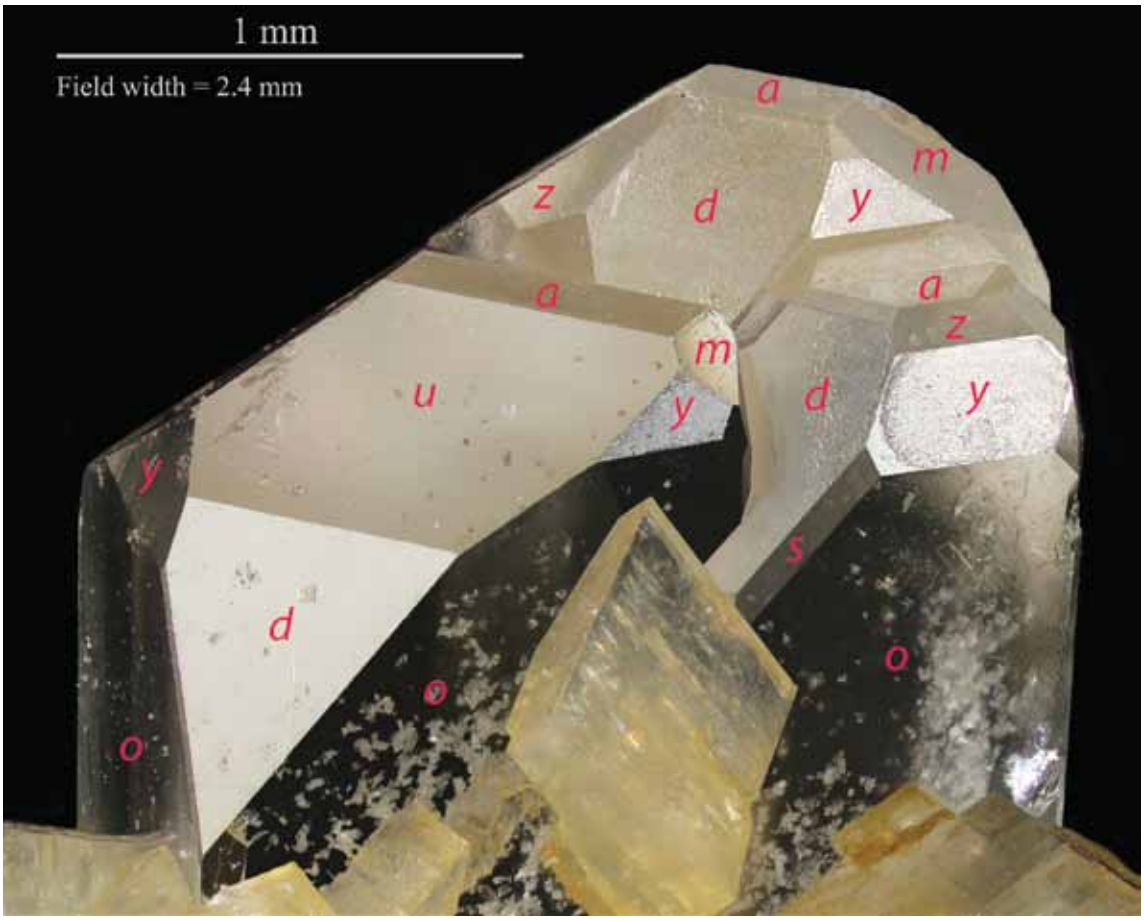

Figure 16. The termination of a prismatic baryte crystal from Hickleton Colliery, Thurnscoe, with form letters after Dana (1892). Miller indices for the lettered forms are *o* {011}; *d* {101}; *u* {201} *a* {100}; *m* {210}; *y* {111}; and *z* {211}. The face labelled with the letter *s* could not be measured, but visual inspection suggests it is likely to be μ {112} (see Figure 21). The photograph has the *a*-axis approximately vertical. Specimen number 149 in the Uttley Collection; photo John Chapman.

Figure 18. Transparent prismatic baryte crystals, elongated on the *a*-axis and showing dominant prismatic *o* {011} terminated by triangular *d* {101} on a 250 mm wide specimen presented by Arthur T. Thomson, the manager of Manvers Main Colliery, to Sheffield Museum in February 1930. Small sphenoidal chalcopyrite crystals, misidentified as pyrite on the original label, are present as euhedral inclusions near the surface of some of the baryte crystals and on dolomite on the back of the specimen. Sheffield Museum specimen, SHEFM: 1930.1; photo Peter Briscoe. **Inset**. Many early specimens in the Sheffield Museum mineral collection have accession numbers preceded by the letter code I, which was used to indicate that they were part of the mineral collection. This convention was eventually abandoned and the letter code is no longer a valid part of the accession number. The letter I can still be seen preceding the accession number on many older specimens and on the letters and documents in associated history files.

> by Mr. Finn were 5 yards in length, 5 yards in height, and from 12 to 15 inches wide at the base, tapering to nothing at the apex, and it was discovered only by the falling away of the sandstone roof".
> "The baryte crystals, which are colourless and more or less transparent, are of two distinct types, prismatic and tabular, the occurrence of the two habits in the same cavity being somewhat remarkable. They are attached to small cream-coloured rhombohedra of dolomite, which form a coating on the sandstone, both baryte and dolomite being for the most part more or less thickly sprinkled with small, up to 2½ mm., bright twinned crystals of chalcopyrite ...".

Two distinct crystal habits, described as prismatic and tabular, were found. Both were measured using an optical goniometer[10] (Russell, 1934: p. 319). The prismatic crystals reach 70 mm in length, contain rare chalcopyrite inclusions, and have a similar habit to the baryte from Silverwood Colliery, Hickleton Colliery, Kellingley Colliery and Thurcroft Colliery. Baryte specimens from Manvers Main Colliery (Figs 19 and 20) are preserved in the Russell Collection at the Natural History Museum (BM 1964,R11694–11697). A crystal drawing converting the measurements in Russell (1934) to modern Miller indices is provided as Figure 21.

Chemical analysis of one of the baryte crystals (Finn, 1930) revealed a near end-member composition, containing 98.5% $BaSO_4$. The reported density of 4.5 g cm^{-3}, is very close to the accepted density of 4.48 g cm^{-3} for end-member $BaSO_4$. Small amounts of strontium (0.18% $SrSO_4$) and calcium (0.65% $CaSO_4$) are the only impurities noted in solid solution.

[10] Traditional Miller indices are used by Russell (1934) in descriptions of crystals from Manvers Main Colliery; these use morphological axes of reference with $a : b : c = 0.8152 : 1 : 1.3136$. Indices based on the unit cell determined by X-ray crystallography with $a = 0.8884(2)$ nm, $b = 0.5457(3)$ nm and $c = 0.7157(2)$ nm, and axial ratios $a : b : c = 1.628 : 1 : 1.312$ are used herein. They are not identical.

Figure 19. Typical prismatic baryte crystals with chalcopyrite and dolomite from Manvers Main Colliery, Wath-upon-Dearne; given to Sir Arthur Russell by Cornelius Finn in July 1933 (BM 1964,R11697). The crystal fragment in the tube was used for goniometry. From the collections of the Natural History Museum, London. Photo Roy Starkey.

Figure 20. Unusual tabular baryte crystals on dolomite from Manvers Main Colliery, Wath-upon-Dearne, in the collection of Sir Arthur Russell at the Natural History Museum, London (BM 1964,R11694). From the collections of the Natural History Museum, London. Photo Roy Starkey.

Orgreave Colliery

Red massive baryte (originally misidentified either as ankerite, according to a handwritten note on a file-card; or as gypsum, according to Uttley, 1993), interlayered with mudstone was collected from the roof of the Swallow Wood Seam at Orgreave Colliery, about 5 miles south of Rotherham, by Steve Dumpleton, the mine geologist. A specimen is preserved at Caphouse Mining Museum according to Uttley (1993), but could not be found on a visit in 2016; others were donated to Sheffield Museum (Fig. 22).

Sandy Flat Borehole

The Sandy Flat Borehole was started from SK 4767 9095, on Sandy Flat Lane, Wickersley, Rotherham. The log records "subvertical barytes infilled joints from 867.6 – 868.5[m] with 2 cm displacement" in the Silkstone Rock, a thick channel sandstone of Langsettian Age (British Geological Survey, 2017). Baryte is described as a "Single transparent orthorhombic crystal on dolomite from [a] fissure" in Uttley (1993). The corresponding specimen,

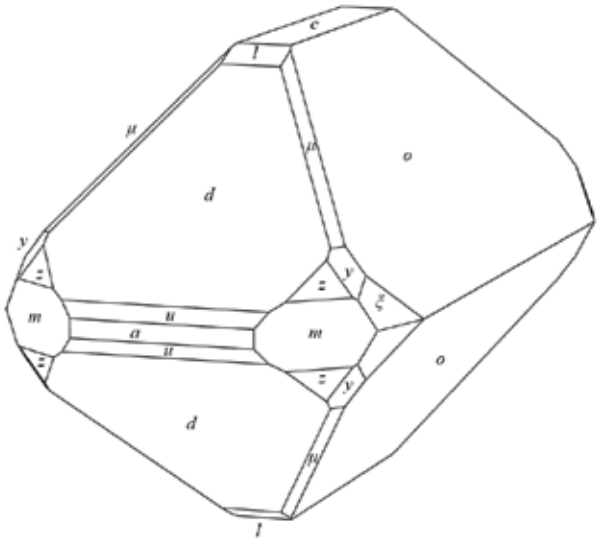

Figure 21. Idealised crystal drawing showing the forms and typical crystal habit of prismatic baryte from Manvers Main Colliery, Wath-upon-Dearne, based on goniometric measurements listed in Russell (1934). Miller indices (using modern axes) for the lettered forms are *o* {011}; *c* {001}; *d* {101}; *u* {201}; *a* {100}; *m* {210}; *y* {111}; *z* {211}; *μ* {112}; and *ξ* {121}. Form letters are after Dana (1892). Drawing produced using SHAPE software.

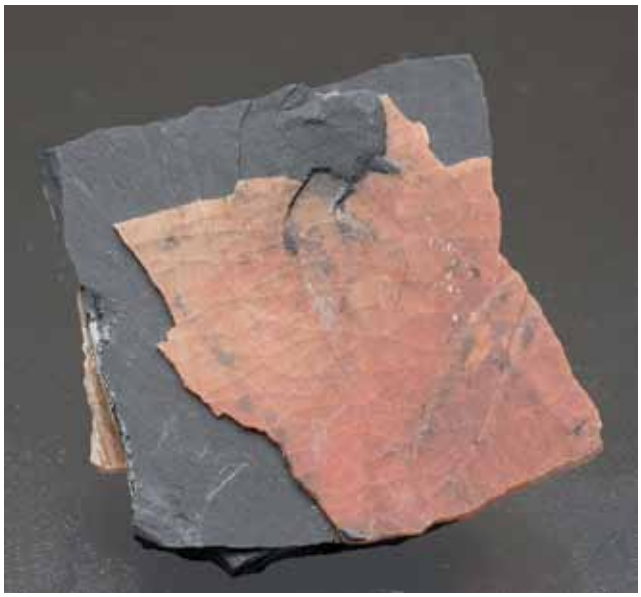

Figure 22. Massive pink baryte infilling fractures in typical dark grey mudstone above the Swallow Wood Seam at Orgreave Colliery. Donated by Steve Uttley to Sheffield Museum, and accessioned as SHEFM: 1988.17. Photo Peter Briscoe.

number 268 in the Uttley Collection, is a 50×60 mm section of a near-vertical dolomite-lined fissure removed from a borehole core. Drusy, pale buff dolomite with a pearly lustre coats the fissure walls. A double terminated, colourless, transparent, prismatic baryte crystal, 9 mm in length (Fig. 23), is conspicuous, and other mostly broken crystals are also present. The large crystal is prismatic, elongated on the *a*-axis, and has a complex termination. One of the smaller crystals has a minor dolomite overgrowth. Chalcopyrite occurs rarely as brassy yellow sphenoidal crystals up to 0.9 mm on edge and as inclusions in dolomite. There is also a single slightly distorted pyrite crystal 0.8 mm on edge with unequally developed octahedral faces.

Silverwood Colliery

Baryte is recorded from Silverwood Colliery, to the east of Rotherham, South Yorkshire by Uttley (1987):

> "When, recently, a large specimen came into the office covered with dolomite and minor pyrite [the pyrite described herein is a misidentification which was subsequently corrected to chalcopyrite (Uttley, 1993)], it looked nothing out of the ordinary. It was only on close observation that, on one side of the sample, small (<0.5 cm) orthorhombic clear crystals, some double terminated, were found on the dolomite with far less pyrite than the other side. It was decided to test these further".
>
> "The sample was found by Roy Fry, a British Coal mine geologist in a fissure on S21's Intake Trunk Roadway at Silverwood Colliery. It consists of a large irregular piece of sandstone on which an 18 cm, area is highly mineralised, this being completely covered by dolomite as small clear curved rhombohedral crystals, the pyrite and orthorhombic mineral show a gradual zoning as shown in Figure 1".
>
> "As the pyrite concentration declines, the orthorhombic mineral comes more into prominence and finally takes over completely from the pyrite. Visually, the orthorhombic crystals especially the double terminated one led us to believe they were barite. It was tested in the office and gave possible results for barite. To confirm this it was sent to British Coal's Yorkshire Regional Laboratory for S.E.M. testing. This confirmed our assumption, as it showed barium and sulphur".

Additional stratigraphic data is provided in Uttley (1993) in which it is noted that that the baryte crystals were found in "... fractures in the rock above the Swallow Wood Seam ...".

Figure 23. A double terminated, colourless, transparent, prismatic baryte crystal, 9 mm long, elongated on the *a*-axis, showing prominent prismatic *o* {011} and a complex termination including *d* {101}; *a* {100}; *m* {210}; *y* {111}; and *z* {211}. Specimen number 268 in the Uttley Collection, from Sandy Flat Borehole, Wickersley, Rotherham. Photo John Chapman.

Two baryte specimens from Silverwood Colliery were found in the Uttley Collection in 2016. Specimen number 206 is a roughly quadrilateral 40×50 mm piece of pale grey sandstone, one side of which is coated in colourless translucent drusy dolomite crystals up to about 2 mm on edge. There is a prismatic double terminated baryte crystal 6.5 mm long and other smaller crystals scattered on the dolomite. Sphenoidal chalcopyrite up to 0.8 mm on edge also occurs and examination at high magnification reveals minute (<0.1 mm) pyrite cubes overgrowing baryte, chalcopyrite and dolomite.

Specimen number 250 (Fig. 24) is a small triangular piece of sandstone with very similar mineralisation to specimen 206. It has one relatively large (5 mm) double terminated baryte and a few much smaller crystals. The large prismatic baryte contains three well formed chalcopyrite crystals as near-surface inclusions. Smaller inclusions of pyrite and dolomite, showing stoss-side development, are present just below the crystal surface.

The large Silverwood Colliery specimen (described and sketched in Figure 1 of Uttley, 1987) was not found when the Uttley Collection came into the authors' possession. It is tempting to conjecture that it was broken into smaller pieces and that specimens 206 and 250 are two of these. The notion that the large specimen was broken up would fit with later descriptions, as Prowse (1988) notes that he had received "one of the only four specimens from the site" for morphological studies and another specimen had been donated to the Natural History Museum in London [however, no specimens from Silverwood Colliery are recorded in NHM databases (Mike Rumsey, *personal communication*, 2017)]. The specimen used by Brian Prowse in his goniometric studies was a well-formed single crystal, which was returned to Steve Uttley (Brian Prowse, *personal communication*, 2017). The 2.5 mm and 3 mm crystals labelled "Pyrite on barite", which were photographed by Max Freier and figured in Uttley (1987), were not found in the Uttley Collection in 2016.

A second find at Silverwood Colliery is noted in Uttley (1993) as follows:

> "Crystals similar to S21's found in fault on S51's Return Access but also Galena found with other minerals".

The specimens were collected by Roy Fry, the mine geologist, and are described as present in the Uttley Collection in 1993. They were not found in 2016.

Thurcroft Colliery

A programme of underground drilling was undertaken at Thurcroft Colliery near Rotherham at the time that Steve Uttley held the position of assistant mine geologist (Uttley, 1993). In May 1988 he discovered:

> "Transparent orthorhombic [baryte] crystals similar to [the] ones found at Silverwood Colliery with dolomite and chalcopyrite from [a] fissure in [a] sandstone borehole core".

A specimen, catalogue number 205, is preserved in the Uttley Collection (Fig. 25). It is a piece of pale brown sandstone core from underground borehole number 27. A partly filled fracture is exposed over an area of 40×50 mm. The walls are coated by translucent dolomite rhombs up to 1.5 mm on edge. Baryte occurs as colourless transparent prismatic crystals up to 5 mm long. The crystals are elongated on the *a*-axis with prominent prismatic *o* {011} terminated by *d* {101}. The baryte overgrows complex chalcopyrite crystals up to 1.5 mm on edge. Several crystals have minute chalcopyrite crystals scattered as a stoss-side deposit on their outer surface and stoss-side dolomite is included just below the crystal surfaces in a similar orientation. Two thirds of the fracture is filled with colourless translucent calcite, forming a fissure vein 4 mm thick, which post-dates

Figure 24. Double terminated prismatic baryte, 5 mm long, with prominent prismatic *o* {011} and triangular *d* {101} from dolomite-lined fractures in the sandstone above the Swallow Wood Seam at Silverwood Colliery, Rotherham, South Yorkshire. Three sphenoidal chalcopyrite inclusions are conspicuous as near-surface inclusions. Much smaller dolomite crystals show a stoss-side development. Specimen number 250 in the Uttley Collection; photo John Chapman.

Figure 25. Colourless baryte, 5 mm long, with prominent prismatic *o* {011} and triangular *d* {101}, on biscuit-coloured dolomite with tarnished chalcopyrite. Found in the core from Underground Borehole No. 27 at Thurcroft Colliery, Rotherham in May 1988. Specimen number 205 in the Uttley Collection; photo John Chapman.

the deposition of dolomite, chalcopyrite and baryte. White minutely crystalline kaolinite is exposed in tiny cavities and fissures along one edge of the specimen.

The borehole log records a grid reference for the No. 27 underground borehole at Thurcroft Colliery [SK 5008 9050] and describes the mineralisation found in fractures in sandstone between the Swallow Wood and Haigh Moor seams as "Dolomite, Barite, Calcite, Chalcopyrite, Kaolinite and minor hydrocarbons" (British Geological Survey, 2017). A marginal note in the log records that a specimen was donated to the Natural History Museum, London. It is accessioned as BM 1988,364 and consists of a mineralised fracture exposed along most of the 220 mm length of a borehole core in pale brown sandstone. A single 35 mm tabular grey baryte crystal has grown across the fracture, and there are smaller transparent crystals on translucent dolomite and scattered sphenoidal chalcopyrite. A printed label notes that the core was collected on "17 May 1988, at a depth of 745m below surface by Roy Fry, mine geologist". An accompanying datasheet in Steve Uttley's distinctive handwriting describes "Dolomite, Calcite, Barite, Chalcopyrite, [and] Kaolinite".

Unknown Locality

The only specimen in the Uttley Collection which has become separated from its label and lacks any associated data is one of the most interesting. It is an 80×60 mm plate between 4 and 6 mm in thickness which shows an unusually complete sequence of vein mineralisation. The central section of the plate consists of two thin dolomite-sulphide cheeks with well formed inward pointing crystals which appear to have formed in an open fracture in sandstone. The fracture is filled by massive colourless to white baryte.

Movement subsequently detached one side of this dolomite-baryte vein from the wall and produced a polished slickensided surface on which baryte precipitated. This baryte shows conspicuous slickensiding and must have crystallised at the time the movement occurred. Minute prismatic crystals with a similar habit to other coalfield specimens and their prism zones oriented in the direction of movement are present in open spaces. Subsequent dilation detached both surfaces of the vein from the fracture walls and calcite was deposited as a vein filling (which shows no evidence of slickensiding) and as small scalenohedral crystals in the void spaces.

It is tempting to assume this specimen is one of the lost specimens collected by Roy Fry at Silverwood Colliery, but in the absence of a label it is impossible to be sure.

CALCITE, $CaCO_3$

Calcite is commonly reported in boreholes; it forms white vein infills in near-vertical joints, fractures and faults (Uttley, 1993). Calcite is noted in parallel faults at Bullhouse Colliery with "comby pyrites" (Bromehead *et al*., 1933: p. 88). Calcite and pyrite occur in fractures in coarse Oaks Rock sandstone in the Bolton Dearnsides Borehole; calcite-pyrite mineralisation is also recorded in the Thurcroft Colliery No. 12 Underground Borehole; the Tall Trees Borehole (described in more detail under sphalerite); Hatfield Colliery No. 1 Shaft; the Womersley No. 2 Borehole; and the Wood End Borehole. A fault zone containing heavily brecciated mudstone and siltstone clasts cemented by calcite was encountered in the Backford Lane Borehole. The Rayton Farm Borehole, which is described in more detail under sphalerite, is one of many where near vertical mineralised fractures containing calcite and occasional pyrite were encountered. Fractures in sandstone containing calcite crystals are described at a number of horizons below the Blocking Coal Seam in the Clayton Hall Borehole. Calcite was encountered in near-vertical fractures in sandstone and siltstone at numerous horizons in the Bunker Surface Borehole. An oil-filled cavity lined with calcite crystals is noted in a fault above the Flockton Thin Seam in the New Lodge No. 3 Borehole. Calcite and pyrite are recorded in open fractures in sandstone about 10 m above the Abdy Coal in the Whitwell Wood No. 2 Borehole. Mineral veins are rarely reported in coal seams, but vein calcite is recorded at two horizons in coal seams in the Fenwick Hall Borehole. These localities are summarised in Table 1.

Calcite is recorded with botryoidal siderite and a clay mineral in fractures in septarian ironstone nodules exposed in the banks of Cottingley Beck near Bradford (Deans, 1934). Ironstone with calcite and pyrite bands was found at an unspecified horizon in the East Hardwick No. 5 Borehole. Veins of calcite occur in ironstone nodules at Robin Hood Quarry near Leeds (Burnet and Everett, 1912); in the Goose Carr Lane Borehole, Todwick; in the Silverwood Colliery No. 9 Underground Borehole; and in the BP No. 1 borehole near Hatfield. Further details are included in Table 1.

Calcite is the principal constituent of 'bullions', 'baum pots', and 'coal-balls' carbonate-rich concretions associated with coal seams which are prized by palaeobotanists for their beautifully preserved fossils (Galtier, 1997). A contemporary account of coal balls and baum pots, with mineralogical notes and chemical analyses is provided by Stocks (1884). Calcite coal balls were so abundant at some collieries that they were burned to produce lime (Green *et al*., 1878).

Notable localities for calcite specimens, most of which are represented by specimens in the Uttley Collection or noted in Uttley (1993), are described in the following text.

Bentley Colliery

Bentley Colliery near Doncaster produced "Colourless scalenahedral [*sic*] crystals up to 20mm from [a] fault ... [above the] Parkgate Seam on P02's face" (Uttley, 1993). A large hand specimen, catalogue number 204, in the Uttley Collection consists of colourless transparent scalenohedral calcite crystals up to about 12 mm long on grey siltstone (Fig. 26). Similar scalenohedral crystals were noted by the mine geologist, Chris Robson, in faults in the Swallow Wood to Barnsley Drift at the colliery, but no specimens were preserved (Uttley, 1993). Two specimens of calcite vein breccia from Bentley Colliery were donated to the Caphouse Colliery Collection (accession number YKSMM: 2012.512) by Steve Uttley.

Borehole Location	Description in Log
Bolton Dearnsides Borehole, sunk from SE 4618 0240 near Bolton upon Dearne in 1976.	Calcite and pyrite occur in fractures in the Oaks Rock sandstone.
Thurcroft Colliery No. 12 Underground Borehole. sunk in 1968 from SK 5092 9061.	A 3 cm "calcite and pyrites vein" is recorded about 1 m below the base of the Haigh Moor Coal.
Hatfield Colliery No. 1 Shaft, about 1.6 km northwest of Hatfield.	Calcite veins with pyrite are recorded at a depth of about 11 ft below the High Hazel Coal. There are also records of calcite and pyrite in "stone clunch" [seatearth] in Wilson (1926: p. 191–194).
Womersley No. 2 Borehole sunk from SE 5362 1864 on Churchfield Lane just south of the village of Womersley in 1978.	Mineralised joints containing calcite and pyrite are recorded in sandstone between 687.17 and 687.25 m about 6.5 m above the top of the Silkstone Coal.
Wood End Borehole, sunk from SE 6287 1317, east of Thorne, in 1973.	The borehole intersected "Strong cemented coarse grey sandstone with fine vertical calcite filled pyritised fractures" at a depth of 986 m about 30 m below the base of the Permian and 75 m above the Mansfield [Aegiranum] Marine Band. Calcite-filled fractures are recorded at several other horizons.
Backford Lane Borehole, also known as the Dinnington Colliery No. 8 Surface Borehole, sunk in 1981 from SK 5408 8297, northwest of Worksop.	The language suggests the calcite-filled fault zone, intersected at a depth of 511 m, was particularly complex.
Clayton Hall Borehole, sunk from SE 2667 1178 on the south bank of the river Dearne east of Clayton West in 1975.	Calcite is recorded in vertical or near vertical fractures at numerous horizons.
Bunker Surface Borehole, also known as Shireoaks No. 11 Borehole, sunk in 1977 from SK 5600 8085 on the Chesterfield Canal in Worksop.	Calcite is recorded in vertical or near vertical fractures at numerous horizons.
New Lodge No. 3 Borehole, sunk from SE 3352 0928 about 2 km NNW of Barnsley in 1979.	An oil-filled cavity lined with calcite crystals is noted in a fault above the Flockton Thin Seam.
Whitwell Wood No. 2 Borehole, sunk in 1981 from SK 5272 7788 in Whitwell Wood, about 1.2 km north of the village of Whitwell.	The log notes: "common planar open fractures with euhedral calcite and pyrites coating at 80–85° dip average spacing 0.10–0.15 [m]" in sandstone between 380.61 m and 382.16 m; calcite is also present in joints in sandstone at a depth of 735 m.
East Hardwick No. 5 Borehole sunk from SE 4647 1687 between Ackworth and Thorpe Audlin.	Calcite and pyrite were encountered in ironstone at two horizons, but no stratigraphic details are recorded.
Goose Carr Lane Borehole, also known as Brookhouse No. 13, sunk in 1969 near Upper Cannon Farm, off Goose Carr Lane, Todwick, Sheffield.	The log records "ironstone with calcite veins" 7 inches thick at a depth of 564 ft 3 inches about 5 feet above the Winter Coal.
Silverwood Colliery No. 9 Underground Borehole sunk in 1967 from SK 5244 9369.	The log notes veins of calcite in ironstone.
BP No.1 borehole sunk from SE 693 070 near Hatfield northeast of Doncaster in the search for oil.	Siderite nodules with and kaolinite were encountered at an unspecified horizon, possibly just below the base of the Lower Coal Measures, at a depth of 1121.5 m.
Fenwick Hall Borehole sunk from SE 6054 1616, a few hundred metres east of the village of Fenwick, in 1979.	Records of calcite veins and pyrite at numerous horizons, including two of calcite in coal: "prominent calcite veins" in an unnamed coal at a depth of 326.67 m; and "calcite veins" in the bottom 8 cm of the Newhill Coal at a depth of 351.1 m.

Table 1. A selection of records of the mineral calcite in the Pennine Coal Measures Formation taken from borehole logs made available by the British Geological Survey (2017), from which all of the quotes are taken. Note the common association of calcite and pyrite.

Figure 26. Colourless transparent scalenohedral calcite crystals up to 12 mm long on slickensided siltstone, 110×90 mm, from a fault above the Parkgate Seam at Bentley Colliery near Doncaster. Specimen number 204 in the Uttley Collection; photo Peter Briscoe

Clipstone Colliery

At Clipstone Colliery, Mansfield, Nottinghamshire, colourless transparent to translucent white scalenohedral calcite crystals up to 18 mm in length occur on fractured coarse grey sandstone (Uttley Collection: specimen number 201). A calcite specimen showing scalenohedral crystals up to about 12 mm long on an angular sandstone clast was donated to the Sheffield Museum in 1987 by Steve Uttley and Bob Moore (Fig. 27).

A large hand specimen from Clipstone Colliery (Fig. 28) consists of a vein of pale brown dolomite, about 10 mm thick, overgrown by massive white calcite, which encloses both the dolomite and wallrock clasts. It was deposited following a fracturing event which post-dates the dolomite deposition. Scalenohedral calcite crystals up to 18 mm long are present in an open fracture, which post dates both the white vein calcite and brown dolomite.

Dinnington Colliery

At Dinnington Colliery near Rotherham, calcite was noted by Roy Fry, the mine geologist, as "Colourless "nail head" crystals on massive slickensided calcite from fault associated fracturing on S20's face" (Uttley, 1993). No specimens have been preserved.

Figure 27. Scalenohedral calcite crystals up to 12 mm long on a 70×70 mm specimen from Clipstone Colliery, Mansfield, Nottinghamshire, donated to Sheffield Museum by Steve Uttley and Bob Moore in 1987. Accessioned as SHEFM: 1993.513; photo Peter Briscoe.

Figure 28. Scalenohedral calcite crystals up to 18 mm from Clipstone Colliery, Mansfield, Nottinghamshire. Specimen number JH0 in the Peter Briscoe Collection; photo Peter Briscoe.

Figure 29. Calcite with a dominantly rhombic crystal habit, 9 mm on edge, on dolomite in a fracture in sandstone. Specimen number 199 in the Uttley Collection, from Harworth Colliery, Bassetlaw, Nottinghamshire. Photo John Chapman.

Figure 30. Tabular calcite crystal, 2 mm across, on ankerite from Kiveton Park Colliery, Rotherham. Specimen number 230 in the Uttley Collection; photo John Chapman.

Harworth Colliery

Complex lustrous calcite rhombs up to 10 mm on edge overgrow opaque off-white dolomite on a small hand specimen from Harworth Colliery, Bassetlaw, Nottinghamshire (Fig. 29). The site is not described in *Coalfield Minerals of South Yorkshire* (Uttley, 1993) even though the location is only just outside the coalfield boundary and the mineralisation and geological environment are very similar.

Kiveton Park Colliery

Calcite was found as a vein filling surrounding earlier ankerite from "a cavity in the sandstone roof of H01's face" at Kiveton Park Colliery (Uttley, 1993). It is noted as "transparent, tabular crystals with dolomite and pyrite in the roof of the High Hazel seam" in Uttley (1988a). A specimen with translucent white calcite crystals up to 11 mm across, which have short prism faces and nailhead terminations is preserved in the Uttley Collection (catalogue number 203) and described under ankerite.

On a second specimen (catalogue number 230) from the same locality, colourless transparent euhedral calcite crystals, up to 16 mm across, with short prism faces and nailhead terminations, overgrow ankerite and chalcopyrite (Fig. 30). Other calcite specimens from Kiveton Park Colliery are in the private collection of Bob Moore, and at Sheffield Museum (according to Uttley, 1993); the museum specimens were not found on a visit in 2016.

Figure 31. Grey tabular calcite on a 200×160 mm specimen (SHEFM: 1904.3) from Orgreave Colliery, Sheffield; one of several specimens purchased by Sheffield Museum in 1904 from Mr Waddington of Irving Street. Photo Peter Briscoe

Orgreave Colliery

A "group of "nail head" crystals from [the] Flockton Seam" at Orgreave Colliery about 5 miles south of Rotherham, South Yorkshire is figured in Uttley (1993: pp. 5 and 10). The specimen is in Sheffield Museum, measures "roughly 10 inch by 9 inch", and is "coated with iridescent pyrite". The occurrence is further described by Bradshaw (1914) in the *Proceedings of the Sheffield Naturalist Club*.

The figured specimen could not be identified with certainty on a visit to Sheffield Museum in late 2016. Three specimens from Orgreave Colliery were located. They display tabular rhombohedral crystals up to about 50 mm across on sandstone; some of the crystals are coated in drusy pyrite (Figs 31 and 32).

Figure 32. Thin tabular calcite crystal up to about 50 mm on edge on a large cabinet specimen (230×180×120 mm), from Orgreave Colliery (SHEFM: 1904.2). One of several specimens purchased by Sheffield Museum in 1904 from Mr Waddington of Irving Street. Photo Peter Briscoe.

Townend Quarries

Fine specimens of calcite were found in the ganister quarries and mines on Townend Common, near Deepcar, Sheffield. They are described by Kenworthy (1915: p. 18):

> "Calcite or Calc Spar, is often found in the fissures which sometimes occur in our beds of gannister [*sic*]. It assumes the form of lovely milk-white crystals ... and ... crystallizes in the hexagonal system, occasionally yielding very good specimens of Nail Head Spar ... These crystals, which are sometimes encumbered with pyrites, are of great interest in themselves, but their presence would be detrimental to the quality of the gannister [*sic*] if they were allowed to remain, hence the miner rejects them, with some amount of disgust, as a useless product of his labour".

A superb cabinet specimen from the ganister workings in the Little Don Valley is figured in Kenworthy (1915: p. 19). No specimens from the site have been located during this study and the quarry sites have been reclaimed.

CERUSSITE, $PbCO_3$

Cerussite is noted at a single locality in the South Yorkshire Coalfield in Uttley (1993). White acicular crystals less than 1 mm in length were found on massive galena by Roy Fry, the mine geologist, in a core from underground borehole No. 40 at Treeton Colliery, 4 miles south of Rotherham. No specimens have been preserved.

CHALCOPYRITE, $CuFeS_2$

There are few records of chalcopyrite in Coal Measures rocks other that those in Uttley (1993). However, it is common, even for practicing geologists, to confuse pyrite and chalcopyrite. This was the case, for example, in Cornelius Finn's account of the mineralisation at Manvers Main Colliery (Finn, 1930), which was corrected in Russell (1934); and in Steve Uttley's account of the mineralisation at Silverwood Colliery (Uttley, 1987), which was corrected in Uttley (1993).

One of the more intriguing records of Coal Measures mineralisation is of "Dolomitic lst & Copper pyrites" between the High Hazel (or Hazles) Coal and the Two Foot Coal at Hatfield Colliery No. 1 Shaft (Wilson, 1926). At the time it was suggested that it was a bed of dolomitic limestone, an interpretation occasioned considerable debate among coalfield geologist of the day. In light of subsequent discoveries, it seems much more likely that the shaft intersected a large mineralised fracture.

In the Holbeck Borehole, near the village of Whitwell in Nottinghamshire, "Calcite and ? chalcopyrite crystals" are recorded in a mineralised joint in Coal Measures sandstone between 288 ft 10 in. and 290 ft 4 in. (British Geological Survey, 2017). In the nearby Buskeyfield Lane Borehole, joints containing "a white powder-like deposit [kaolinite or dickite]; mineralised with chalcopyrite and calcite" occur in the seatearth below the Clowne Seam (British Geological Survey, 2017).

Chalcopyrite occurs in ironstone nodules but records are few. Meade (1882: p. 349) notes that: "A distinct trace of copper was detected in 500 grains of [ironstone] the White Bed Mine" near Sheffield. Copper was also identified in the Old Man and Old Woman nodule bands at Hady near Chesterfield, Derbyshire; and chalcopyrite is noted in the syneresis cracks (Smyth *et al*., 1864: p. 58).

Chalcopyrite is noted, on the basis of specimens in Sheffield Museum, from South Kirkby Colliery, Wakefield, West Yorkshire; and Denaby Colliery, Mexborough, South Yorkshire, in Uttley (1993). It is associated with dolomite at these localities, but no further information is given. More detailed information is available for the following localities.

Brookhouse Colliery

A 60×40 mm area of iron-stained dolomite in a fracture in well-bedded sandstone, overgrown by sharp sphenoidal chalcopyrite crystals up to about 4 mm on edge, from Brookhouse Colliery, Rotherham, is accessioned in the Sheffield Museum Collection (Fig. 33).

Dinnington Colliery

Chalcopyrite is described from Dinnington Colliery, Rotherham, South Yorkshire with "dolomite and marcasite from faulting on Throapham Main Intake" by Uttley (1993). A specimen labelled "Marcasite Dolomite" is present in the Uttley Collection, but there is no associated chalcopyrite. The golden yellow tarnish on some of the marcasite crystals would make them easy to mistake for chalcopyrite. The occurrence at Dinnington Colliery must, therefore, be treated with caution.

Frickley Colliery

Frickley Colliery, near the centre of South Elmsall in West Yorkshire, was one of the largest coal mines in Britain. Chalcopyrite crystals "up to 2mm on dolomite from

Figure 33. Complex sphenoidal chalcopyrite crystals up to 4 mm on edge on translucent rhombohedral dolomite, from a fracture in well-bedded sandstone above the Silkstone Seam at Brookhouse Colliery, Rotherham. Sheffield Museum specimen, SHEFM: 1989.107; photo Peter Briscoe.

[a] fault in [the] North West Intake Roadway", are described by Uttley (1993). There are two specimens in the Uttley Collection. One was in a card tray with a Steve Uttley label and a second similar specimen had a Peter Briscoe label. In both cases, sphenoidal chalcopyrite crystals up to about 2 mm on edge, some with a slight iridescent tarnish, are abundantly scattered on pale brown rhombohedral dolomite on a matrix of pale grey sandstone (Fig. 34).

Goldthorpe Colliery

A core sample with a 120×60 mm dolomite-lined fracture, overgrown by millimetre-size sphenoidal chalcopyrite crystals, is accessioned as YKSMM:2012.513 in the Caphouse Colliery Collection (Fig. 35). It is labelled "Mineralised Fracture in Drill Core ... Chalcopyrite (Copper Sulphide) on Dolomite" in Steve Uttley's characteristic handwriting. The locality is given as Goldthorpe Colliery, which became part of the Goldthorpe/Hickleton complex in 1986. It seems unlikely that the specimen is from the area of Hickleton Colliery described in Uttley (1988b), as there is no specific mention of mineralised core samples. Surprisingly, the specimen is not recorded in Uttley (1993).

Harworth Colliery

Minute sphenoidal chalcopyrite crystals up to about 0.5 mm on edge, many with a blue to purple iridescence, overgrow opaque off-white dolomite on a small hand specimen (catalogue number 199) in the Uttley Collection from Harworth Colliery, Bassetlaw, Nottinghamshire.

Hickleton Colliery

Chalcopyrite from Hickleton Colliery near Thurnscoe is described and figured in Uttley (1988b); chalcopyrite was:

> "The second most common mineral, it occurs as sphenoidal brassy crystals with striated faces. The largest crystals are 3 mm ... and occur mainly on the dolomite, they also coat some of the barite crystals. Some of the crystals show multiple twinning forming interesting crystals but these are usually small ... There is no secondary mineralisation, most of the crystals being bright and unaltered".

Tarnished sphenoidal and twinned chalcopyrite crystals up to 2 mm on edge are present on dolomite on a large uncatalogued specimen from Hickleton Colliery in the Uttley Collection.

Kellingley Colliery

A metre-scale dolomite-lined cavity containing small bright sphenoidal chalcopyrite crystals was encountered at Kellingley Colliery near Knottingley in North Yorkshire. A few specimens are preserved in the Jon Evans Collection.

Kiveton Park Colliery

Although they are not noted in the subsection of Coalfield Minerals of South Yorkshire that describes chalcopyrite (Uttley, 1993: pp. 5–6), there are three chalcopyrite specimens from Kiveton Park Colliery in the Uttley Collection. Two of them, catalogue numbers 203 and 230 have been described in the foregoing text (under ankerite and calcite, respectively). In both case chalcopyrite occurs as small sphenoidal crystals on ankerite–dolomite and is overgrown by later calcite. On a third specimen sphenoidal chalcopyrite crystals, typically less than 1 mm on edge, are liberally scattered on slightly curved biscuit coloured ankerite rhombs up to 5 mm across on a thin 35×25 mm matrixless dolomite selvedge.

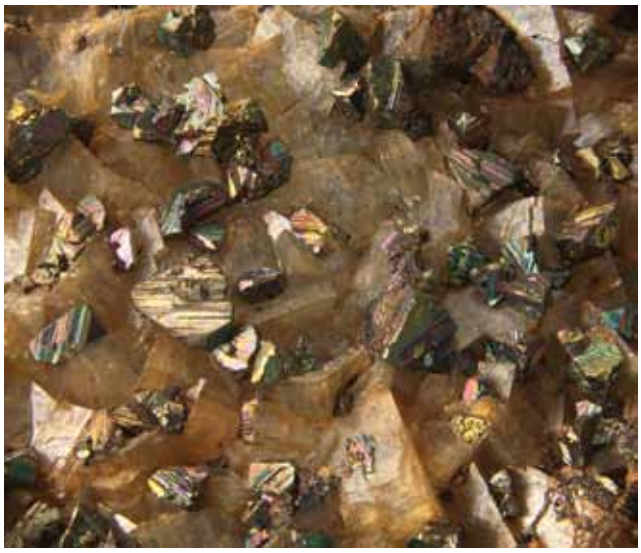

Figure 34. Complex sphenoidal crystals of chalcopyrite, up to about 2.5 mm across, with a slight iridescent tarnish, on pale brown dolomite. Collected by Chris Robson, the Mine Geologist, from the fault in the NW Intake Roadway at Frickley Colliery, South Elmsall. Specimen number 207 in the Uttley Collection; photo John Chapman.

Figure 35. Bright golden-yellow chalcopyrite crystals up to 1 mm on edge on dolomite. Part of a mineralised fracture in a drill core from Goldthorpe Colliery, Thurnscoe, South Yorkshire. Donated to the National Coal Mining Museum for England by Steve Uttley and accessioned as YKSMM: 2012.513. Photo John Chapman.

Maltby Main Colliery

Maltby Main Colliery was sunk on the eastern edge of the village of Maltby in 1908 and was the last of the Rotherham pits to close, early in 2013. A 150×90 mm specimen in the Caphouse Colliery Collection (YKSMM: 2012.565) labelled "Maltby" and assumed therefore, to be from Maltby Main Colliery, contains open dolomite-lined fractures with a few crystals of sphenoidal chalcopyrite.

Manton Colliery

Brassy yellow sphenoidal chalcopyrite crystals up to about 2 mm on edge occur on cream-coloured dolomite on a specimen (catalogue number 210) from Manton Colliery, Worksop, Nottinghamshire (Fig. 36). The locality is not listed in Uttley (1993), perhaps because of its location in Nottinghamshire, outside the South Yorkshire Coalfield.

Manvers Main Colliery

Chalcopyrite from a cavity in the roof of the Parkgate Seam at No. 3 Pit, Manvers Main Colliery, Wath-upon-Dearne, South Yorkshire was described as pyrite by Finn (1930) and corrected by Russell (1934) who notes that the baryte and dolomite in the cavity was:

> "thickly sprinkled with small, up to 2½ mm., bright twinned crystals of chalcopyrite which enhance the beauty of these remarkable specimens. In Mr. Finn's notes these crystals of chalcopyrite were in error called pyrite".

Russell also notes that the baryte crystals from the colliery rarely contain minute included crystals of chalcopyrite. Euhedral chalcopyrite crystals are included in, and overgrow, baryte on a specimen from Manvers Main Colliery in Sheffield Museum.

Nunnery Colliery

Nunnery Colliery, near the centre of Sheffield, was said, at one time, to have supplied coal to more than half of the houses in the city. Two specimens with sphenoidal chalcopyrite crystals, up to about 2.5 mm on edge, sparsely scattered on curved dolomite rhombs, were donated to Sheffield Museum in April 1949 by W. Chadwick and are accessioned as SHEFM: 2002.62 and SHEFM: U1410.

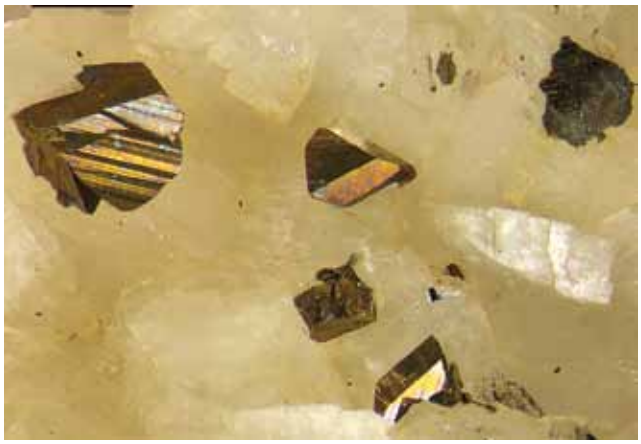

Figure 36. Striated sphenoidal chalcopyrite crystals up to a little more than 1 mm across, on pale dolomite, from Manton Colliery, Bassetlaw, Worksop, Nottinghamshire. Specimen number 210 in the Uttley Collection; photo John Chapman.

Orgreave Colliery

Sphenoidal chalcopyrite crystals up to about 2 mm on edge are sparsely scattered on biscuit-coloured dolomite on two groups of specimens in Sheffield Museum (SHEFM: 1900.12 and SHEFM: 1907.74) from Orgreave Colliery.

Silverwood Colliery

Chalcopyrite from Silverwood Colliery was described and figured as pyrite in Uttley (1987) an error which is corrected in Uttley (1993). Chalcopyrite occurs as crystals "up to 3 mm with pyrite, dolomite and barite from fissures in [the] S21's Intake Roadway". Two specimens with chalcopyrite from Silverwood Colliery were found in the Uttley Collection. Inconspicuous sphenoidal chalcopyrite crystals up to about 0.8 mm on edge are scattered on dolomite on specimen 206. On specimen 250 a double terminated baryte crystal contains three relatively large euhedral chalcopyrite crystals as near-surface inclusions.

Thurcroft Colliery

Chalcopyrite was found in fractures in the sandstone below the Swallow Wood Seam intersected by underground borehole No. 27 at Thurcroft Colliery near Rotherham. It forms complex striated crystals up to about 1.5 mm on edge on specimen 205 in the Uttley Collection. Some of the crystals have a bright metallic lustre, whereas others separated by just a few millimetres have a thick black tarnish. The chalcopyrite overgrows dolomite, some of the larger crystals are overgrown by baryte and the dolomite-chalcopyrite-baryte assemblage is overgrown by later calcite.

CHAMOSITE, $(Fe^{2+},Mg,Al,Fe^{3+})_6(Si,Al)_4O_{10}(OH,O)_8$

Authigenic chamosite is widespread in ironstones, sandstones and siltstones. In a review of ironstones from the West Riding of Yorkshire, Deans (1934) distinguishes lithological units containing 'spherulitic ironstone' from the more typical beds of massive to nodular clay ironstone. Several varieties of spherulitic ironstones are noted, including "chamosite ironstones containing spherulites of siderite".

Nodules found in the Lower Coal Measures in the banks of Cottingley Beck, near Bradford are almost entirely green chamosite and a specimen from the "Wappy Springs Ironstone" near Huddersfield is 70% chamosite (Deans, 1934: p. 56). Polarised light microscopy, density determinations and quantitative chemical analyses, which show iron to be the dominant cation, are all consistent with chamosite.

Chamosite is reported in measures between the Kilburn and Low Silkstone seams by Smith *et al*. (1973: p. 56) and as the principal component of green nodules in seatearth below the Pot Clay Coal by Stephens *et al*. (1953: p. 77). It is described in many Coal Measures siltstones in the

Askern No. 1 Oil Well, which was drilled by BP Exploration in 1957 from SE 565 150 near Askern.

CRANDALLITE, $CaAl_3(PO_4)(PO_3OH)(OH)_6$

Crandallite is noted without comment with quartz and kaolinite in tonstein in the Brown Metal Bed (Pennine Lower Coal Measures) at the Oxbow Opencast Site near Oulton, Leeds, West Yorkshire (Perrin, 1971: p. 77). It may be more widespread than this single record suggests, as it also occurs in tonstein in Staffordshire (Tindle, 2008). Several tonsteins are present near the top of the Lower Coal Measures in Yorkshire (Lake, 1999: p. 37) and more detailed analyses are desirable.

DICKITE, $Al_2(Si_2O_5)(OH)_4$

Dickite occurs as a rock-forming mineral in sandstones of the Millstone Grit Group. It is commonly found in veins, pockets and cavities and is probably widespread in the Coal Measures, although examples are likely to be recorded as the more common polymorph kaolinite, from which dickite cannot be distinguished visually. A history of early discoveries, including several Yorkshire localities, is provided by Smithson and Brown (1957).

Dickite occurs as minute white scaly crystals associated with apatite and siderite in fractures in septarian nodules found in backfill at the defunct Smithy Wood Opencast [SK 366 950), Chapeltown, Sheffield (Neall, 2004). It is commonly associated with kaolinite in ironstone nodules from Robin Hood Quarry near Leeds; both minerals were identified in close association during detailed studies by X-ray diffraction (Brindley and Robinson, 1948).

DOLOMITE, $CaMg(CO_3)_2$

Dolomite is ubiquitous in the cleat of coal seams (e.g. Spears, 2015), although as noted in the foregoing text, it is commonly Fe^{2+}-rich and described as 'ankerite'. Dolomite is an important rock-forming mineral in bands of carbonate-rich mudstone known as cank, the most persistent of which is associated with the Aegiranum Marine Band. It is found in many other lithologies, particularly in the Lower and Middle Coal Measures, where dolomite is very common as a late-stage cement in sandstones (Huggett, 1984).

One of the more intriguing reports is of a bed of dolomitic limestone eight inches in thickness at a depth of 2110 ft in the Lindholme Borehole, which was sunk in 1923 from SE 7108 0789, in peatland about 16 km ENE of Doncaster (Gaunt, 1994). It provoked considerable debate at the time of discovery as no bed with a precisely similar lithology had been encountered in the Coal Measures.

In ironstone from the Thorncliffe or Old Black Mine near Sheffield, Smyth *et al*., (1856: p. 35) record that:

> "Some of the larger nodules ... exhibit cracks formed by contraction which have been filled up with brown spar, the carbonate of lime, magnesia, and iron [presumably Fe^{2+}-rich dolomite]".

A horizon at Hady near Chesterfield produced ironstone nodules described by Smyth *et al*. (1856: p. 43) as:

> "cheeses ... remarkable for the symmetrical cracks caused by contraction in the interior. These are mostly filled with a carbonate of lime containing some iron and magnesia [again presumably Fe^{2+}-rich dolomite], and, where an open space has been left, crystals of zinc-blende are also present".

Dolomite is common in fractures and faults in the South Yorkshire Coalfield. It typically forms relatively uniform drusy crystalline crusts of pale rhombohedral crystals on sandstone or siltstone wallrock. In addition to the localities described in the following paragraphs, dolomite is noted without description on the basis of specimens in Sheffield Museum from South Kirkby Colliery, Wakefield, West Yorkshire in Uttley (1993). It is recorded as veins in laminated sandstone from the Brincliffe Edge Rock (Lower Coal Measures) at the Sheaf Brewery Borehole, Eccleshall, Sheffield where hydrocarbons were found in dolomite-lined vugs (Eden *et al*., 1957: p. 216).

A specimen in the Peter Briscoe Collection from Clipstone Colliery, Mansfield, Nottinghamshire, which gives valuable information about vein parageneses in the Coal Measures, is described under calcite.

Brookhouse Colliery

A hand-written file-card with the Steve Uttley Collection describes dolomite crystals infilling joints and small fractures at Brookhouse Colliery southeast of Sheffield, on the edge of the borough of Rotherham. The mineralisation was found in March 1979 on the Thorncliffe Development beyond the Upper Whiston Fault on the No.1 Intake heading, associated with small scale faulting.

A specimen from Brookhouse Colliery with a 60×40 mm area of iron-stained dolomite rhombohedra up to about 3 mm on edge overgrown by sphenoidal chalcopyrite is accessioned in the Sheffield Museum Collection (SHEFM: 1989.107).

Dinnington Colliery

At Dinnington Colliery near Rotherham, dolomite occurs with marcasite "from faults in the Throapham Main Intake" (Uttley, 1993). A specimen in the Uttley Collection, with a label but no catalogue number, consists of dark brown sandstone with a few coarse pale grey clasts overgrown by sharp colourless transparent dolomite rhombs up to about 1 mm on edge. Iridescent marcasite crystals are scattered on the dolomite and the sandstone wallrock. A precise grid reference, SK 5487 8906, is included for the locality.

Frickley Colliery

At Frickley Colliery, South Elmsall, dolomite occurs as pale brown rhombohedra up to 3 mm on edge in fractures in sandstone from the North West Intake Roadway.

Harworth Colliery

Opaque white dolomite occurs as a vein infill between sandstone clasts on a small hand specimen (catalogue number 199) in the Uttley Collection from Harworth

Colliery, Bassetlaw, Nottinghamshire. In void spaces between the clasts, drusy dolomite is overgrown by small chalcopyrite crystals and complex calcite rhombs.

Hickleton Colliery

Dolomite was very common at Hickleton Colliery. It was identified by energy-dispersive X-ray analysis at British Coal's laboratories and is noted in Uttley (1988b) as follows:

> "This is by far the most common mineral, filling most of the vughs and fractures, it occurs usually as 1mm to 2mm crystals and also massive. The crystals are white to transparent, curved rhombohedra occurring as compact groups, with occasional single crystals up to 3mm. This mineral forms the base for the other minerals and also coats the barite crystals".

A large specimen in the Uttley Collection from a fault zone at Hickleton Colliery consists of a 200×100 mm fracture surface coated by millimetre-size buff dolomite rhombs, which form a continuous crust between 1.5 and 2.5 mm thick. Chalcopyrite occurs as subhedral inclusions in the dolomite, which is overgrown by a later generation of euhedral chalcopyrite and baryte. Minor late-stage dolomite occurs on a few of the baryte crystals, but the main dolomite formation precedes baryte crystallisation. A small specimen (SHEFM: 1988.20) was donated to Sheffield Museum by Steve Uttley in 1988.

Kellingley Colliery

A dolomite-lined cavity containing minor chalcopyrite and a single baryte crystal was cut in a roadway at Kellingley Colliery (Jon Evans, personal communication, 2016).

Manton Colliery

Creamy white curved dolomite rhombs up to about 3 mm on edge occur in a uniform crust about 5 mm thick on a specimen from Manton Colliery near Worksop, Nottinghamshire (Fig. 37). They are overgrown by sparse sphenoidal chalcopyrite crystals.

Figure 37. Dolomite crystals up to about 3 mm on edge with chalcopyrite from Manton Colliery, Bassetlaw, Worksop, Nottinghamshire. Specimen number 210 in the Uttley Collection; photo Peter Briscoe.

Maltby Main Colliery

A 150×90 mm specimen of fine-grained Coal Measures sandstone with carbonate veins in the Caphouse Colliery Collection (YKSMM: 2012.565) labelled "Maltby", (and misidentified as calcite), contains fractures up to about 10 mm in width lined with pale brown dolomite rhombs up to about 2 mm on edge.

Manvers Main Colliery

A large dolomite-baryte-chalcopyrite cavity was encountered in the roof of the Parkgate Seam at No. 3 Pit, Manvers Main Colliery, Wath-upon-Dearne, in 1930. Dolomite occurs as "small cream-coloured rhombohedra ... which form a coating on the sandstone" (Russell, 1934).

Nunnery Colliery

Two specimens of curved white translucent dolomite with crystals up to 12 mm on edge from Nunnery Colliery were donated to Sheffield Museum in 1949 by W. Chadwick and are accessioned as SHEFM: 2002.62 (Fig. 38) and SHEFM: U1410. The specimens were found in laminated siltstone above the Flockton Coal.

Orgreave Colliery

Dolomite occurs as rough curved composite crystals, the largest about 15 mm across, on two groups of specimens in Sheffield Museum, donated by K. Savile (SHEFM: 1900.12) and Arnold Robinson (SHEFM: 1907.74) respectively, in the 1900s. In both cases, sphenoidal chalcopyrite crystals up to about 2 mm on edge are sparsely scattered on the dolomite (Fig. 39).

Sandy Flat Borehole

Opaque, drusy, pale buff dolomite with a distinct pearly lustre forms a crust between 1.5 and 3 mm thick on the

Figure 38. Simple curved dolomite crystals up to 12 mm on edge in siltstone from above the Flockton Coal at Nunnery Colliery. This 170×130 mm specimen has been expertly restored, it was donated to Sheffield Museum in 1949 by Mr W. Chadwick. SHEFM: 2002.62; photo Peter Briscoe.

walls of a fracture intersected by the Sandy Flat Borehole [SK 4767 9095] on specimen number 268 in the Uttley Collection. The stratigraphic horizon is not recorded on the label, but the specimens is almost certainly from the Silkstone Rock, near the base of the Duckmantian, where mineralised fractures with a displacement of 2 cm were intersected at a depth of 868 m according to the borehole log (British Geological Survey, 2017).

Silverwood Colliery

Two specimens on which colourless, translucent to transparent dolomite rhombs up to about 2 mm on edge overgrow pale grey sandstone were found in the Uttley Collection. Dolomite is recorded in sandstone above the Swallow Wood Seam in the Conisbrough Lodge Borehole [SK 5053 9560] which was drilled to prove reserves at Silverwood Colliery (British Geological Survey, 2017).

Thurcroft Colliery

Dolomite was found in fractures intersected by underground borehole No. 27 by Steve Uttley in May 1988, while he was assistant mine geologist at Thurcroft Colliery. A specimen in the Uttley Collection preserves a near complete vein section in which sharp transparent dolomite rhombs up to about 1.5 mm on edge coat a fracture surface in brown sandstone. Chalcopyrite and baryte are also present, and the dolomite-chalcopyrite-baryte assemblage is overgrown by later calcite.

A hand-written file-card describes dolomite in a fault gouge associated with brecciated coal and a little calcite from the Haigh Moor Seam at Thurcroft Colliery. The mineralisation was examined in June 1978 before Steve joined the geological team; this and other file-cards in the same sequence appear to have been written by one of Steve's colleagues. Dolomite is recorded in sandstone and siltstone below the Haigh Moor Coal in the Penny Hill Borehole, which was drilled in 1977 to prove reserves at Thurcroft Colliery. The borehole log records that "occasional dolomite

Figure 39. Curved composite dolomite crystals up to 15 mm across on grey sandstone from Orgreave Colliery. Small chalcopyrite crystals are sparsely scattered on the specimen which was donated to Sheffield Museum by Arnold Robinson on 30 March 1907 (SHEFM: 1907.74). Photo Peter Briscoe

infilled joints (dip 75°–80°) cross [the] core"; dolomite mineralisation is also noted in the sandstone above the Haigh Moor Seam (British Geological Survey, 2017).

GALENA, PbS

Galena is widespread in small amounts in the Yorkshire Coal Measures. It is commonly present in the cleat of the coal (Spears, 1987) and "frequently found in septarian nodules of the Coal Measures of Nottinghamshire and north Derbyshire" (Ineson *et al*., 1972: p. 148). Well-defined crystals with cube and octahedron faces are recorded by Smyth *et al*. (1856) in ironstone nodules in the Old Man and Old Woman bands at Hady near Chesterfield.

An early reference to galena from the Lower Coal Measures is provided in a description of Ralph Thoresby's Museum Thoresbyanum[11], a Leeds-based 'museum of curiosities', which attracted learned gentlemen from the 1690s onward. The museum catalogue (Thoresby, 1715: p. 469) includes a description of:

> "A good Lead Oar found in casting down a Bank near Shipscar Bridge at Leedes, where never were any Mines; as neither at Secroft, yet I have a Sample of rich Oar found there".

These localities are in modern day Sheepscar, near the centre of Leeds, and at Seacroft, which was a village to the east of the city until the end of the Second World War, but which has subsequently been swallowed by urbanisation.

Specimens of galena from the Coal Measures of Derbyshire are noted in a sale catalogue of White Watson's geological collection (Watson, 1805).

[11] Ralph Thoresby (1658–1725) was a diarist, author and antiquary who produced the first 'history' of the city of Leeds and its environs. He inherited a small museum on the death of his father, John Thoresby, in 1679, and added to it throughout his life. It became a considerable attraction and a descriptive catalogue was published as an adjunct the 'history' (Thoresby, 1715). The museum was gradually dismantled after Thoresby's death and the remnants of the collection sold at auction in 1764.

Watson's collection was sold in lots, many of which were arranged stratigraphically. The first lot includes:

> "A variety of [ironstone], cut and polished, containing Crystals of Galina [*sic*] and Blende", and "Galina [*sic*], crystallized in Coal".

John Hustler donated "Galena, from a fault in a Coal mine, near Bradford" to the Yorkshire Philosophical Society's museum in February 1825 and Samuel Hailstone donated a specimen of "Lead ore from above the Coal at Bradford" in 1848 (Yorkshire Philosophical Society, 1826; 1849). Galena occurs in spherulitic siderite nodules in the Lower Coal Measures at Cottingley near Bradford; Deans (1934) notes:

> "Spherulitic nodules from Cottingley Beck ... show a peculiar system of concentric partings with striated surfaces sometimes lined with galena".

Galena is noted by Russell (1934) as rare aggregates of minute bright octahedra on dolomite in a cavity that was encountered in the roof of the Parkgate Seam at No. 3 Pit, Manvers Main Colliery, Wath-upon-Dearne. It is also recorded as "tiny strings" in nodules in the shale above the Mansfield Marine Band in the area around Manvers Colliery by Mitchell *et al*. (1947: p. 77). Silver-rich galena cubes up to about half an inch across were found in a fault in sandstone between the Haigh Moor and Parkgate seams at Kilnhurst Colliery near Rotherham according to Forster-Smith (1959). Galena is recorded in sandstone at several horizons in the Warren Vale Shaft, which was begun in 1934 at Kilnhurst Colliery (Mitchell *et al*., 1947: p. 150; British Geological Survey, 2017). At New Stubbin Colliery, near Greasbrough, Rotherham, "Light grey siltstone seatearth, galena and pyrites" are recorded in the No. 12 Underground Borehole [SK 4262 9679] just below a thin seam of cannel coal between the Whinmoor Seam and the Black Band Seam (British Geological Survey, 2017). A mineralised fracture cut by the Mexborough Montagu Borehole, between 698 ft 6 inches and 700 ft 3 inches from surface, contained "predominantly calcite with occasional pyrites and galena" (Table 2). The fracture is in fine-grained sandstone just below the Manton 'Estheria' Band.

Crystals of galena occur at the top of a grey siltstone about 80 feet below the main sandstone unit in the Oaks Rock (Sheppard, 2005) in the Dentdales Borehole. Galena is noted in a fracture with calcite in lime-rich sandstone at

Borehole Location	Description in Log
New Stubbin Colliery No. 12 Underground Borehole, sunk from SK 4262 9679 near Greasbrough, Rotherham.	"Light grey siltstone seatearth, galena and pyrites" just below a thin seam of cannel coal between the Whinmoor Seam and the Black Band Seam.
Mexborough Montagu, or Barnburgh Colliery No. 19 Borehole sunk from SE 4744 0060, near Mexborough, South Yorkshire, in 1976.	A mineralised fracture between 698 ft 6 inches and 700 ft 3 inches from surface contained "predominantly calcite with occasional pyrites and galena".
Dentdales Borehole, sunk from SK 5413 8279, just off the A57 near Lindrick Dale in 1972.	"Grey siltstone with layers of complexly bedded silt/sandstone [and with] crystals of galena at [the] top" was encountered at a depth of 877 feet 10 inches, about 80 feet below the top of the Oaks Rock.
Wormley Hill Borehole, sunk from SE 6690 1638 on Wormley Hill Lane, beside the River Don between Thorne and East Cowick in 1981.	A "mineralised sub-vertical fracture with calcite and galena" in a 37 cm thick grey "canky" sandstone at a depth of 583 m 97 cm, about 7 m below the Newhill Coal
Went Edge Road Borehole, sunk from SE 5079 1681 about 1 km west of the village of Kirk Smeaton in 1983.	Cut a joint lined with galena from 450.8 m to 451.3 m in upper Middle Coal Measures siltstone. Fractures lined with calcite are logged at several horizons.
Buskeyfield Lane Borehole, sunk from SK 5617 7198, about 0.8 km north of the village of Cuckney, in 1972.	Galena with baryte, in sandstone, at a depth of 696 ft (32 ft above the Wales Seam); and in the mudstone directly above the Manton Estheria Band at a depth of about 1066 ft.
Bondhay Lane Surface Borehole, sunk from SK 5158 7789, about 1 km northwest of the village of Whitwell.	Galena is recorded on joints in sideritic siltstone containing kaolinite 'ooliths' at a depth of 276.53 m about 5.3 m above the inferred position of the Main Bright Seam.
Penny Hill Borehole, also known as the Thurcroft Colliery No. 3 Surface Borehole, sunk from SK 4824 8752, southwest of Thurcroft.	Galena was found with calcite "in a mineralised joint 418 m below O.D.".

Table 2. A selection of records of galena in the Pennine Coal Measures Formation, taken from borehole logs made available by the British Geological Survey (2017).

a depth of 584 m in the Wormley Hill Borehole. The Went Edge Road Borehole encountered a "joint lined with galena" in fine grained sandstone about 10 m above the top of the Kent's Thick Coal. Galena is recorded at two horizons in the Buskeyfield Borehole (described under baryte), southeast of the village of Whitwell: it occurs with baryte, in sandstone, at a depth of 696 ft; and in the mudstone directly above the Manton Estheria Band at a depth of about 1066 ft. The log of the Bondhay Lane Surface Borehole, which is also near Whitwell, records galena in siderite and kaolinite-rich siltstone. Further details of these occurrences are included in Table 2.

Galena localities noted in Uttley (1993) include the following. At Treeton Colliery, four miles south of Rotherham, mine geologist Roy Fry found dull grey massive galena partly altered to cerussite in underground borehole No. 40. Galena was found with calcite "in a mineralised joint 418 m below O.D." in the Penny Hill Borehole, Thurcroft, Rotherham. At nearby Silverwood Colliery, lustrous cuboctahedral galena crystals up to 3 mm across were found with dolomite and baryte in a fault in the S51's Return Access Roadway. A specimen from this locality is recorded as present in the Uttley collection in 1993, but was not found in 2016.

GOETHITE, FeO(OH)

In the Coal Measures, goethite typically forms by the supergene alteration of siderite (e.g. Hallimond, 1925; Deans, 1934; Taylor, 1971), or iron sulphides. In a discussion of ironstones, Deans (1934: p. 36) notes that "By weathering the spherulites are altered to limonite, and all stages can be traced from colourless siderite to red powdery limonite". Goethite and hematite are the most thermodynamically stable iron oxide minerals in typical conditions at the surface of the earth and the end-points of most alteration sequences (Cornell and Schwertmann, 2003).

> An intriguing early reference (Thoresby, 1715) to:
> "*Brush-Iron* found at *Leedes* [*sic*]; it is composed of strait, round, long Stiriæ about the Thickness of a small Knitting-Pin"

refers to the well-known acicular variety of goethite. It is likely that Thoresby's 'brush iron' was found in one of the many small shaft workings for iron ore to the south and east of Leeds city centre (Kendall and Wroot, 1924).

A clay-ironstone specimen from the defunct Smithy Wood Opencast, Chapeltown, Sheffield examined in this study has brown botryoidal goethite crusts on its outer surface. Goethite is also present as brown crusts in Langsettian rocks from Thurstonland Bank near Holmfirth on specimens preserved at Cliffe Castle Museum, Keighley.

Limonite is responsible for the brown colour that is characteristic of many weathered sandstones and siltstones of the Pennine Coal Measures. Ochre staining, presumably limonite, is noted in fractures in the Treeton Rock in the Spa Hill No. 2 Borehole, sunk in 1976 from SK 4389 8786 just east of Treeton on the outskirts of Sheffield. In a discussion of the Treeton Rock, which is part of the "Mansfield Marine Band Cyclothem", Taylor (1971: p. 320) notes that:

> "Oxidation of siderite to limonite is primarily responsible for the brown colour of the coarser upper section of the Treeton Rock. Limonite, which also replaced hydrobiotite to a minor degree, precluded the X-ray identification of siderite in the latter bed. An optical evaluation, however, confirmed that siderite was originally present in about the same volumetric proportions in both massive sandstone and shaly partings alike–11.5 per cent limonitized siderite in sample TB5, 12.0 percent siderite in the partings".

GYPSUM, $CaSO_4 \cdot 2H_2O$

Gypsum is widespread in the Coal Measures of south Yorkshire. It forms as a result of the reaction between acidic sulphate-rich solutions produced by the oxidation of iron sulphides and calcium ions produced by the dissolution of calcite and dolomite.

An early report of the transparent variety selenite, in Coal Measures shale at Idle near Bradford, is provided by Sowerby (1817: p. 98) in a transcription of a letter from the Rev. Henry Steinhauer[12] of Fulneck near Leeds. Several specimens of transparent to translucent gypsum in shale from the coal mines near Idle, Bradford are preserved in the collection of Steinhauer's friend Joseph Dawson. Dawson's manuscript catalogue, which is preserved at Cliffe Castle, Keighley, records "Crystallized Gypsum or Selenite found in the Coal at Idle" (Dawson, 1810–1813). A glass-topped museum box with Dawson's label contains four specimens, the largest is a translucent fish-tail twin 60 mm long (Fig. 40). A second box in the Dawson Collection, containing "Crystallized Gypsum as it lies in Shale" is more typical of gypsum from the Coal Measures (Fig. 10), on this specimen crystalline gypsum is developed along thin bedding planes in disintegrating shale.

Gypsum is particularly common where pyrite-rich marine shales are exposed to weathering. Lithological descriptions of Lower Coal Measures strata in quarries between Halifax and Huddersfield note gypsum as selenite in association with jarosite in the Honley Marine Band, Upper Parkhouse Marine Band, Amaliae Marine Band and Langley Marine Band (Wilson and Chisholm, 2004). Gypsum was identified by X-ray diffraction in samples taken from a spoil heap at Yorkshire Main Colliery near Doncaster, the appearance of the grains in thin section indicated that the gypsum was present in coal fragments before they were tipped; suggesting rapid alteration of iron sulphides in the cleat of the coal (Spears *et al*., 1971).

Colourless, transparent, prismatic and tabular post-mining gypsum crystals up to 4 mm in length with characteristic oblique terminations and conspicuous striations parallel to the elongation direction are present

[12] The Reverend Henry Steinhauer (1782–1818) was a nonconformist minister to the Moravian Community at Fulneck between Leeds and Bradford. He made significant contributions to palaeobotany (Torrens, 2005). His collection, which survived until quite recently, was discarded before its geological importance was realised.

Figure 40. The contents of a glass-topped museum box, and label, showing four gypsum specimens and some crystal fragments from Idle near Bradford from the Joseph Dawson Collection held at Cliffe Castle Museum, Keighley; accession number BRFMS: 25.4.5/29. Photo John Chapman.

on an uncatalogued dolomite-chalcopyrite specimen from Kiveton Park Colliery, Rotherham in the Uttley Collection (Fig. 41). Given the abundance of pyrite and carbonate minerals, post-mining gypsum is likely to have been common in south Yorkshire's collieries, but very few specimens survive in collections.

HALITE, NaCl

Halite is noted in Uttley (1983) at Manvers Main Colliery, Wath-upon-Dearne, in a postscript to a short article about the minerals of South Yorkshire:

> "During a large oil seepage in the roof of the Parkgate Seam at Manvers Colliery in 1902, the total flow of oil contained 80 - 90% of salt water, and as this evaporated it formed halite stalactites. Recently a sample of this sort found in the Silkstone workings at Manvers, was shown to me".

Several oil-water seepages at Manvers Main Colliery are described by John R. R. Wilson in Cohen and Finn (1912); Mitchell *et al*. (1947: p. 144) note that halite stalactites formed as the water evaporated. Such brine seepages were common in deep coal workings in the Yorkshire area and "apt to form heavy deposits of salt" (Edwards *et al*., 1940).

An article in the first issue of the *UK Journal of Mines & Minerals* describes halite from Hickleton Colliery (Uttley, 1985b):

> "On the recent removal of the core store of the old N.C.B. Doncaster Area, Geological Branch, a Small cardboard box was found in a corner of the room, at first sight this contained nothing special, just two samples wrapped in old paper, but on unwrapping the samples I was surprised to find two fine examples of Halite with no labels to indicate their location. I decided that these needed further investigation as they were well crystallised groups, one 2"x2", the other, 5"x2" with crystals of between ½" and ¾" in size, of an orange tint probably due to iron inclusions,

Figure 41. Prismatic gypsum, 4 mm long, on dolomite with minor chalcopyrite, from Kiveton Park Colliery, Rotherham, South Yorkshire. Steve Uttley Collection (with a Peter Briscoe label); photo John Chapman.

one of the samples was attached to a piece of old wood, the other, free grown".

"On taking them back to the main office, I found out from the Geologist Chris Robson that he had collected them six years previously in a Parkgate Seam to Thorncliffe Seam underground drift on the west side of Hickleton Main Colliery, where a pool had formed from natural strata water rich in Sodium Chloride the crystals growing on the outer edges of the pool. The best crystals were forming on a piece of timber in water, according to the Deputy for the district, this area had been stood for about eight years".

"Since this discovery, Chris Robson has brought into the office a piece from this location which must rate as one of the best recent British Halite specimens. It measures 7"x4"x2" and the crystals range from ¼" to 1" in size arranged in multiple twinned cubic growths almost like crystal stairways, the crystals are clear to opaque with a very pale pink tint. The specimen is kept in a sealed plastic bag so that the atmosphere does not destroy this fine specimen".

A single halite specimen (catalogue number 202) was found in the Uttley Collection in 2016 (Fig. 42). It measures 170×100×50 mm (7×4×2 inches) and is made up of colourless translucent halite cubes up to 25 mm across with included fibrous brown timber. It is undoubtedly the specimen collected by Chris Robson and described as "one of the best recent British Halite specimens". The whereabouts of the other specimens is unknown.

Halite is described in Uttley (1988a) from Brodsworth Colliery near Doncaster where "one roadway equalled a Derbyshire Cave having ironstained stalactites hanging in curtains". Well crystallised specimens are also described from Hatfield Colliery. The collection of the National Coal Mining Museum for England includes two halite stalactites. The largest (YKSMM: 2012.61) has no location data; the other (YKSMM: 1991.77) is from Grimethorpe Colliery near Barnsley and is 220 mm long (Fig. 43). A crystalline halite specimen from a disused area of Kellingley Colliery is preserved in the Jon Evans Collection (Jon Evans, *personal communication*, 2016).

Figure 42. Halite from Hickleton Colliery, Thurnscoe, South Yorkshire; 170×100×50 mm with colourless translucent halite cubes up to 25 mm on edge. Specimen number 202) in the Uttley Collection, collected by Chris Robson and described as "one of the best recent British Halite specimens" in Uttley (1985b). Photo Peter Briscoe.

HEMATITE, Fe_2O_3

Although most of the Pennine Coal Measures are 'grey' rather than 'red' beds, authigenic hematite is abundant in the rocks just below the angular unconformity at the top of the Westphalian sequence. The Middle Coal Measures (Bolsovian) sandstone known as the Mexborough Rock is probably the best known of the red beds in south Yorkshire. It was quarried extensively in the nineteenth and early twentieth centuries and can be seen in many buildings around Sheffield and Rotherham.

Hematite nodules are well-known in the red sandstones that crop out around Mexborough and Conisbrough (Green *et al*., 1878). Pisolitic hematite is present on joint planes in the Mexborough Rock near Thrybergh (Mitchell *et al*., 1947: p. 80). Nodules of hematite found near the top of the Coal Measures on Clifton Common near Micklebring were sufficiently abundant that they were smelted on a small scale (Green *et al*., 1878: p. 478). In the concealed coalfield, large nodules of hematite were found "lying close under the Mexborough Rock at 1056 ft from surface" in the No. 4 Shaft at Manton Colliery near Worksop (Eden *et al*., 1957: p. 172). Other nearby sinkings met with similar nodules near the top of the Coal Measures. One of the more unusual occurrences is of abundant "balls of reddle" met with in grey sandstone at several horizons including the Treeton Rock (Upper Coal Measures) in the shaft at Dinnington Colliery (British Geological Survey, 2017).

In the Severals Borehole, which was sunk from SE 7034 0976 on the line of the M180 motorway 5 km east of Hatfield, near the eastern limit of mining in the concealed coalfield, hematite is recorded replacing ironstone in the Upper Coal Measures a little more than 71 ft below the base of the Permian. There are numerous records of purple staining in the Upper Coal Measures in this borehole log, which is one of very few in which hematite is specifically described replacing ironstone. An unusually detailed

Figure 43. Two sides of a halite (salt) stalactite, 220 mm in length, from Grimethorpe Colliery, Barnsley, South Yorkshire, in the collection of the National Coal Mining Museum for England (YKSMM: 1991.77). Photos John Chapman.

description of iron-rich mudstone below the Carboniferous–Permian unconformity is given in the Town Ing Borehole:

> "core rather fractured and disturbed below 1278ft 6in and mainly chocolate brown in colour. 3in deep red brown. ?sphaerosideritic ironstone at 1279ft 0 in. Core below of chocolate brown silty mudstone with lumps of red ironstone. badly fractured".

The borehole was sunk in 1974 from SE 6680 1399, about 2 km northwest of Thorne on the banks of the Rover Don; again, it seems likely that hematite is replacing siderite.

The Coal Measures rocks are unconformably overlain by siliciclastic rocks of the Yellow Sands Formation and limestone of the Cadeby Formation to the east of Rotherham. Raddle, an earthy variety of hematite, was extracted from the Coal Measures strata just below the Carboniferous–Permian unconformity around the hamlet of Micklebring to the north of Maltby (Smith, 1974). It occurs in thin seams at a relatively shallow depth and was used in paint-making, as a dye, as a polish for glass and steel, and for marking sheep. The antiquarian Ralph Thoresby had a specimen of:

> "*Terra Fabrilis Rubrica, Rubrick* or *Ruddle*, very good from Edlington near Doncaster, the Seat of my honoured Friend Robert Molesworth Esq",

in his museum in Leeds (Thoresby, 1715: p. 471). The raddle mines, although small, were well known in the eighteenth and nineteenth centuries; in a history of Doncaster, Edward Miller (1804: p. 10) notes:

> "Reddle or ruddle. – Is an argillaceous earth ... impregnated with an oxyd of iron. ... By levigation and washing it is rendered fit for sale as a coarse pigment which is of very extensive use. This earth is found in large quantities at Micclebring [*sic*] about six miles from Doncaster. At this place Messrs. Gleadhill and Shephard have mills for grinding it, and carry on a considerable trade in this article".

Adam Sedgwick, Woodwardian Professor of Geology at the University of Cambridge, who surveyed the area in the early 1820s reported that the raddle was found in seams 4 inches and 9 inches thick, separated by two feet of red and yellow clay (Sedgwick, 1835: p. 59). The deposits were worked until the First World War. An account of their geology, and of the history of the mines, is provided by Brown and Cowdell (1967).

Massive hematite from the South Don Fault could be found on the tips of Denaby Colliery near Mexborough before they were overgrown by vegetation. It is described in Uttley (1988a) as follows:

> "Hematite of a more solid variety was encountered at Denaby Colliery as they worked through the South Don Fault. It was a massive variety rich in silica which in some vughs has crystallised as Quartz. The hematite was red-grey colour and appeared to be nodular. Specimens of this material have occasionally appeared on the old Denaby tip, but this has now been landscaped."

A large hand specimen, collected by David McCallum in 1976, was donated to Manchester Museum in the early 1990s and is accessioned as MANCH: N11428. Hematite specimens listed as present in the Uttley Collection in 1993 could not be traced with certainty; several quartz-hematite-goethite specimens were found, but sadly they lacked labels. Fortunately, a specimen was donated to Sheffield Museum (Fig. 44). It consists of massive hematite (100×140 mm), with rare patches of minute specular crystals and cavities lined with colourless transparent prismatic quartz up to about 3 mm in length. A small area of the specimen has rhombohedral casts, which are almost certainly the result of dissolution of a dolomite-group mineral or possibly calcite.

Figure 44. Massive hematite (140×110 mm) containing cavities lined with drusy quartz from the tips of Denaby Main Colliery. Donated to Sheffield Museum by Steve Uttley in 1988 (SHEFM: 1988.21). Photo Peter Briscoe.

HYDROCARBONS

Many nineteenth century mineralogy texts include coal as a mineral species. Greg and Lettsom (1858) begin their *Manual of the Mineralogy of Great Britain and Ireland* with descriptions of coal and other 'organic minerals'. Coal is produced by the lithification of lignin and other complex polymers found in plants; it lacks a distinct crystal structure and chemical composition and is a rock rather than a mineral. Coal is made up of more homogeneous organic components described as 'coal macerals', which are classified using a system developed by the International Committee for Coal and Organic Petrology.

Hydrocarbons are commonly found in coal-bearing strata and vary from gassy phases of low molecular mass (the ubiquitous firedamp) to oily fluids and natural waxy, pitchy and glassy polymers. At Robin Hood Quarry near Leeds, a supply of methane gas sufficient to provide lighting and some heat to the brickworks was obtained simply by boring to a moderate depth and inserting a pipe (Burnet and Everett, 1912). The more fluid hydrocarbon phases commonly harden and change colour on exposure to the atmosphere, probably due to the loss of volatile components.

Hydrocarbons are recorded in many boreholes, but with little analytical data. In the Whitwell Wood No. 2 Borehole, which was sunk from SK 5272 7788 about 1.2 km north of the village of Whitwell, the log notes sandstones at a depth of 830 m with "abundant dark brown oil staining and bleeding, with strong oil smell". In the Sidcop Road Borehole, which

was sunk from SE 3850 0996 north of Cudworth, Barnsley, records include "light grey, fine grained jointed [sandstone] with abundant deposits of yellow waxy hydrocarbons" (British Geological Survey, 2017).

Limited analyses were done on a brown waxy substance encountered in mineralised joints in a fine grained sandstone at a depth of 548 m in the Tall Trees Borehole, which was sunk in 1978 from SE 4448 1832 northeast of High Ackworth; it was found to be "a mixture of aliphatic hydrocarbons from hexances [*sic*] (C4) to parrafin [*sic*] waxes (C30)" (British Geological Survey, 2017).

A few natural hydrocarbons are sufficiently distinctive to be approved as mineral species by the International Mineralogical Association (IMA), and a number of substances that were proposed as minerals before appropriate analytical techniques became available remain to be fully investigated. Historically, the most important of these, in south Yorkshire, are 'middletonite' (Johnston, 1838a; Greg and Lettsom, 1858), which is named after one of the mines in the coalfield; and 'hatchettite', which is described without entirely convincing analytical data from several localities. Recently, hand specimens of a yellow-brown resinous material from Kellingley Colliery in North Yorkshire have appeared at mineral shows labelled as 'resinite'. In modern nomenclature, all of these phases are probably best described as coal macerals of the liptinite group, the classification of which is outlined in Taylor (1998).

Hatchettite, $C_{23}H_{48}$

Hatchettite was named for the distinguished chemist Charles Hatchett[13] by John J. Conybeare[14]. It was found in septarian ironstones in the Coal Measures near Merthyr Tydfil (Conybeare, 1821) and analysed by Johnston (1838b) in one of a series of papers about minerals of organic origin. Numerous occurrences in the collieries of south Wales are summarised in Bevins (1994). Recent research has shown that hatchettite is synonymous with evenkite (Spangenberg and Meisser, 2000; Kotelnikova *et al*., 2004), which is the species name currently approved by the Commission on New Minerals, Nomenclature and Classification of the International Mineralogical Association (CNMNC, 2017). However, the analytical data gathered from material from the South Yorkshire Coalfield is not of sufficient quality to be sure that specimens are evenkite.

In a discussion of natural paraffins and oils found in the coal seams of south Yorkshire, Cohen and Finn (1912) describe "balls of vaseline" associated with an oil seepage from a fault in the Haigh Moor Seam at Hemsworth Colliery, near Fitzwilliam, Wakefield. Analyses showed that paraffins with a variety of molecular weights were present, including crystals with a melting point corresponding to hatchettite, but no XRD data is available.

In a letter from John R. R. Wilson[15] reproduced in Cohen and Finn (1912), it is noted that "a piece of solid crude petroleum (Hatcheline ? [*sic*]) ... 15 inches in circumference" was found while sinking a shaft at Manvers Main Colliery, Wath-upon-Dearne. The specimen was found "461 yards from the surface or 85 yards above the Parkgate and 185 yards below the Barnsley seam". This appears to be the mass of solid "hatchettite?" recorded from Manvers Main Colliery by Mitchell *et al*. (1947: p. 144).

Middletonite, $C_{22}H_{24}O$

Middletonite was described by James F. W. Johnston (1796–1855), in one of a series of papers on organic minerals (Johnston, 1838a). It was brought to Johnston's attention by Thomas William Embleton (1810–1893), a founder member of the Yorkshire Geological and Polytechnic Society, who was involved in the management of the Middleton collieries[16] to the south of Leeds for many years (Reynolds, 1893). Johnston proposed the name middletonite for the red-brown resinous patches forming thin discontinuous seams and pea-sized nuggets parallel to the bedding in coal from the Haigh Moor Seam (Fig. 45). Middletonite does not appear in the IMA list of approved mineral species (CNMNC, 2017), but there does not appear to be a formal discreditation. However, Smythe (1927) observed that the literature was:

> "... encumbered with ... names, most of which it would be well to suppress vigorously; as examples we may quote: Earth wax, Mineral wax, Ozokerite,

[13] Charles Hatchett (1765–1847) was a chemist and mineralogist who discovered the chemical element niobium while working at the British Museum in London. It was originally named columbium to honour Christopher Columbus as the specimen of columbite in which the element was found was from the New World. Hatchett was particularly active in science between 1796 and 1806, making many important contributions to chemistry and mineralogy. Later, involvement in his father's coach-making business restricted his scientific work.

[14] The Rev. John Josias Conybeare (1779–1824) was a member of a distinguished ecclesiastical family. In common with many members of the clergy he had an interest in geology. His principal academic work was, however, in literature as Professor of Anglo-Saxon and later of Poetry at the University of Oxford. He was an elder brother of the palaeontologist William Daniel Conybeare (1787–1857).

[15] John Robert Robinson Wilson (1862–1923) began his career at Edmunds Main Collieries, Barnsley. In 1892 he was appointed as one of H.M. Inspectors of Mines in Yorkshire and in 1907 Chief Inspector of Mines in India for a period of 3 years. At the end of 1910, he returned to England as a Senior Inspector of Mines in the Yorkshire and North Midland Division. He took charge of the Lancashire and North Wales Inspection District in September 1912; and was made a Divisional Inspector of Mines in charge of the Northern Division in June 1913.

[16] The mining remains in Middleton Park, 5 miles south of Leeds, were the subject of an investigation by the Middleton Park Community Archaeological Project (Roe, 2008). The park is one of relatively few places in the Leeds area where early coal mining remains can still be seen. Guided walks are regularly held and make an excellent half-day out. The area also includes the famous Middleton Railway, now run by volunteers, which operates passenger services at weekends and on public holidays over approximately one mile of track between its headquarters at Moor Road, in Hunslet, and Park Halt, on the outskirts of Middleton Park.

Elaterite, Elastic bitumen, Urpethite, Middletonite and Hatchetite".

Recalculating Johnston's original chemical analysis produces a formula close to $C_{22}H_{24}O$. The conchoidal fracture and appearance strongly suggest it is an amorphous glassy polymer rather than a crystalline phase. However, the composition is distinct from the fossilised tree resin, amber, with which some researchers, including Thomas Embleton, suggested it was synonymous. The atomic ratio of carbon : hydrogen in amber is never close to 1 : 1.

Resinite

Resinite was found in kilogram quantities in coal from Kellingley Colliery near Knottingley in about 2012 (Colin Robinson, *personal communication*, 2016). It occurs as translucent honey-brown masses with a distinctive conchoidal fracture and contains numerous minute bubble inclusions (Fig. 46).

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

Hydrozincite was found in the Rayton Farm Borehole, also known as the Manton Colliery No. 8 Borehole, which was sunk in 1982 from Rayton Farm [SK 6155 7950] near Worksop, where "a 5mm fracture in the core was found to be crystallised with 2mm black tetrahedral [sphalerite] crystals with occasional hydrozincite coatings" (Uttley, 1993). Hydrozincite is not recorded in the borehole log, but it seems likely that it was associated with sphalerite and dolomite veins that were encountered at a depth of about 448 m (British Geological Survey, 2017). A specimen lodged at Caphouse Mining Museum according to Uttley (1993), was not found when the authors visited in 2018.

Figure 45. Dark red resinous patches of middletonite in coal (field width 3.7 mm) from the Haigh Moor Seam, Middleton Colliery, Leeds. David Green specimen: photo John Chapman

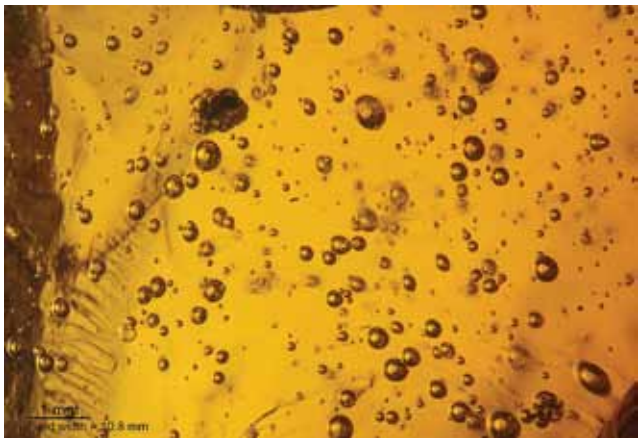

Figure 46. Resinite from Kellingley Colliery, Knottingley, North Yorkshire, showing its typical yellow colour and abundant bubble inclusions; field width is 10.8 mm. Photo John Chapman.

JAROSITE, $KFe^{3+}_3(SO_4)_2(OH)_6$

Jarosite can be expected at any near-surface exposure in the Coal Measures where iron sulphides are present and conditions are sufficiently acidic. It was identified on joint planes in weathered Carboniferous shale at three Yorkshire localities (Hartley, 1957). Two of the localities, at Bolton Abbey and Denshaw, are in pre-Westphalian rocks, but the third is in Lower Coal Measures shale near Bradford. Hartley records:

> "Shales above the Halifax Hard Bed Coal are cut into and exposed by the Noon Nick overflow channel ... The jarosite forms thick, yellow, pulverulent masses on cleavage-surfaces and is very abundant. On the specimens collected jarosite was virtually the only mineral present, brown, powdery limonite being very sparse and gypsum absent".

This appears to be the first report of jarosite from the British Isles, but it is not included in L. J. Spencer's *Third supplementary list of British minerals* (Spencer, 1958: p. 797) which only records localities in Cumberland, which were described in the following year (Kingsbury and Hartley, 1958). In a footnote, Hartley (1957: p. 21) reports:

> "Jarosite was first discovered by A. W. G. Kingsbury and the author at several localities in the Lake District and Cornwall. Description of the occurrences is at the moment in press".

Despite Hartley's footnote, the specimens from Yorkshire appear to be the first definite records of jarosite in Britain.

Powdery yellow jarosite encrustations commonly occur in dark fissile mudstones and pyrite-rich marine bands. Jarosite is bright yellow when fresh, but oxidises to a dull brown as it is replaced by iron oxyhydroxides; it was misidentified as sulphur on the basis of its yellow colour in early publications (e.g. Trueman, 1954: p. 23). Its abundance is shown in detailed lithological descriptions of Lower Coal Measures sequences reported in Wilson and Chisholm (2004) which notes jarosite in the Holbrook Marine Band, Springwood Marine Band, Honley Marine Band, Listeri Marine Band, Lower and Upper Parkhouse Marine bands, Amaliae Marine Band and Langley Marine Band, in quarries between Halifax and Huddersfield.

Jarosite occurs as an oxidation product of pyrite near the surface of coal mine spoil heaps in south Yorkshire (Spears *et al*., 1971; Evans *et al*., 2003). It was identified by X-ray diffraction in the uppermost layers of spoil at Yorkshire Main Colliery near Doncaster by Spears *et al*. (1971).

Jarosite was reported in association with decomposing pyrite in a fireclay seatearth below a coal seam in Lower

Carboniferous limestone at Meal Bank Quarry near Ingleton, North Yorkshire (Hodson and Cosgrove, 1963). Although this locality is outside the South Yorkshire Coalfield it is included here as detailed chemical analyses showed that potassium was the dominant cation.

KAOLINITE, $Al_2(Si_2O_5)(OH)_4$

Kaolinite (with quartz, illite, illite-smectite and minor chlorite) is a major component of fireclay, a seatclay used in the manufacture of refractory products (Smith, 1974; Highley, 1982; Spears, 2012). Kaolinite is the most abundant mineral in almost all tonsteins where it forms by the diagenetic alteration of volcanic ash (Spears, 1987; 2006; 2012). It is widespread in the coals and clastic sedimentary rocks of the South Yorkshire Coalfield (Perrin, 1971; Chisholm *et al*., 1996); authigenic kaolinite dominates in some low-ash coals and in sandstones, but in other coals, shales and mudstones it is mostly detrital (e.g. Chisholm *et al*., 1996; Spears and Tewalt, 2009; Spears, 2015).

Kaolinite is common in syneresis cracks in ironstone nodules (e.g. Smyth *et al*., 1856; Dunham, 1960). In a description of ironstone nodules from the Bottom Rake near Chesterfield in Derbyshire, Gibson and Wedd (1913: p. 116) describe "cracks coated with white powder" from ironstone nodules in two beds described as the "Over lumps" and "Nether lumps". A log of the Barnburgh Colliery No. 31 underground borehole records kaolinite in septarian ironstone nodules below the Top Beamshaw Coal and a log of the BP No.1 Borehole at Hatfield describes kaolinite and calcite in siderite nodules in a seatearth at a depth of 1121.5 m. An ironstone nodule with kaolinite veins is recorded in the Whitwell Wood No. 3 Borehole, which was sunk from SK 5180 7874, north of the village of Whitwell in 1981.

Kaolinite has been identified by X-ray diffraction in spoil from the Yorkshire Main Colliery near Doncaster (Spears *et al*., 1971) and from the Parkgate Seam at many localities in Yorkshire (Spears and Tewalt, 2009).

Peloidal[17] kaolinite in an ironstone matrix was reported from the Yorkshire Coal Measures by Deans (1936). Kaolinite peloids are not uncommon in fine grained sedimentary rocks in the Coal Measures (Taylor, 1971), but the peloidal ironstones are remarkable in that kaolinite can make up more than 50% of the rock. Detailed petrographic accounts of three horizons in the neighbourhood of Leeds and Bradford, each just above a coal seam, are given by Deans (1936). Peloidal kaolinite occurs "in the roof of a coal seam thirty feet above the Top Haigh Moor Coal at Robin Hood Quarry, Thorpe On The Hill, four miles south of Leeds"; it occurs in "the roof of the Blocking Bed Coal at two collieries ... at Birkenshaw"; and in "the roof of the Black Bed Coal at Birch Lane brickworks, Bowling, Bradford". The kaolinite peloids commonly enclose fragments of carbonised plant matter described as fusain. At Robin Hood Quarry, crystalline kaolinite occurs in the peloids as thick hexagonal plates up to 0.05 mm across, which grade into vermicular aggregates.

Peloidal ironstone is sporadically present just above the Clowne Seam at many collieries in south Yorkshire. In a description of the Clowne Ostracod Bed, Rippon (1984) records:

> "The top 200 mm to 400 mm of the bed are commonly more carbonaceous, more silty, and somewhat sideritic and the ostracods are much less common. In the Shirebrook and Warsop area north of Mansfield, a distinctive bed of highly carbonaceous siltstone with large siderite-infilled Anthracosia shells (both valves present) and occasional ostracods, forms a mappable feature over many square kilometres. This bed, known by miners as the 'nut toffee' because of the hardness and the visual appeal of the bivalves, passes laterally in places into a silty, pyritic and sideritic mudstone with many kaolinite ooids. In the study area, such ooids are known at this horizon from most collieries that have worked the Clowne Seam, although the distribution is somewhat patchy. Wherever present, the ooid band is the topmost part of the Lower Roof Beds, and may be the only lithology present where those beds are of minimal thickness".

Kaolinite occurs in peloidal ironstone at the defunct Smithy Wood Opencast [SK 366 950], near Chapeltown, Sheffield. Specimens contain abundant sub-millimetre-size kaolinite peloids in sideritic matrix (Fig. 47). A similar ironstone, containing "ooliths filled with white clay-mineral" is recorded 8 m below the "Top Marine Band" in the Wentbridge No. 2 Borehole. Kaolinite "ooliths" are also noted in an ironstone above the Shafton Coal Seam

Figure 47. White kaolinite peloids up to about 1 mm across in dark siderite-rich clay-ironstone, some enclosing black fragments of fusain, and one (top right) enclosing a broken orange-brown sphalerite crystal. Collected by Tim Neall at Smithy Wood Opencast, Chapeltown, Sheffield. Photo John Chapman.

[17] Recommended terminology for use in the description of oolitic and pisolitic rocks is outlined as a glossary to Young (1989). Ooids and pisoids refer to grains with recognisable concentric structures, ooids are generally less than 2 mm across and pisoids larger the 2 mm across. Peloids are similar in shape to ooids and pisoids, but are made up of fine grained material without recognisable internal structure. The kaolinite from Smithy Wood Opencast, Robin Hood Quarry and the other localities noted in Deans (1936) is best described as peloidal as the grains lack concentric structures. In a description of the "oolitic ironstone", Deans (1936) notes that "the kaolinite ooliths show no sign of zonary structure".

in the King Royd No. 5 Borehole; and similar lithologies are recorded in logs of the Grove House Borehole; the Ulley Lane Borehole; and the Manor Hills Borehole. Two "ironstones containing white ooliths", both 3 cm thick, are recorded in the Walden Stubbs Borehole, one lies above a thin band of coal and the other above a seatclay. Further details of these occurrences are provided in Table 3.

A tonstein marker horizon containing abundant kaolinite was encountered at the Oxbow Opencast site near Oulton, Leeds. It varies between kaolinite-rich coal and pelletal tonstein, and is 0.15 m below the top of the Third Brown Metal Coal near the top of the Pennine Lower Coal Measures Formation (Lake, 1999). An extensive tonstein associated with the Sharlston Muck Coal in the Pennine Upper Coal Measures consists of a dense pink to brown kaolinitic mudstone about 25 mm thick. It is present across a very wide area and makes a useful marker horizon (Lake, 1999: p. 51).

Kaolinite is commonly associated with dolomite in fractures and faults (Uttley, 1993). However, only one specimen (from Hickleton Colliery), with a kaolinite coating was found when the Uttley Collection was examined in 2016. At Hickleton Colliery, kaolinite was identified as a late-stage powdery fracture fill by energy-dispersive X-ray analysis on a scanning electron microscope (Uttley, 1988b); however, this technique is not by itself sufficient to differentiate kaolinite from its polymorphs.

Leedsite, $(Ca,Ba)SO_4$

The mineral which became known as leedsite was first described by Thomson (1836) as "baryto-calcite", a strange choice of name given that Thomson did not report any carbonate in his analysis! Thomson (1836: p. 106) noted that:

> "There is another species of calcareous sulphate of barytes which occurs in Yorkshire, between Leeds and Harrowgate, [*sic*] connected with the millstone grit and mountain limestone beds, which occur in such abundance in that county".

The name leedsite was considered more appropriate than 'baryto-calcite' by subsequent workers and it is listed as such by Hall (1868) who notes that it was found in the Coal Measures near Leeds.

Leedsite is described as a mechanical mixture of baryte and gypsum in Greg and Lettsom (1858: p. 408) and as a mixture of baryte and anhydrite in Palache *et al*. (1951). The strata that crop out between Leeds and Harrogate belong mostly to the Millstone Grit Group which underlies the Coal Measures, but some Coal Measures rocks are found near to the city and there were several small coal mines on the

Borehole Location	Description in Log
Whitwell Wood No. 3 Borehole, sunk in 1981 from SK 5180 7874, north of the village of Whitwell.	The borehole intersected an ironstone nodule with kaolinite veins.
Wentbridge No. 2 Borehole, sunk from SE 4868 1724 near Wentbridge, in 1948.	Ironstone, containing "ooliths filled with white clay-mineral" is described at a depth of 63.9 m, about 8 m below the Top Marine Band [in modern terminology the Cambriense Marine Band, which lies at the base of the Pennine Upper Coal Measures].
King Royd No. 5 Borehole, sunk from SE 4321 1746 between Gordonsfield and Featherstone in 1978.	Kaolinite was encountered at a depth of 61 m just above the Shafton Seam, near the top of the Pennine Middle Coal Measures.
Grove House Borehole was sunk from SE 7163 1105 km ESE of Thorne, in 1973.	At a depth of 1580 ft 8 inches, a band of brown ironstone, about 2 inches thick, had a "cellular texture with some small white mineral filled cavities".
Ulley Lane Borehole, also known as Brookhouse No. 12, sunk from Ulley Lane, SK 4652 8589, Aston, Sheffield, in 1969.	The borehole encountered "ironstone with kaolin ooliths" at an unspecified horizon just above a coal seam at a depth of 936 ft 11 in.
Manor Hills Borehole, also known as Shireoaks No. 12 Surface Borehole, sunk from SK 5755 7545, about 3 km south of Worksop, in 1977.	Pyritic ironstone with "kaolin ooliths" is recorded at a depth of 1344 ft 4 inches between the Mansfield Marine Band and the Haughton Marine Band.
Walden Stubbs Borehole sunk from SE 5478 1680 about 2 km north of the village of Norton, in 1951.	A bed of "Ironstone with white ooliths", 3 cm thick, was cut at a depth of 175.95 m resting on 5 cm of "inferior coal". A similar bed was cut at a depth of 183.69 m,. above a "hard light grey clunch with ironstone nodules"; the term clunch refers to seatclay

Table 3. A selection of records of kaolinite in the Pennine Coal Measures Formation, taken from borehole logs made available by the British Geological Survey (2017)..

road between Leeds and Harrogate. No leedsite specimens are listed in the current (December 2017) databases at the Natural History Museum. Further investigation to trace the precise locality and establish whether leedsite is from the Coal Measures is desirable.

MARCASITE, FeS_2

Diagenetic marcasite is widespread in the South Yorkshire Coalfield, but is commonly reported as 'pyrite'. The few studies that make explicit mention of marcasite (e.g. Rippon, 1984: pp. 36–37) typically include notes to the effect that:

> "Laboratory study shows that some sulphide is in the form ... [of] marcasite; normally it is not possible to be precise about the form of the sulphide, and it is, therefore, referred to throughout as pyrite".

In a study of the mineralogy of the Alton Marine Band and associated strata in the Lower Coal Measures, Love *et al*. (1983), noted that marcasite was relatively uncommon and formed at a later stage than most of the diagenetic pyrite. Nodular sedimentary pyrite and marcasite were commonly found in the waste from Kellingley Colliery in North Yorkshire (Jon Evans, *personal communication*, 2016). The marcasite nodules were much less stable than the pyrite; none survived for long.

Marcasite was found in a fault exposed in the Throapham Main Intake at Dinnington Colliery near Rotherham. A specimen in the Uttley Collection displays tabular equant to elongated prismatic, metallic, brassy yellow crystals up to 2 mm in length, some with a red to blue iridescent tarnish, on dark brown sandstone and colourless to white dolomite (Fig. 48). Another specimen from Dinnington Colliery, collected by the mine geologist, Roy Fry, was donated to Sheffield City Museum (Uttley, 1993); it is accessioned as SHEFM: 1991.260. Tabular crystals up to about 2 mm across, with sparse dolomite in fine-grained sandstone, were found in a fault zone adjacent to the Swallow Wood Seam.

Figure 48. Bladed marcasite crystals, the largest just over 1 mm long, showing conspicuous blue–purple iridescence from a fault exposed in the Throapham Main Intake at Dinnington Colliery near Rotherham. Uncatalogued specimen in the Uttley Collection; photo John Chapman.

MELANTERITE, $FeSO_4 \cdot 7H_2O$

Melanterite is a common alteration product of iron sulphides, but due to the ephemeral nature of most occurrences, records are few. Melanterite has been reported in the Lower Carboniferous Draughton Shales at Hambleton Quarry near Bolton Abbey (Purton and Youell, 1969). Similar lithologies are common in the Yorkshire Coal Measures, but none of the descriptions of efflorescent salts (e.g. Holgate, 1909) is supported by analytical data. Nonetheless melanterite is likely to be common. In a summary of minerals from the northeast of England, Smythe (1924) noted that:

> "it is possible, in dry weather, to gather considerable quantities of efflorescent copperas [melanterite] from the outcrops of coal seams and the old waste heaps adjoining them. It is often encountered, too, in coal mines".

Joseph Dawson recorded "Sulphate of Iron or Natural Coperas" in his mineral catalogue (Dawson, 1810–1813: p. 179); the locality is illegible, but it is almost certain to be in the Coal Measures near Bradford. In his museum in Leeds, Ralph Thoresby (1715: p. 470) had a specimen which he described as:

> "A Sort of Mineral Salt found in the Coal-Mines (adhering to a Brass Lump) near Coln Com. Lanc. whence it was sent me by Dr. Hargreavs : It was found shot into Needle like Chrystals three Inches long, but now as small as Dust, with shining Sparks".

The 'brass lump' is likely to refer to pyrite; the remainder of the description may refer to melanterite or another soluble sulphate species[18]; unfortunately neither the specimen, nor Thoresby's collection, have survived.

In a description of a Yorkshire ganister working, Bromehead *et al*. (1933) noted that "Iron salts derived from the old workings in the coal incrust the joints". These are likely to include melanterite, which is a common decomposition product of pyrite. Joseph Kenworthy (1915: p. 18) records the presence of "thin vertical veins of bluish-green matter" in ganister near Deepcar in Sheffield;

[18] In this context it is worthwhile noting that J. A. Smythe (1925) observed that epsomite was common in coal and ironstone mines in northeast England "usually as bundles of exceedingly slender needles, up to 4 inches in length and of dazzling whiteness. It is known by the pitmen under the name of Old Men's Whiskers, a singularly good descriptive term, especially applicable when the brilliant natural lustre of the crystals is somewhat dimmed by a slight coating of dust".

a description that is consistent with melanterite, which is commonly pale blue-green.

MICA-GROUP MINERALS

Muscovite, 'Biotite', 'Illite' and 'Glauconite'

Mica-group minerals (Rieder *et al*., 1998) are important detrital and authigenic components of many Coal Measures rocks. Detrital muscovite grains are conspicuous on the bedding planes of Lower Coal Measures sandstones. An early reference is provided by Thoresby (1715) who had a specimen of:

> "a Sort of red Argil, full of Mica or Cat-Silver, I found a great Quantity near the Coal-Mines of John Gascoigne Esq; cast up in a vast Drain betwixt Parlington and Berwick in Elmet".

Berwick in Elmet refers to the village of Barwick in Elmet to the east of Leeds where coal was mined in opencast operations until the 1970s.

Dark micas, generally described as biotite, are less common than muscovite in the Coal Measures, and typically make up less than 1% of sandstones except the Langsettian Silkstone Rock, in which they are slightly more abundant. The dark micas commonly alter to chlorite-group minerals (Huggett, 1984).

The diagenetic alteration of muscovite releases potassium to produce a mica-group mineral of variable composition which is commonly described as 'illite'. Despite the widespread use of the term, especially in petrology, illite is not considered to be a valid mineral species (CNMNC, 2017); it is a potassium-deficient variety of muscovite, with a composition in the range $K_{0.6–0.85}(Al,Mg)_2(Si,Al)_4O_{10}(OH)_2$. Illite is particularly abundant in Yorkshire fireclays (Grimshaw *et al*., 1962), where it may make up 30% of the rock. One of the earliest investigations of the mineral in the British Isles was based on samples from the Better Bed Clay, at Tong near Leeds (Carr *et al*., 1953).

Diagenetic alteration of dark micas can produce glauconite, the 'ferromagnesian equivalent' of illite. It is not reported commonly in Coal Measures lithologies, but the log of the Askern No. 1 Oil Well, which was drilled by BP Exploration in 1957 from SE 565 150 near Askern, has a few references to glauconitic siltstone (British Geological Survey, 2017).

The illitisation of smectite clays is a well-known reaction during burial diagenesis. It produces material which is commonly described as mixed-layer illite-smectite, and abbreviated I-S (Spears, 2006). Mixed-layer illite-smectite is a common diagenetic component of many Coal Measures lithologies. The smectite to illite alteration sequence has been studied for many years but is still not completely understood (Lanson *et al*., 2009).

PYRITE, FeS_2

In an early and perhaps apocryphal illustration of the value of mineralogical study, Mawe (1818) noted that:

> "It daily occurs, that gentlemen unacquainted with Mineralogy, whose studies, in other respects, have been liberal, bring Pyrites from a bed of Coal, thinking it may be Gold".

The term pyrite is used *sensu lato* in most of the references quoted herein to include both pyrite and marcasite. Diagenetic pyrite, which occurs as globular, framboidal and nodular aggregates, is abundant in Coal Measures rocks, especially in and around marine bands (Eden *et al*., 1957); Uttley (1988a) notes that "any old spoil tip ... will yield specimens".

Pyrite is produced by the reaction between ferrous iron in solution and sulphide species generated by the bacterial reduction of (mostly seawater) sulphate (Spears and Tewalt, 2009; Spears, 2015). Isotopic studies of the formation of pyrite in the Alton Marine Band and associated coal and ganister in the Lower Coal Measures at Penistone have shown that most of the pyrite formed at a very early stage, predating compaction of the sediment. The earliest pyrite forms framboidal masses and is followed by more localised and intense deposition in a variety of textures (Love *et al*., 1983). Euhedral crystals are uncommon, one of the few records being from the Shafton Marine Band in the Dale Mount Farm Borehole, sunk in 1973 from SE 7046 1013 about 5 km east of Hatfield; even at this locality only the bottom few inches of an abundantly pyritic sequence contained well formed crystals.

Most coal seams in the Yorkshire area contain significant amounts of pyrite. In the cleat of coal, where it post-dates compaction, it is the principal host of a number of environmentally important trace elements, including mercury, arsenic, selenium, thallium and lead (Spears, 2015). The mechanism by which diagenetic pyrite concentrates these trace elements has been a mystery ever since it was noted in the 1960s (Rickard *et al*., 2017).

Pyrite is described replacing fossils at coal mines in Derbyshire and south Yorkshire in Sowerby (1817: pp. 97–98), where it is noted that "in a short time it decomposed". Localities for Coal Measures pyrite noted by Sowerby include strata exposed near Halifax, Bradford and Leeds. Specimens from the mines at Idle near Bradford are catalogued in Joseph Dawson's collection (specimens 1736 and 1737; Dawson, 1810–1813). John Farey's account of the minerals of Derbyshire and its environs records that 'brasses' were found at many mines in the coal districts including those at Eccleshall Barlow near Sheffield (Farey, 1811: p. 219). They were collected to produce copperas.

Pyrite is common in Coal Measures ironstones. It was found replacing siderite at High Birks Pit, Thornton, Bradford and near Siddall, Halifax (Deans, 1934), and noted in most of the clay ironstones analysed by Smyth *et al*. (1856). It occurs in other carbonate concretions including "Limestone balls" (e.g. Steinhauer in Sowerby, 1817: p. 98) at mines near Halifax, Bradford and Leeds. In a comment on Sowerby's work, a correspondent known only by the initials F. O. E., notes that:

> "specks of pyrites are seen in such Limestone Balls, and some shelly balls, are all pyrites ... particularly so at other Collieries to the NE and E [of Halifax and]

as the stratum ranges, E of Idle, near to Calverley, and Farsley, across the Air [*sic*] to the S of Horsforth, &c" (F. O. E., 1812).

There is a record of a donation of "Pyrites and calc spar from a 'fault' in coal measures near Barnsley" in a list of mineralogical donations to the Yorkshire Museum for 1836 (Yorkshire Philosophical Society, 1837). Pyrite is noted from the Coal Measures around Barnsley in Hall (1868); and it is described as being particular common in seams such as the Halifax Hard Bed and Shafton Coal, which have marine roofs (Ramsbottom *et al*., 1974).

Fine grained sedimentary pyrite from Coal Measures localities is unstable near the surface of spoil heaps, oxidising to produce an acidic solution from which iron sulphate, hydroxide and oxyhydroxide minerals precipitate. There has been relatively little detailed investigation of these phases, although they are common in coal tips and abandoned workings in south Yorkshire and surrounding areas (e.g. Spears *et al*., 1971; Evans *et al*., 2003; Davis-Vollum *et al*., 2016). In this context it is interesting to note that nodules of sedimentary pyrite were commonly present in the waste from Kellingley Colliery. Unlike the sedimentary marcasite from this locality, which is highly unstable and oxidises within a very short period, some of the pyrite specimens have remained stable in storage for more than ten years (Jon Evans, *personal communication*, 2016).

Pyrite is recorded in fracture assemblages in a number of boreholes in the South Yorkshire Coalfield. It was noted in fractures in sandstone in the Peak Lane Borehole, sunk in 1978 from SK 5250 9105 southwest of Maltby, where "irregular open steeply hading breaks lined with pyrite crystals" were encountered in the Bolsovian Wickersley Rock. In the Woodend Borehole, "pyrite filled fissures" are recorded in sandstone a few metres below the Carboniferous–Permian unconformity (British Geological Survey, 2017) and there are similar records in the Woodhouse Green Borehole, which was sunk from SE 6369 1318, north of Stainforth. Pyrite-calcite veins, described more fully under calcite, occur at Bullhouse Colliery (Bromehead *et al*., 1933: p. 88); the Bolton Dearnsides borehole; Thurcroft Colliery No. 12 Underground Borehole; Womersley No. 2 Borehole; and Hatfield Colliery No. 1 Shaft (Wilson, 1926: pp. 191–194).

Pyrite is commonly found with calcite in fault and fracture assemblages. Three pyrite localities in fractures in Coal Measures sandstone are noted in Uttley (1993): "Cubo-octohedral [*sic*] crystals with chalcopyrite, dolomite and barite from fissures in [the] S21's Intake Trunk Roadway" at Silverwood Colliery, and "Brassy cubic crystals up to 10mm from faulting in Axle Access Roadways" and "Cubic crystals with calcite and ankerite from [a] fissure in H01's Roof" at Kiveton Park Colliery. Although specimens from these localities are listed as present in the Uttley Collection in 1993, they have not survived.

Drusy coatings of cubic pyrite crystals, some with a marked purple iridescence, are present on calcite specimens from Orgreave Colliery in Sheffield Museum. Unusual columnar pyrite crystals up to about 5 mm in length (Fig. 49) occur with smaller cuboctahedral crystals in dolomite-lined cavities in siltstone at Treeton Colliery near Rotherham (Andy Norman, *personal communication*, 2018).

QUARTZ, SiO_2

Chalcedonic quartz occurs in sideritic mudstone about 10 m above the Forty Yards Marine Band [now the Meadow Farm Marine Band] in the Gringley No.1 Oil Bore, which was drilled in 1945 by Anglo-American at Gringley on the Hill, east of Bawtry [SK 7457 9064] (Smith *et al*., 1973: p. 54). Chalcedonic quartz and secondary silicification in the form of chalcedonic overgrowths are not uncommon in Coal Measures sandstones, marine bands and coals (Taylor, 1971; Rippon, 1984).

In coal seams, chemically precipitated quartz occurs as layers described using the German term "Quartz Lagen" (Uttley, 1993); "quarzlager" (Pearson, 1974a); or "quarzlagen" (Rippon, 1984). The last spelling appears to be correct (Hoehne, 1956) and is adopted herein. In the East Pennine Coalfield, quarzlagen have been reported near the top of the Kent's Thick, Clowne, Deep Soft, Top Silkstone, and Blackshale or Low Silkstone seams (Rippon, 1984; British Geological Survey, 2017). In the Kent's Thick Seam, the top plie is described as "inferior with quartzitic lenses" in many underground boreholes northeast of Doncaster.

The Clowne Seam along the south Yorkshire boundary is particularly prone to quarzlagen, which are undesirable as they constitute a sparking hazard. Sections through these structures are figured in Rippon (1984: pp. 37–38). The quartz occurs as layers, varying between 50 mm and 200 mm in thickness, which may extend laterally for more than 100 m. The layers are commonly bordered by acicular crystals. In the Clowne Seam at Whitwell Colliery on the Yorkshire-Derbyshire border, there are records of acicular quartz crystals interleaved with bright coal in a regular fashion.

Figure 49. Cuboctahedral pyrite crystals, the largest preferentially elongated on one axis, in a dolomite lined cavity, 17 mm across, from Treeton Colliery, Rotherham. Andy Norman Collection; photo John Chapman.

The origin of quarzlagen is problematic, Rippon (1984) suggested that silica derived from plants may have been responsible. Plant phytoliths are much less stable than detrital quartz and would provide a ready source of silica. Recent research, which suggests that the abundance of silica in some early lycopsid species was particularly high (Trembath-Reichert *et al*., 2015) adds weight to this conjecture. Some researchers objected on the grounds that quarzlagen are concentrated near the top of coal seams. The recent recognition of the importance of silica in biological cycles (e.g. Lahr *et al*., 2015) suggests that the biogenic silica released into the lower layers of peat by plant phytoliths may have been reused by the ecosystem.

Quartz has been recorded in ironstone at several localities in the Yorkshire Coal Measures. The label for specimen number 1829 in the Joseph Dawson Collection at Cliffe Castle, Keighley records "common Clay Ironstone with Rock Crystals" from Low Moor near Bradford. Unfortunately, the specimen cannot be identified with certainty. Quartz crystals in ironstone are recorded in the sale catalogue of a collection belonging to the Derbyshire petrifactioneer White Watson (1805: p. 28) which included: "Half a nodule of Argillaceous Iron-stone containing Quartz crystals.—Yorkshire". Quartz has also been recorded as minute crystals in kaolinite peloids in ironstone at Robin Hood Quarry, south of Leeds (Deans, 1938).

Carbonate minerals dominate the fault and fracture assemblages across most of the South Yorkshire Coalfield; however, quartz veins are recorded at numerous horizons in the Two Gates Borehole, which was sunk in 1982 from SE 4138 1045 between Brierley and Grimethorpe, and less commonly at other boreholes in the Barnsley area. Unfortunately, there is no indication of their paragenetic relationship to other coalfield minerals.

Quartz occurs with hematite in the South Don Fault, at Denaby Colliery near Mexborough (Uttley, 1988a; 1993). A large hand specimen with colourless, transparent, equant, pyramidal quartz crystals up to 5 mm long in cavities in massive hematite was collected by David McCallum in 1976. It was donated to Manchester Museum and is accessioned as MANCH: N11428. Similar specimens, which are listed as present in the Uttley Collection in 1993 could not be traced with certainty. However, a specimen donated to Sheffield Museum shows drusy colourless pyramidal quartz crystals up to about 3 mm in length, some cut by planar fractures, lining cavities in massive hematite.

The only record of semi-precious cryptocrystalline quartz from the Coal Measures is of red jasper pebbles up to 10 mm across from the Woolley Edge Rock at the Havercroft Lane Borehole, which was sunk from SE 4939 2015 in 1979 from Havercroft Lane, between Havercroft and Fitzwilliam, near Wakefield (British Geological Survey, 2017).

RHODOCHROSITE, $MnCO_3$

Post-mining rhodochrosite occurs with undifferentiated black manganese oxides in recent flowstone at Caphouse Colliery near Wakefield (Davies-Vollum *et al*., 2016). It is probably common in similar geological environments across the South Yorkshire Coalfield, but easily overlooked as it does not have the characteristic bright pink colour which is typical of collector specimens. The source of the manganese may be dissolving dolomite; Fe^{2+}-rich dolomite from Yorkshire Main and Thoresby collieries contains an average of 1.75 wt% $MnCO_3$ according to Spears and Caswell (1986).

SIDERITE, $FeCO_3$

The abundance of early authigenic siderite in Coal Measures rocks is notable. The log of the Walden Stubbs Borehole, in Middle Coal Measures strata between the Cambriense Marine Band and the Kent's Thick Coal, records siderite as either ironstone or sphaerosiderite in 56 of 242 lithological units. The 'Coal Measures' might, with equal justification, have been named the 'Siderite Measures'.

Siderite is the principal rock-forming mineral in the sedimentary ironstones of south Yorkshire (e.g. Hallimond, 1925; Deans, 1934; 1936; Dunham, 1960; Spears, 1989). Coal Measures ironstones are divided into two groups by Deans (1934; 1936): clay ironstones occur in argillaceous rocks and are commonly well developed above coal seams; spherulitic ironstones are well developed in seatclays and associated rocks. Radiating microcrystalline siderite, which is described by the petrographic term sphaerosiderite, is abundant in the Coal Measures; it occurs in small amounts in most lithologies (e.g. Deans, 1934; 1936; Dunham, 1960; Eden *et al*., 1957; Ramsbottom *et al*., 1974; British Geological Survey, 2017).

Clay ironstones were of importance as ores until the end of the nineteenth century. Chemical investigations were made by Joseph Dawson, manager of the Low Moor Ironworks, in the late eighteenth century (Pacey, 2003). An analysis by Richard Phillips[19] (1824) of a variety of clay ironstone which was "called at Low Moor Iron Works near Bradford, Yorkshire, Black Iron Stone", concluded that the ore which was "usually but improperly called argillaceous iron ore, is in fact a carbonate of iron". In the area around Sheffield and Rotherham, beds between the Silkstone and Joan Coals were particularly productive. In the area between Leeds and Bradford, the Black Bed or Low Moor Ironstone was worked.

A study of the composition of siderite in diagenetic clay-ironstone concretions associated with the Langsettian Alton Marine Band near Hazlehead, Penistone showed large variations in composition. Chemical analyses revealed extensive replacement of Ca and Mg for Fe in some samples (Pearson, 1974b) and structural studies showed that the

[19] Richard Phillips (1778–1851) was a talented chemist and founder member of both the Geological Society and the Chemical Society; his brother William Phillips (1775–1828) produced the well known *Elementary Introduction to Mineralogy*, of which five editions, each extensively revised, were published (Torrens, 2004; 2009). Richard Phillips' analysis of clay ironstone from Bradford is included in the third edition of an *Elementary Introduction to Mineralogy* (Phillips, 1823).

outer portions of the siderite nodules were particularly rich in magnesium (Pearson, 1974c). A detailed interpretation of the mineralogy and geochemistry of the Hazlehead siderite nodules is provided by Curtis *et al*. (1975), who used a combination of analytical techniques to show that the most important source of iron was hydrated iron oxides present in ancient soils. As the sediment was buried, authigenic siderite formed relatively quickly, with the Fe^{2+}(aq) being supplied by the microbial reduction of the hydrated iron oxides. Organic carbon was the principal carbon source. The siderite so-formed was enriched in ^{13}C, and relatively pure, containing little Ca and Mg in solid solution. The surrounding siderite precipitated more slowly as the sediment was buried. By this time the supply of Fe^{2+}(aq) had reduced and the activities of Ca^{2+}(aq) and Mg^{2+}(aq) increased, perhaps due to the dissolution of unstable biogenic aragonite and magnesium-rich calcite. This produced magnesium-rich siderite (described as pistomesite) in the outer layers of the clay-ironstone nodules, containing significant Ca in solid solution and enriched in ^{12}C.

A large number of specimens of clay ironstone from Yorkshire and Derbyshire were on display at the Museum of Practical Geology in the 1860s. Crystalline siderite is recorded with pyrite, chalcopyrite, galena and sphalerite in syneresis cracks in a clay-ironstone nodules from Hady, Chesterfield (Smyth *et al*., 1864: p. 58).

The only record of well crystallised siderite in a fracture in the Coal Measures is in one of a series of letters written in 1915 by H. N. Berry, the manager of the Hatfield Main Colliery, to Walcot Gibson[20] (British Geological Survey, 2017). In a reply to Gibson's identification of "clusters of red crystals" as siderite, Berry notes that "veins of calcite crystals containing clusters of iron carbonate" were found in grey sandstone "2 yds 1 ft 6 in." thick at a depth of "391 yds 2 ft 4½ in." in the shaft. This is in the Upper Coal Measures about 30 m below the Carboniferous–Permian unconformity.

SPHALERITE, ZnS

Although it is probably widespread in the Pennine Coal Measures, records of sphalerite are few. Crook (1911) noted that sphalerite was found in dolomite veinlets in the cleat of English coals in much larger amounts than galena. He examined specimens from Yorkshire and Nottinghamshire but did not provide detailed records of the localities.

Sphalerite occurs in cracks in ironstone nodules known as "cheeses" at Hady near Chesterfield, Derbyshire (Smyth *et al*., 1856: p. 43), and in cracks in the "chance balls" at Civilly Rake and the "tufty balls" from below the Kilburn Coal near Ambergate in the same county. Nodules in the Old Man and Old Woman bands at Hady near Chesterfield contained dolomite and "abundant crystals of zinc-blende" (Smyth *et al*., 1856: p. 43).

Sphalerite is noted in Russell (1934) as a very rare component of cavity mineralisation in the roof of the Parkgate Seam at No. 3 Pit, Manvers Main Colliery, Wath-upon-Dearne. The only locality documented in Uttley (1993) is the Rayton Farm Borehole, sunk in 1982 from Rayton Farm [SK 6155 7950] near Worksop, where:

> "a 5mm fracture in the core was found to be crystallised with 2mm black tetrahedral crystals with occasional hydrozincite coatings".

The borehole log records sphalerite and dolomite in fractures in mudstone and siltstone at a depth of approximately 448 m, between the Two Foot and Clowne seams, a few metres above the Two Foot Marine Band [now known as the Maltby Marine Band]. A hand-written note on a file-card found in Steve's personal effects records "calcite, pyrite and zinc-blende ... below [the] Manton Estheria Band [in the] Mexborough Montagu BH" at a depth of about 700 feet. A "brown vitreous cubic" phase, thought to be sphalerite, in fine-grained sandstone between 546.75 m and 548.29 m about 6 m below the position of the Flockton Thick Seam is recorded with calcite and pyrite in the Tall Trees Borehole, which was sunk in 1978 from SE 4448 1832 northeast of High Ackworth (British Geological Survey, 2017).

Sphalerite occurs as small orange to red-brown tetrahedral crystals in kaolinite peloids found in ironstone at the Smithy Wood Opencast, Chapeltown, Sheffield (Fig. 50). Sphalerite crystals occur in kaolinite peloids in other similar ironstones (which are described in detail under kaolinite) including that at Robin Hood Quarry near Leeds,

Figure 50. Orange-brown sphalerite cleavage about 0.3 mm across in a kaolinite peloid. The colour suggests a relatively low iron content. Collected by Tim Neall at Smithy Wood Opencast, Chapeltown, Sheffield. Photo John Chapman.

[20] Walcot Gibson (1864–1941) was born in Bromsgrove. He was educated at Bromsgrove School and Mason College, Birmingham where he was the first geological pupil of Charles Lapworth. He prepared the first edition of *The concealed coalfield of Yorkshire and Nottinghamshire* (Gibson, 1913), and supervised much of the work for the second edition (Wilson, 1926). He became Assistant Director of the British Geological Survey, was awarded the Murchison Medal in 1924, and elected a Fellow of the Royal Society in 1925.

from where a crystal of "dark blende" is figured in Deans (1938). Sphalerite was reported to be common in peloidal ironstone at Birkenshaw near Bradford, where it occurred in hand specimens as "red resinous grains and strings" (Deans, 1936: p. 172).

DISCUSSION

The localities described in the foregoing text must represent only a tiny fraction of the places where mineralisation was encountered. In discussing silver-rich galena found in a fault fissure at Kilnhurst Colliery near Rotherham in 1932, J. R. Forster-Smith (1959) noted that he had heard of "several other such minor occurrences in the South Yorkshire coalfield at that time"; none appear to have been recorded. In a discussion following Ineson *et al*. (1972) it is noted that:

> "Conversations with miners often revealed that galena, chalcopyrite etc., were found in the course of working, but records were rarely kept, and the specimens usually disappeared onto mantlepieces!".

Many collieries discouraged collecting: a crystal-lined cavity in which miners were able to stand at Houghton Main Colliery east of Barnsley was destroyed on the orders of management before any record could be made (Andy Norman, *personal communication*, 2017).

Few specimens from the coal mines have survived and records which contextualise the fracture mineralisation are almost non-existent. It is unfortunate that the suggestion in the discussion following Ineson *et al*. (1972); that it was "high time that a comprehensive survey of the distribution of such minerals in the coalfields was undertaken", was not pursued while the collieries were working.

The Uttley Collection

As specimens from the Uttley Collection provided the catalyst for this research, and the observations recorded in Uttley (1993) made a major contribution to the descriptive text, it seems appropriate to begin with a discussion of the collection. One simple recommendation would have enhanced the security of the specimens, it is well known but bears repeating: glue a small label with locality details onto every important specimen. The label need not be obtrusive and the glue should be reversible. Fortunately, all but one of the coalfield minerals in the Uttley Collections survived in their respective card trays with associated labels; if the box containing them had been dropped, it would have been impossible to match specimens back to localities.

Private collections are at risk when their owners die. Relatives may not appreciate the significance or value of the specimens (and in extreme cases they may be discarded). Friends and colleagues who understand their importance can be helpful in these circumstances. The preservation of collections often depends on such interventions. In the current austere climate, public museums do not usually have the resources to absorb large numbers of specimens; indeed, in the UK, few dedicated mineralogy curators remain outside the national museums. As a result, specimens tend to pass to like-minded individuals, either via dealers or by private arrangement.

If a collection is dispersed it is inevitable that information is lost. Suites of minerals from particular areas or localities are commonly split up, and it may not be possible to keep all of the documentation with all of the specimens. Collection catalogues are particularly vulnerable as it is not easy to find an appropriate place to lodge them. A period in which research can be undertaken prior to dispersal is useful. It provides a final opportunity to see all the specimens together and garner information that would otherwise be lost. However, a great deal of contextual data is almost always locked in the collector's memory. This underlines the importance of recording detailed information when specimens are added to a collection and publishing important data while it is reasonably fresh in the mind. Fortunately, Steve wrote several descriptive accounts of his coalfield specimens.

Authigenic Minerals

A summary of the authigenic minerals in Coal Measures lithologies makes a worthwhile starting point in a discussion of the mineralisation. Geochemical modelling is beyond the scope of this study; it would require reliable estimates of the pressure, temperature and chemical composition of the relevant mineralising solutions (abbreviated as *P-T-X* hereafter) and models of the ways in which Carboniferous biological processes affected the cycling of elements. Almost all of the elements in the important authigenic minerals, including calcium, carbon, iron, magnesium, oxygen, and silicon, played important roles in Coal Measures ecosystems; there are models of such elemental cycles for modern ecosystems (Gadd, 2010) but they cannot be extended to the Carboniferous with confidence.

The most important authigenic minerals in Coal Measures rocks are siderite, quartz, kaolinite, illite, mixed layer illite-smectite, pyrite, calcite and dolomite. Siderite is almost always early, forming before and during sediment compaction. Quartz, kaolinite and other phyllosilicates commonly form authigenic overgrowths on detrital grains in the clastic rocks. Dolomite, and less commonly calcite, occur as late-stage diagenetic cements and in concretions. Authigenic hematite is locally common; it formed in a Permian desert environment when basin inversion exposed the Coal Measures rocks to weathering. The 'limonite' which gives Coal Measures sandstones their distinctive brown colour is recent.

Clay Ironstone

Most of the iron in the surface layers of Coal Measures ecosystems appears to have been immobilised as highly insoluble iron oxides and oxyhydroxides, which are the common and stable phases at the earth's surface (Cornell and Schwertmann, 2003). Mud containing these minerals accumulated in shallow lakes and soils, particularly where the sedimentation rate was low. As the land subsided and sediment was buried, conditions changed from oxidising to reducing and microbial activity destabilised the iron oxyhydroxides, releasing Fe^{2+} into solution.

In anoxic conditions, the activity of $Fe^{2+}(aq)$ is usually limited by reduced sulphur species which precipitate highly

insoluble iron sulphides. In the Coal Measures, the most important source of sulphur in its reduced and oxidised forms was seawater sulphate (Spears, 2015), bacterial reduction producing the former from the latter (Rickard *et al*., 2017). A detailed study of pyrite from the Lower Coal Measures in and around the Alton Marine Band near Penistone showed that most of it crystallised at a very early stage in unconsolidated sediment (Love *et al*., 1983). The supply of sulphate into the flood-plain muds and soils was limited, and in most Coal Measures lithologies it was depleted long before Fe^{2+}(aq). In the absence of reduced sulphur, the activity of Fe^{2+}(aq) increased until the solubility of the iron carbonate siderite was exceeded. Thus, in typical Coal Measures mudstones, siltstones and seatclays, the principal control on Fe^{2+}(aq) is siderite. The relative stability of pyrite and siderite in Coal Measures sediments is illustrated in Deans (1934: p. 56), which notes the partial replacement of siderite by pyrite, if there was a renewed supply of reduced sulphur.

The formation of clay ironstones is reasonably well understood (Pearson, 1979; Young, 1989). The nodules present in many clay ironstones probably nucleated at shallow redox boundaries in unconsolidated sediment in places where oxidising organic matter provided additional carbonate and acted as a focus for reduction. Petrographic studies show that much of the Coal Measures siderite formed at an early stage. The early formation of clay ironstonesiderite nodules is supported by observations at exposures such as the 'Dumb Fault' of north Derbyshire where Coal Measures rivers eroded well-formed ironstone nodules from contemporary sediment in the channel banks (Guion *et al*., 1995: p. 324).

Some ironstone nodules contain syneresis cracks. They are not present at every horizon [indeed in a study of the fossil content of many hundreds of ironstone nodules from the spoil heaps at Yorkshire Main Colliery (Lomax *et al*., 2014), very few were found to contain syneresis cracks or other noticeable mineralisation (Dean Lomax, personal communication, 2017)]. If cracks are present, the assumption that the mineralisation is simply a reflection of the composition of local pore fluids might at first appear reasonable, but observations made while the ironstone mines were working suggest otherwise (Smyth *et al*., 1856: p. 43):

> "The "Old man" and "Old woman," [nodule bands] ... exhibit numerous cracks ... [which contain dolomite and] abundant crystals of zinc-blende, and isolated crystals of galena (sulphide of lead) in well-defined crystals combining the faces of the cube and octahedron. Copper pyrites and iron pyrites also occur occasionally in the same manner, sometimes even in the partial hollows left around the cast of a fossil shell; and it need scarcely be pointed out what an important bearing on the formation of mineral veins is afforded by the presence, under such circumstances, of the metallic sulphides. It is, moreover, remarkable that they occur more abundantly in the vicinity of the small faults which traverse the measures and which would appear to have been the channels for the passage of waters holding these substances in solution".

The last sentence of this paragraph is of particular importance as it demonstrates a link between small local faults and sulphide mineralisation in the ironstone nodules.

There is insufficient data to assess mineral parageneses in the cracks in the ironstone nodules, but a summary of the species that are present is worthwhile. Apatite is probably common as suggested by the presence of phosphate in most chemical analyses (e.g. Smyth *et al*., 1856). Baryte is widespread; Ineson *et al*. (1972: p. 147) note that:

> "large ironstone concretions associated with the Overseal Marine Band frequently yielded galena and baryte".

Calcite occurs in fractures in ironstone nodules at Cottingley near Bradford (Deans, 1934) and in nodule bands cut by a number of borehole cores. Chalcopyrite galena and sphalerite have each been reported from a handful of locations across the coalfield; they are probably widespread in small amounts. Dolomite is recorded lining syneresis cracks in several nodule bands and is probably common. Kaolinite (or dickite), and pyrite or marcasite are also likely to be common as indicated by reports of white powder in shrinkage cracks and numerous films and thin veins of 'pyrite'. Quartz has been found as small pyramidal crystals in nodules at Low Moor near Bradford, and is probably more common than this single record suggests. Thus, the suite of minerals is almost identical to that found in the cleat of coal and in the faults and fractures that traverse the Coal Measures.

Coal-Cleat Mineralisation

The minerals that have been recorded in the cleat make an interesting comparison to the fracture assemblages. The development of the microfractures which form the cleat post-dates the deposition of the early diagenetic minerals (principally siderite and pyrite) but appears to have happened soon after lithification. Clasts of Westphalian coal with a well-developed cleat have been found in later Westphalian assemblages (Gayer and Pešek, 1992). Cross-cutting relationships show that the fracture assemblages post-date the development of the cleat (Fig. 51), and where they intersect coal seams, the carbonate content increases over a wide area (Pearson, 1974a).

Fortunately, there were economic reasons to study the coal-cleat minerals as they are a source of some of the undesirable impurities emitted by power station (Spears and Caswell, 1986; Spears, 1987). This led to the recognition of a distinct paragenesis (Spears, 1987):

> "The early vitrain cleat is dominated by sulphides, mainly pyrite and marcasite but including sphalerite and galena. The major cleat cutting several coal types is generally multimineralic. Kaolinite post-dates the sulphide but quartz is relatively rare and difficult to date with respect to the kaolinite. In the Pennine coals carbonates follow the silicates ... ankerite is present and pre-dates the calcite".

The cleat mineralisation in coal seams does not represent a single mineralising event. Spears and Caswell

(1986) related the paragenesis to different stages of burial diagenesis, with the availability of ions in the coal being controlled by coalification reactions and diagenetic processes in adjacent mudrocks. A feature of this proposal is that the ions were sourced from both coal and the enclosing sediments, with the anions derived from the coal, and the Fe, Pb, Zn and Cu from pore fluids in the mudrocks.

The species diversity of the cleat mineralisation in south Yorkshire is typical of coalfields north of the Wales–Brabant High, but significantly less than in south Wales. The South Wales Coalfield has a different thermal and deformational history and a more diverse mineralogy; more than fifty species have been recorded in the cleat of the coal (Gayer and Rickard, 1994; Rippon *et al*., 2006).

Fracture Mineralisation

The fracture-hosted vein assemblages, which are the principal subject of this account, have not been described in detail in previous studies. All of the coalfield specimens in the Uttley Collection are from fractures in siliciclastic units, although it is clear from borehole logs and museum specimens (e.g. Fig. 51) that mineralised fractures extend into other lithologies. A diagram of a 'typical' fault zone (Uttley, 1993: p. 13) shows a relatively wide WNW trending fault system with metre-scale vertical displacements and numerous separate fractures. All of the extant Uttley Collection specimens, except the hematite-quartz from Denaby Colliery, are from fractures associated with small normal faults.

The available specimens show that two separate fracture assemblages are present in south Yorkshire. One is dominated by dolomite and chalcopyrite, with minor baryte, and rare pyrite, marcasite, sphalerite and galena. The other is dominated by calcite, with pyrite and rare galena. The claim that these are separate assemblages is based on cross-cutting relationships noted on four of the five specimens in which veins of dolomite and calcite occur together. Dolomite and calcite veins are present on specimens from Clipstone Colliery, Harworth Colliery, Kiveton Park Colliery, Thurcroft Colliery and an unidentified site. In every case calcite post-dates dolomite-chalcopyrite. On all of the specimens except the Harworth Colliery calcite, a period of brecciation post-dates the deposition of chalcopyrite-dolomite and pre-dates the calcite mineralisation. Vein calcite overgrows dolomite-chalcopyrite and, in some cases, encloses thin wallrock fragments detached during reactivation of the fracture system. Two temporally separate parageneses: early dolomite-chalcopyrite with minor baryte; and later calcite with minor pyrite are required to account for these observations.

The two assemblages are well shown on a specimen from Kiveton Park Colliery (Fig. 52). Rafts of brown dolomite–ankerite with minor chalcopyrite (the early mineralisation) and a little adherent wallrock have become detached from the fracture walls and enclosed in later calcite. The dolomite rafts are relatively fragile and do not appear to have moved far from the surfaces on which they crystallised. The later mineralisation was not sufficiently energetic to completely fragment the dolomite and deposit it as a collapse breccia at the base of an open fluid-filled fracture. Nor were the later fluids sufficiently aggressive to remobilise the earlier mineralisation.

Figure 51. Dolomite rhombs up to 6 mm on edge, with minor chalcopyrite, in a fracture in coal, on an unregistered specimen in Sheffield Museum, thought to be from a local Coal Measures site. The mineralisation clearly post dates lithification of the coal and the development of the cleat. One of the very few specimens with well developed crystals in coal seen during this study. Photo Peter Briscoe.

Figure 52. A brown dolomite selvedge with minor chalcopyrite, about 2 mm thick, with a few remnant grains of wall rock on the base, which has been detached from the wall of a fracture and enclosed in later calcite. Two stages of fracture mineralisation are shown very clearly; the label is glued to a thin piece of wall rock at the bottom of the photograph. From the sandstone roof of the High Hazel Seam at Kiveton Park Colliery, near Rotherham, South Yorkshire. Specimen 203 in the Uttley Collection. Photo John Chapman.

A pressure differential between pore and fracture fluids would account for the separation of dolomite selvedges, especially if they acted as baffles to fluid flow. Coal Measures sandstones and siltstones have low primary intergranular permeabilities, but their secondary permeabilities are high in fractured areas (Lake, 1999). A reduction in pressure during dilatational fracturing would lower the pressure in a fluid-filled fracture more rapidly than in the surrounding pore fluids, potentially creating a pressure differential sufficient to detach selvedges from the walls.

It may be that crystallisation of the Fe^{2+}-rich dolomite in the dolomite-chalcopyrite fracture assemblage is an extension of the processes that deposited late-stage dolomite cements in Coal Measures sandstones. Huggett (1984) showed that the development of dolomite cements in Coal Measures sandstones is associated with the expulsion of fluids from argillaceous lithologies. Fluid mixing is also proposed in Spears and Caswell (1986) to account for some of the minerals found in micro-fractures in coal.

Large crystals of saddle dolomite require temperatures of more than about 50°C to crystallise directly from solution (Xiao *et al*., 2013; Rodriguez-Blanco *et al*., 2015). The geological setting suggests that the fractures in which the minerals formed are the result of differential subsidence in an extensional regime. In a porous but relatively impermeable medium such as Coal Measures sandstone, extensional fracturing might be expected to reduce the fluid pressure. Carbonate equilibria are commonly represented by systems of equations in which the independent variable is the partial pressure of carbon dioxide, $p(CO_2)$. A qualitative argument that a reduction in fluid pressure could induce rapid carbonate crystallisation can be made in these circumstances (see for example Bridges, 2015: p. 7).

The question naturally arises as to why sulphide minerals are concentrated in the fracture assemblages. It is clear that the fractures acted as conduits, facilitating fluid mixing. The metal contents and sulphur speciation of pore fluids in coal, sandstone and mudstone are likely to have been different. It seems likely that reduced sulphur was relatively concentrated in coal, and base metals in the fine-grained clastic rocks (Spears and Caswell, 1986). Fracturing would form pathways between differing lithologies, allowing rapid diffusion and fluid flow. Sulphide minerals (and baryte) are likely to have formed as ions drawn from chemically distinct pore fluids mixed. The least soluble of the common sulphides in a typical basinal brine is chalcopyrite, and it is almost always the first sulphide to crystallise if suitable concentrations of copper are present (Fontboté *et al*., 2017). The ion activity product in the early dolomite-lined fractures appears to have exceeded that required for the formation of chalcopyrite over a wide area.

The chemistry of the solutions from which the early dolomite-chalcopyrite-baryte and later calcite-pyrite fracture assemblages were deposited was clearly very different. This almost certainly reflects a significant evolution in fluid composition and suggests a substantial temporal gap between the two periods of fracturing and styles of mineralisation.

Red Beds and Hematite Mineralisation

Borehole logs typically record signs of oxidative alteration in the ten to thirty metres of Coal Measures rocks below the Carboniferous–Permian unconformity. The oxidation is the result of basin inversion and weathering in dry desert conditions which prevailed in Permian times. It penetrates most deeply in faulted sequences. Borehole logs typically describe Coal Measures mudstones as purple or chocolate brown if they are highly oxidised, and blue or green if they are less oxidised. The oxidised sandstones are commonly red but may be yellow or brown; the less oxidised units are pale brown or green. Ironstones, which are highly susceptible to oxidation, may be bright red or chocolate brown; coloured haloes are commonly recorded around sphaerosiderite.

There is a clear link between Permian weathering and the hematite mineralisation at the top of the Coal Measures. The most conspicuous and extensive alteration is the replacement of clay ironstone and sphaerosiderite by hematite. The abundant "balls of reddle" (British Geological Survey, 2017) met with in grey to brown sandstone at several horizons in the shaft at Dinnington Colliery were almost certainly produced by oxidative replacement of clay-ironstone nodules and the same probably applies to the nodules of hematite found below the Mexborough Rock around Manton Colliery. Surprisingly few geological descriptions comment on the replacement process. The Severals Borehole, where oxidative alteration extends almost 100 ft below the unconformity, is one of very few where there is a definite report of replacement in a "Haematitic core, deep purple (replacing ironstone)" (British Geological Survey, 2017).

It seems possible that there is a link between Permian oxidation and the hematite found in the South Don Fault at Denaby Colliery. The hematite-quartz mineralisation is the only example reported herein of mineralisation associated with a large structural fault[21]. It may be that this structure allowed unusually deep penetration of oxidising solutions. Alternatively, Lopingian or post-Lopingian fault movement may have allowed oxidising fluids to migrate from the reddened rocks at the Carboniferous–Permian unconformity (Leake *et al*., 1997). The fault extends into the overlying Permian rocks, which are displaced by up to 20 m (Mitchell *et al*., 1947), indicating repeated periods of movement until at least the end of the Permian.

The few specimens from the South Don Fault at Denaby Colliery that have survived, and the absence of any contextual data, renders any interpretation speculative.

[21] Faults were of great practical importance to colliery companies. As a result, several hierarchies of faulting have been proposed for the Coal Measures rocks (e.g. National Coal Board, 1984: pp. 98–103). In this discussion, a large structural fault is considered to correspond to a principal fault as described by Mitchell *et al.* (1947); a tectonic fault (National Coal Board, 1984) or a basement fault (Addison *et al*., 2005). A plan showing the principal faults in the Barnsley area, including the South Don Fault, is provided by Mitchell *et al*. (1947: p. 128).

The mineralisation is unlike either the dolomite-chalcopyrite or calcite-pyrite fracture fills, which were deposited in relatively reducing conditions in small faults.

Peloidal Ironstone

Authigenic kaolinite is widespread in Coal Measures sequences and peloidal aggregates have been reported in a number of lithologies (Taylor, 1971). Although this is not a petrographic study, the specimens of ironstone containing kaolinite peloids that have come to light are of sufficient mineralogical interest to warrant discussion. This distinctive rock (Fig. 53) has received little attention in modern accounts of Coal Measures lithologies.

The most detailed geological description of peloidal ironstone dates from before the Second World War and is based on locations around Leeds and Bradford (Deans, 1936). Similar material has subsequently been recorded in numerous boreholes including the Wentbridge No. 2 Borehole; King Royd No. 5 Borehole; Grove House Borehole; Ulley Lane Borehole; and Walden Stubbs Borehole (Table 3). Peloidal ironstone is noted by Rippon (1984: pp. 29–30) just above the Clowne Seam across an extensive area of south Yorkshire and adjacent counties. It was so well known to coal-mine geologists that "kaolinite ooid bands" were used in seam correlation and mapping (National Coal Board, 1984: p. 57). Despite its abundance, specimens are surprisingly rare; the peloidal ironstone (described under kaolinite) from the Smithy Wood Opencast, examined in this study, was provided through the kindness of Tim Neall, who was able to rescue a number of specimens while he worked there.

Beds of peloidal ironstone typically lie above seams of coal, or more rarely above seatclays. The presence of desiccation cracks (e.g. Lucas, 1873) and common association with freshwater mussel fossils suggests they formed on the beds of shallow freshwater lakes which occasionally dried out. The kaolinite peloids must have formed in a low-energy environment as they are well preserved despite their fragility. The peloids at Smithy Wood Opencast are most concentrated in the top few centimetres of a thicker ironstone band; a similar upward concentration of kaolinite in peloidal ironstones around Leeds and Bradford is noted by Deans (1936) and implied in Rippon (1984). This may be a reflection of density-driven segregation in unconsolidated iron-rich mud, prior to siderite replacement and lithification.

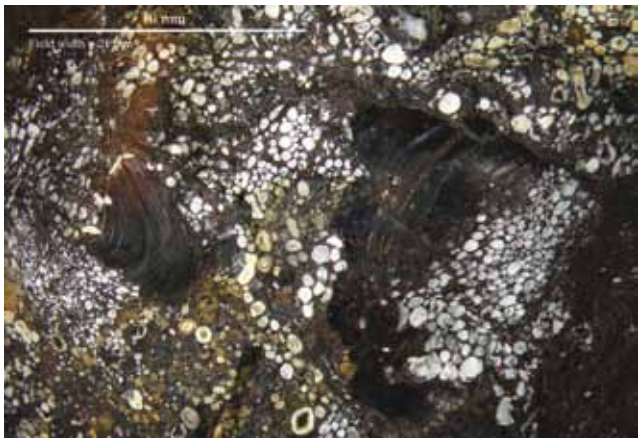

Figure 53. A typical peloidal ironstone with abundant white kaolinite in a sideritic clay-ironstone matrix (field width is 21 mm). In this specimen broken valves of freshwater mussels are replaced by siderite. Collected by Tim Neall at Smithy Wood Opencast, Chapeltown, Sheffield. Photo John Chapman.

Kaolinite peloids can make up more than 50% of the rock. They commonly contain fragments of charred plant material described in Deans (1936) as fusain; this is wind-blown ash from fires which were common in the oxygen-rich atmosphere of the time (Scott, 1989; 2002). The fragments of plant ash are so fragile that they would have been destroyed in most sedimentary environments; their abundant preservation in peloidal kaolinite is another indication of formation in a low-energy near-surface environment.

The abundance of plant ash suggests a process by which elements might accumulate in Carboniferous lakes with little sedimentary input. Modern plant ash contains major calcium, potassium and magnesium, and is rich in sulphur, phosphorus, iron, aluminium and zinc (e.g. Mahendra *et al*., 1993: p. 111). Some of these elemental inputs might be carried away in suspension or solution, but others might be geochemically concentrated in sediment.

Regional Context

An attempt was made in Uttley (1993) to assess potential zonation patterns in the coalfield mineralisation; further data were gathered in this study and plotted both geographically and stratigraphically (by DM). The datasets are not sufficiently large, detailed or reliable to reveal meaningful patterns. All that can be reasonably concluded is that dolomite-chalcopyrite (with rare crystalline baryte) and calcite-pyrite are widely distributed in fractures in the South Yorkshire Coalfield. Most of the reports of dolomite-chalcopyrite are from the Lower and Middle Coal Measures. Galena, sphalerite and baryte are sporadically distributed in fractures and are also found in other geological situations. Most of the remaining species are either rock-forming or the products of supergene oxidation.

Dolomite and chalcopyrite coat planar fractures in sandstone and siltstone on many of the coalfield specimens in the Uttley Collection. Specimens in the now-dispersed collection of Wigan and Leigh College examined by one of the authors (DIG) in 2010 revealed similar mineralisation in the Lancashire Coalfield. The mineralisation encountered in the Coal Measures in Leicestershire appears similar in terms of the species that are present (Ineson *et al*., 1972; Starkey, 2018), but is not well recorded. The situation is a little better in north Staffordshire, where Burch (1998) noted a suite of minerals similar to those from the South Yorkshire Coalfield, including a fault zone with fractures lined with chalcopyrite and 'ankerite' at Silverdale Colliery. There are accounts of dolomite fracture mineralisation (e.g. Smythe and Dunham, 1947; Hawkes and Smythe, 1935) in the Coal Measures of Northumberland and Durham. Galena and pyrite occur in clay-ironstone nodules (Winch,

1814). Smythe (1923) notes that "Small veins and pockets of galena are frequently encountered in the coal mines" and in a later article (Smythe, 1924) that "Small specimens of copper pyrites are also found in many coal pits". All of these observations suggest that the styles of mineralisation found in south Yorkshire are common and widespread in the surrounding Coal Measures.

The Coal Measures mineralisation in south Wales is well known (e.g. North and Howarth, 1928; Alderton and Bevins, 1995; Bevins *et al*., 1996; Bevins and Mason, 2010), but the coal basin has a significantly different deformational and thermal history and does not make a fair comparison.

Further Research

Although the deep mining of coal is a thing of the past in south Yorkshire, possibilities for mineralogical discoveries remain, and there are opportunities for further research. This has been an almost entirely desk-based study; thoughtful fieldwork would almost certainly reveal further interesting assemblages.

The dolomite-chalcopyrite veins examined in this study are almost entirely from the Lower and Middle Coal Measures. Unlike calcite, which is noted throughout the Coal Measures in borehole logs, there are few records of dolomite-chalcopyrite higher in the sequence (although absence of evidence does not necessarily imply evidence of absence). Saddle dolomite requires temperatures in excess of about 50°C to crystallise and it may be that fracturing in the Upper Coal Measures did not coincide with appropriate *P-T-X* conditions. Unfortunately, there is insufficient evidence to test this hypothesis; to complicate matters, dolomite and calcite, and pyrite and chalcopyrite, are commonly confused. A more detailed inspection of borehole cores would be useful.

The specimens of baryte with chalcopyrite inclusions offer an opportunity to examine sulphur isotope systematics in co-precipitating sulphide and sulphate phases. The isotopic signatures of some of the early authigenic phases are well known, but the fracture minerals have not been studied and the two might make an interesting comparison.

Colliery waste heaps give an opportunity to examine post-mining assemblages, though the fashion for remediation means that exposures are likely to be transient (Lomax *et al*., 2014). The post-mining assemblage is relatively little studied in south Yorkshire and there is the potential to discover a range of supergene minerals similar to those reported in Coal Measures colliery waste at Hawthorn Hive in Co. Durham (Young *et al*., 2008).

CONCLUSION

Perhaps the most important conclusion of this work is the degree to which it emphasises the value of collecting and recording specimens for study and analysis. Mineralogy remains a specimen-based science; without material evidence even the most elegant of theories cannot be tested. It is a sobering thought that everything that records fracture mineralisation, collected by everyone, from everywhere in south Yorkshire, would probably fit into a single small cabinet; and this in an industry which operated in the national interest.

Two distinct fracture assemblages are present in the Yorkshire Coal Measures, and extend into similar lithologies in Derbyshire, Nottinghamshire, Staffordshire, Lancashire and Durham. Dolomite and chalcopyrite, with rare baryte, is widespread in the Lower and Middle Coal Measures and relatively early. It is separated by a period of faulting and gentle brecciation from later calcite and pyrite, which is common throughout the Coal Measures. The relative ages of the two styles of mineralisation are well constrained. The mineralogical differences suggest deposition from fluids with dissimilar chemistry.

Hematite-quartz mineralisation from the South Don Fault is localised and distinct. It is probably associated with oxidising iron-rich fluids that collected in the reddened rocks at the Carboniferous–Permian unconformity and migrated into the Coal Measures, and is unrelated to the carbonate-dominated fracture assemblages.

Post-mining mineralisation includes halite formed by the evaporation of chloride-rich brines, aragonite and rhodochrosite in flowstone crusts, and gypsum, jarosite and melanterite, which formed in the acidic supergene solutions produced by the oxidation of iron sulphides.

Coal Measures sedimentology is generally well studied, but the unusual peloidal ironstone, which is widespread above coal seams, and appears to have formed in shallow lacustrine environments, is little known. It represents a fine-grained iron-rich sediment containing rounded kaolinite peloids which accumulated in a very low energy environment on a shallow lake bed. During subsequent burial the iron oxyhydroxides were replaced by siderite.

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THE POST-ACADIAN, LOWER PALAEOZOIC HOSTED BASE-METAL VEIN MINERALISATION OF SNOWDONIA AND THE LLŶN PENINSULA, NORTH WALES

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In the geological literature, the key pre-Acadian vein provinces in the Lower Palaeozoic rocks of North Wales, namely the Dolgellau Gold-belt and the copper deposits associated with the Late Ordovician Snowdon Caldera, have received considerable coverage. However, with the notable exception of the Llanrwst Orefield, post-Acadian vein mineralisation, which is developed over a much wider area, has seen less attention. Some of this later mineralisation, including the formerly productive Llanengan Orefield on the western Llŷn Peninsula, has not been described in paragenetic terms. The mineralisation is entirely fracture-hosted, often spatially associated with major faults, is coarsely crystalline and is undeformed, except for instances of brecciation accompanying fault reactivation. Open space filling textures are characteristic and the paragenetic structure shows a degree of consistency across the entire district. The mineralogy is uncomplicated with a low species diversity and is thought to have been deposited by low-temperature hydrothermal fluids during the regional extensional tectonic regime that periodically dominated the crustal evolution of North and Central Wales from the early Carboniferous through to at least the Jurassic.

INTRODUCTION

For the purposes of this paper, the part of mainland North Wales under consideration consists of the counties of Gwynedd and western Conwy, north of a line from Tywyn to Bala (marking the approximate position of the Bala Fault) and west of a line from Bala to Conwy (Fig. 1). The area is therefore distal to the major vein province of the Central Wales Orefield, which lies to the south of Machynlleth and to the east of Aberystwyth, and the somewhat similar but less studied Llangynog Orefield, located to the southeast of Bala. The area under discussion is also distal to the Carboniferous-hosted Pennine-type Halkyn–Minera Orefield of northeast Wales and possibly related deposits, hosted by Silurian sedimentary rocks, in Denbigh and eastern Conwy.

Within the district under consideration, late Neoproterozoic igneous and sedimentary basement is exposed on the north coast of the Llŷn Peninsula and in the Arfon district near the Menai Straits. Two major NE–SW-trending basement fractures, the Menai Straits Fault/Llŷn Shear Zone (MSLZ) and the Bala Fault, frame the area. They represent actual and possible terrane boundaries, respectively, with the MSLZ separating crust of Ganderian affinity to the northwest from the Avalonian succession to the southeast (Schofield *et al*., 2016).

Over the entire area, the Neoproterozoic rocks are overlain by a Cambrian to late Ordovician basinal marine sedimentary sequence, intercalated with both acidic and basic eruptive and intrusive igneous rocks of Early to Late Ordovician age. The magmatism was related to subduction of oceanic lithosphere beneath the district from the northwest, with initial arc-type activity transitioning to bimodal back-arc type through time. Middle to Late Ordovician back-arc volcanism and associated intrusive activity were particularly focused on a broad NE–SW-orientated rift, forming a subsiding trough with the modern-day position of Snowdon marking its approximate centre. Evolution of the trough was controlled by movement along a conjugate set of major NE–SW and N–S basement fractures (Campbell *et al*., 1988). Cessation of volcanism was followed by the widespread deposition of a locally thick black shale unit, the Nod Glas Formation and its lateral equivalents (Pratt *et al*., 1995; Howells *et al*., 1997).

Mineralisation genetically connected to the above events is widespread and diverse in nature. Early Ordovician intermediate intrusive rocks are associated with porphyry-style Cu-As-Au-Mo mineralisation to the northeast of Dolgellau and pervasive hydrothermal alteration is widespread in the Cambrian rocks and associated intrusives of that district. Further to the north, later Ordovician acidic intrusions such as the Tanygrisiau Microgranite contain minor Mo mineralisation (Bevins *et al*., 2010). Polymetallic mineralisation, in the form of abundant quartz-sulphide lodes (As-Au-Ag-Cu-Pb-Zn-Fe-Co-Ni-Sb-Te), occurs in both the Dolgellau and Snowdon districts: the lodes pre-date Acadian compressive deformation, which occurred in the mid-Devonian (Reedman *et al*., 1985; Fitches, 1987; Mason *et al*., 1999).

Acadian earth-movements inverted the Welsh basin and shortened it in a NW–SE direction, resulting in folding and the imposition of cleavage. Post-Acadian tectonics were dominated by regional extension, with major basinal subsidence taking place in what is now Cardigan Bay and the Irish Sea, along reactivated N–S- and NE–SW-trending faults. In the context of this paper, two key phases of extension occurred in what was essentially the foreland to the Variscan Orogeny, one in the early Carboniferous and the other in the early Mesozoic. In northeast Wales, an extensive marine carbonate platform developed during the early Carboniferous and slowly spread westwards as sea-levels rose, although much of the area under discussion is believed to have remained emergent, as part of the Wales–

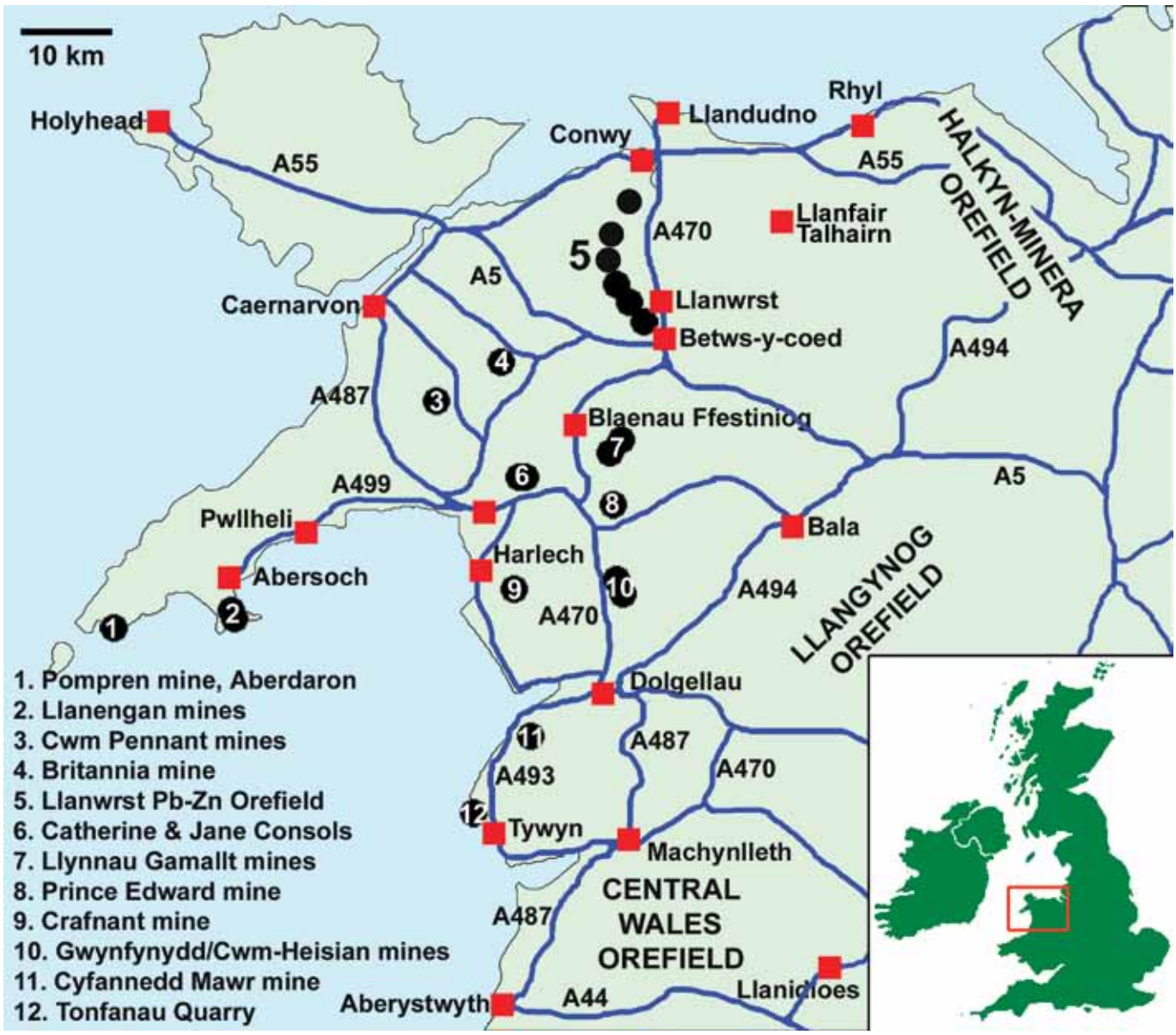

Figure 1. Map of North Wales showing the key localities described in the text.

London–Brabant High. Thick sequences of Carboniferous, Permo-Triassic, Jurassic and Oligocene sedimentary rocks variously constitute the fillings of the offshore basins.

The most detailed work to have been carried out on the post-Acadian mineralisation of North Wales has been in the Llanrwst Orefield (Haggerty, 1995; Haggerty and Bottrell, 1997) and in part of the Snowdon Caldera (Reedman *et al*., 1985; Colman and Laffoley, 1986). In other areas, the paragenesis of the post-cleavage mineralisation has either been mentioned in passing or remains undescribed. This account is based in part upon fieldwork undertaken by the author during the Minescan project, carried out by the National Museum of Wales in the late 1990s (Bevins and Mason, 1998). Further examinations of some key sites, in the late 2000s, were done on behalf of Gwynedd Môn RIGS (Regionally Important Geological Sites), and follow-up work was conducted, where necessary, by the author in more recent years. The account begins with a brief summary of the Llanrwst mineralisation and goes on to catalogue key paragenetic sites in the remainder of the district, from south to north[1].

LLANRWST OREFIELD

The Llanrwst Orefield was a significant producer of lead and zinc, with a total recorded production of several tens of thousands of tonnes of these metals. Like many Welsh Pb-Zn mining districts, the area was highly active during the nineteenth century, but production continued well into the twentieth century with the last mine to close, Parc, finally shutting down in the late 1950s. Veins are hosted by Late Ordovician sedimentary and volcanic rocks. In structural terms, two sets of veins are described by Dewey and Smith (1922), one trending N–S and a second, much narrower set trending E–W. Movement on the N–S veins is reported to have dislocated the E–W veins where they intersect.

[1] Specimens from all of the documented occurrences in this paper are preserved in the collections of the National Museum of Wales in Cardiff. Although representative material may still be found at almost all described sites, it should be emphasised that a lot of the marcasite is highly unstable, so that decay can set in rapidly. Such samples should be stored well away from any other specimens.

In contrast, Haggerty (1995) and Haggerty and Bottrell (1997) describe three sets of veins: north–south veins (M1), cut by ENE–WSW-striking veins (M2), and ESE–WNW-striking veins (M3) which cut both M1 and M2. The amount of lead relative to zinc reportedly increases from M1 through to M3.

All the sets of veins have a similar paragenetic structure. A 'pre-ore' stage of milky quartz and ankerite is followed by an 'ore-stage' with a paragenesis that consists of dolomite, quartz (often with a saccharoidal texture) and calcite with abundant galena (with minor, inclusion-forming chalcopyrite), followed by much iron rich and then iron-poor sphalerite plus coarsely crystalline marcasite and pyrite. There is also a significant 'post-ore' mineralisation, consisting of coarsely crystalline, vuggy calcite associated with abundant well-crystallised marcasite, pyrite and trace amounts of chalcopyrite. At many mines, brecciation events, including the shattering of earlier stages, accompanied the emplacement of each assemblage.

At Llanrwst, K–Ar, Rb–Sr and Pb–Pb dating of altered wall-rock and galena samples respectively (Haggerty *et al*., 1996) indicated that the M1 and M2 veins are of Middle Devonian to Lower Carboniferous age, with K–Ar and Rb–Sr dates of 386 ± 12 Ma to 359 ± 9 Ma and Pb–Pb dates in good agreement. K–Ar and Rb–Sr dates for the M3 veins span the Middle to Late Carboniferous (336 ± 8 Ma to 307 ± 8 Ma). Interestingly, Pb isotope ratios from M3 assemblages, demonstrably later from paragenetic studies, form a highly scattered field, with some Pb–Pb model ages being significantly older than the K–Ar dates. Haggerty *et al*. (1996) interpreted such results to indicate that the lead in the earlier M1 and M2 mineralisation was mostly derived from the underlying Late Ordovician back-arc bimodal volcanic suite, whereas the later M3 lead was derived from more than one source. Although these dates place the lead mineralisation at Llanrwst firmly in the Late Devonian to Late Carboniferous timespan, the veins also carry the 'post-ore' calcite-marcasite assemblage, which must therefore be younger. However, the post-Acadian age of the Llanrwst mineralisation is not in any doubt.

TYWYN–FAIRBOURNE AREA

The Tywyn–Fairbourne area, which was described by Pratt *et al*. (1995), is well known for its slate deposits. Metalliferous mineralisation is, in contrast, sparse. Sedimentary ironstones in Late Ordovician rocks have been tried in places, as has an unusual occurrence of stratiform, banded hematite-magnetite-jasper mineralisation of an exhalative nature, associated with Middle Ordovician pillow-lavas (Mason, 2016). On the coast at Friog, Cambrian sedimentary rocks host spectacularly deformed quartz-carbonate-sulphide veins, which represent the southwestern extremity of the Dolgellau Gold-belt (Mason *et al*., 1999). Two sites feature post-Acadian mineralisation: Tonfanau Quarry and Cyfannedd-Mawr Mine.

Tonfanau Quarry, near the mouth of the Afon Dysinni, to the north of Tywyn (entrance at SH 5704 0321), exploited a composite dolerite sill intruded into the Offwrm Formation of the Middle Ordovician Aran Volcanic Group (Pratt *et al*., 1995). The site lies less than 3 km to the north of the northeast-striking Tal-y-llyn Fault, which is part of the major Bala Fault System.

Mineralisation examined at this large quarry, while it was still being worked in 1997, occurred along steep, NW–SE-striking fractures, up to tens of centimetres in width, and consisted of abundant calcite with quartz, sphalerite, pyrite and traces of galena. Some veins contained calcite alone; others were relatively sulphide-rich, with sphalerite and pyrite occurring in repeated bands in quartz and calcite. Rare traces of galena were paragenetically early with respect to the other sulphides. Quartz occurred as layers of colourless, low pyramidal crystals. Calcite was well crystallised, typically with a nail-head habit, and occurred in white and pale lilac varieties, the latter displaying a strong pinkish-red fluorescence under long-wave UV light. Minor bitumen-like hydrocarbon was noted in association with calcite and pyrite. The mineralisation appears to have been deposited in open fissures produced by simple extension; wall-rock clasts were infrequent.

The isolated remains of Cyfannedd-Mawr Mine are ten kilometres to the northeast of Tonfanau Quarry, in the hills above Fairbourne (SH 6271 1235). The site is not richly mineralised but an old ore-bin contains several tons of low-grade metalliferous mineralisation. The large tips are mostly slate-mining waste, and mark a change of use that is covered, along with other details of the site's history, in Bick (1978). Mineralisation was developed along a NNE-striking fracture in a dolerite intrusion hosted by the Middle Ordovician Offrwm Formation.

Blocks of material in the ore-bin show a quartz-chlorite matrix that has undergone pervasive shattering, with re-cementation by coarse-grained calcite and minor chlorite associated with coarsely crystalline chalcopyrite, galena and sphalerite, forming individual centimetre-sized crystals, often intergrown into coarse-grained crystalline aggregates, most of which are badly damaged from the mining process. Although locally rich sulphide accumulations are present in some hand specimens, the overall grade was clearly sub-economic if the mineralisation is representative of what was encountered during working. The coarsely crystalline, undeformed nature of this post-Acadian mineralisation, and that described from Tonfanau, contrasts strongly with the spectacular vein deformation seen in the pre-Acadian Gold-belt veins at nearby Friog.

DOLGELLAU GOLD-BELT

The Dolgellau Gold-belt stretches around the flanks of the Harlech Dome, a horst-like structure exposing an almost complete Cambrian succession, underlain by late Neoproterozoic volcanic rocks proved in a borehole (Allen and Jackson, 1985). The area of interest from a gold-mining perspective runs from the mouth of the Mawddach Estuary around the horst's southern, eastern and northern flanks, past the communities of Bontddu, Llanelltyd, Ganllwyd, Trawsfynydd and Talsarnau. Pre-Acadian mineralised structures in the Gold-belt contain numerous, mainly ENE–NE-trending quartz-carbonate veins carrying a sulphide assemblage that includes Pb, Zn, Cu, Fe, Co, Ni,

As, Bi, Te, Sb, Ag and native gold (Mason *et al*., 2002 and references therein).

Post-Acadian mineralisation occurs along fractures that cut and sometimes displace the pre-Acadian lodes and was referred to by Gilbey (1968) as the "late crustified assemblage", although the divide in age between the two styles of mineralisation, marked by the Acadian orogeny, was not recognised at that time. Although the post-Acadian mineralisation occurs widely in the Gold-belt, it is best developed in the eastern part of the district. It was encountered at several mines in the Mawddach Valley above Ganllwyd, and especially in the vicinity of the major, NNW-striking Trawsfynydd Fault. In each case, the mineralisation is hosted by Middle to Upper Cambrian clastic and hemipelagic sedimentary rocks and sill-like intrusions (commonly described as 'greenstones') of probable Early Ordovician age. At Cwm-Heisian Isaf Mine (SH 7357 2674), veins filled by this assemblage are exposed in the bed of Afon Mawddach: they consist of banded calcite, sphalerite, galena and marcasite.

The post-Acadian assemblage was mined for lead and zinc, albeit to a limited extent, at West Cwm-Heisian Mine (SH 7369 2770), where workings are developed on an ENE-trending open fissure-filling vein. Mineralisation at West Cwm-Heisian consists of alternating bands of dark brown sphalerite and marcasite, associated with white to pinkish calcite with a rather fibrous texture, forming vein-fillings up to several tens of centimetres in thickness (Fig. 2): up to sixteen individual bands of sphalerite, from less than 1 mm up to 10 mm in width, have been recorded in some samples. The sphalerite bands typically have a reniform outer surface, if the enclosing calcite is broken away. The calcite has a moderate to strong pinkish fluorescence under long-wave UV radiation: the intensity of the fluorescence is variable from band to band (Fig. 3). Some, but not all, sphalerite bands contain abundant, distinctively elongated galena crystals up to about 10 mm in size. The galena-bearing sphalerite bands tend to occur more commonly towards the vein walls. Marcasite overgrows some, but not all, sphalerite bands, forming layers of small (2–6 mm) wedge-shaped crystals and also larger, floret-like coarse crystal aggregates up to several centimetres across. Wall-rock clasts are extremely uncommon away from the vein walls. The texture of the mineralisation is suggestive of pulsed hydrothermal fluid flow into an open fissure, allowing unimpeded mineral growth, but with slight changes in fluid chemistry, with respect to metal content, through time. The site is not easy to access and unfortunately a flash-flood in 2001 carried away much of the tip material; when river levels are low, scattered blocks of the veinstone may be found for a considerable distance downstream.

At Gwynfynydd Mine (SH 7373 2807), post-Acadian mineralisation, described in structural terms by Dominy *et al*. (1996), occurs along intra-vein faults, hosted by the ENE-striking, northerly dipping, pre-Acadian gold lodes and recording later reactivation of these pre-Acadian structures. The above authors noted, with respect to below-adit workings on the Chidlaw Lode, that the intra-vein fault was a persistent feature, with slickenslides on the fault-plane surface showing a plunge of 55–60° to the northwest. The mine closed in the late 1990s and the workings subsequently flooded up to adit level; most of the dumps have since been removed and processed for the gold they contained. Fortunately, excellent specimens of the post-Acadian mineralisation were obtained while the mine was operational.

Samples from this occurrence reveal broken fragments of pre-Acadian milky lode-quartz, cemented by vuggy, coarsely crystalline calcite, with either a nail-head or rhombic habit, plus dolomite and marcasite. In the most distinctive specimens, calcite and dolomite rhombs are overgrown by finely botryoidal red-brown iron oxide with a fine-grained, grey, specularite-like surface. This surface is adorned by tufts of acicular brown goethite up to 5 mm in length, accompanied by distinctive, lustrous cogwheel crystals of marcasite, which the acicular goethite clearly overgrows (Fig. 4). This assemblage, which appears to be primary, since neither marcasite nor carbonates show the slightest sign of weathering, seems to record a transition from sulphur-rich to oxygen-dominated fluids during the final evolution of the hydrothermal system that emplaced the post-Acadian minerals.

Upstream from Gwynfynydd lie further workings at East Cwm-Heisian Mine (SH 7409 2823), a site often visited by students, who are taken there to study the well-exposed, powerful pre-Acadian quartz-sulphide lode that crosses the Afon Mawddach just below the mine. Banded calcite-marcasite mineralisation is widespread, forming veins that both cross-cut and run parallel to the pre-Acadian lode. An interesting feature here is that strong weathering of the calcite at outcrop has resulted in the precipitation of earthy, black manganese oxides on its surface, indicating that the calcite, which has a pinkish-red fluorescence and may be lilac in colour, is manganiferous.

Post-Acadian mineralisation is again present at Prince Edward Mine, near Trawsfynydd (SH 7423 3852). Here, two distinctly different post-Acadian assemblages occur. One consists of galena, sphalerite and minor chalcopyrite associated with vuggy, low pyramidal quartz and is associated with a north striking fault that runs through the mine, displacing the pre-Acadian quartz-sulphide lodes. The second assemblage occurs more widely and is hosted by numerous N–S-striking fractures that cut, but hardly displace, the pre-Acadian lodes: it consists of rather compact, pinkish-red fluorescing, white to lilac calcite, plus dolomite, low pyramidal quartz, pyrite, marcasite, minor bituminous hydrocarbon and late, massive hematite and goethite.

The Dolgellau Gold-belt continues around the north and northwest flanks of the Harlech Dome, until it is truncated by the Mochras Fault, a major N–S fracture delineating the eastern margin of the Mesozoic Cardigan Bay Basin. Crafnant Mine (SH 6220 2890), which is 5 km ESE of Harlech, is in this western sector. Here, massive milky quartz, of Gold-belt affinity, was fractured and brecciated during the emplacement of a crystalline marcasite-dominated assemblage, accompanied by low pyramidal

Figure 2. Large polished block of banded post-Acadian calcite-marcasite-sphalerite-galena mineralisation from West Cwm-Heisian Mine. Collected prior to the tips being washed downstream in 2001. Photo John Mason.

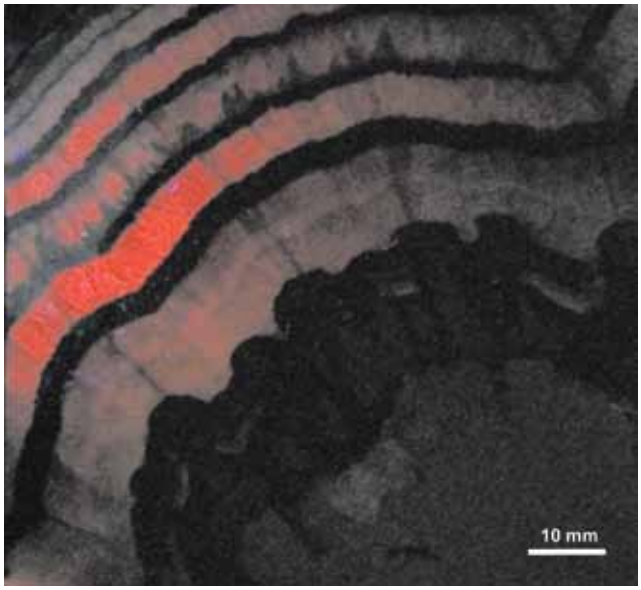

Figure 3. Variably fluorescent calcite from West Cwm-Heisian Mine. Photo John Mason.

Figure 4. Post-Acadian goethite and marcasite on iron oxides overgrowing carbonates cementing shattered quartz from Gwynfynydd Mine. Collected from a boulder in the river in 1998. Photo John Mason.

quartz and late calcite, the minerals forming coatings to fracture walls and clast surfaces. Minor chalcopyrite and sphalerite are also present.

FFESTINIOG–SNOWDON DISTRICT

Numerous mines, many little more than short-lived trials but some significantly productive, lie in a broad belt extending from east of the Crimea Pass, above Blaenau Ffestiniog, westwards to Cwm Pennant, in the country to the north of Criccieth, and northwards as far as the Ogwen Valley. The mines and trials mostly worked pre-Acadian lodes for copper, with subordinate production of Pb, Zn and As. Details of the history of these mines are provided in Bick

(1985). The district is dominated by Cambrian sedimentary and Ordovician sedimentary and volcanic rocks, including the regionally important Snowdon Volcanic Group, plus a number of microgranite and dolerite intrusions. Post-Acadian mineral assemblages occur widely and some of the better examples are described below.

At Llynnau Gamallt Mine, to the east of Ffestiniog (SH 7429 4441), a series of SSW- and SW-striking fault-hosted veins cut shattered and brecciated quartz-latite, an intrusive rock of Middle Ordovician age. The main SSW-striking, WNW-dipping fault has a prominent, steep scarp-like outcrop and is most intensively mineralised in the southern parts of the site, where mineralisation is exposed in an opencast. Here, the fault has quartz-latite in its foot-wall and dark grey Middle Ordovician mudstones in its hanging-wall. Slickensides are indicative of multiphase, strike-slip to normal movement. The fault may be traced for just 2 km to the north but it continues for 8.5 km to the south, veering N–S and then NNW–SSE to the southeast of Trawsfynydd, where it merges with the Craiglaseithin Fault, one of a number of major N–S fractures that transect the eastern side of the Harlech Horst.

The southwest-striking veins, conversely, are concentrated in the northern part of the site, where they are richly mineralised and exposed in a series of opencuts into the fault-scarp. Both sets of veins carry a quartz-galena dominated mineral assemblage, which is present in great abundance both *in situ* and on the extensive spoil heaps. Patches of galena to 30 mm across occur scattered through a quartz-cemented breccia. Minor chalcopyrite, traces of sphalerite, and a little late-stage marcasite are also present. The fine-grained, rather saccharoidal quartz associated with the galena is overgrown, in open cavities, by a coarser generation of quartz with clear crystals to 15 mm long (Fig. 5). A specimen in the National Museum of Wales collection, from Llynnau Gamallt, displays amethystine quartz as purple crystals lining a cavity in the veinstone. The specimen is from the collection of G. J. Williams, Assistant Inspector of Mines for North Wales and dates from the late nineteenth century. As with many of William's specimens, it was probably obtained while the mine was still at work. However, it was obviously a rare find because despite much searching at the site, no further specimens have been found.

Figure 5. Quartz crystals collected in 2008 from Llynnau Gamallt Mine. Photo John Mason.

At the nearby Afon Gamallt Mine (SH 7338 4353), rather sparse mineralisation consists of early milky quartz; cut by crystalline, low pyramidal quartz with galena, chalcopyrite and sphalerite; cut in turn by late quartz-pyrite veins.

Trials situated just to the west of the well-known Alpine Fissure-type vein locality, Manod Quarry, are of interest because they reveal a mineral assemblage apparently identical to one of the later (A2) Central Wales assemblages. The trials, around SH 7070 4460, explore vein mineralisation that strikes almost north–south, and reveal coarsely crystalline quartz forming low pyramidal crystals to 5 cm in height. Crystal terminations are generally damaged but the main interest is in the strong growth-zonation of the crystals and the occurrence, in the outer zones, of abundant millimetre to submillimetre-sized dendritic sulphide inclusions, imparting a dark, speckled appearance to specimens (Fig. 6). This type of sulphide occurrence in association with unusually large zoned quartz crystals, is identical to the A2-d assemblage of Central Wales (Mason, 1997). The nature of the sulphide dendrites is in all cases unresolved and requires further investigation.

The remains of Catherine and Jane Consols (SH 6324 4110), a mine situated in forestry to the northwest of Maentwrog, provide samples of post-Acadian mineralisation. The mine was developed on a WNW-striking lode. Within parts of the lode, massive milky quartz of a pre-Acadian character, with finely disseminated pyrite, chalcopyrite and arsenopyrite, has been brecciated and cemented by a post-Acadian assemblage, dominated by calcite. The calcite is banded and is pinkish in places, weathering to black, which is indicative of the presence of manganese. The calcite contains galena, minor sphalerite and marcasite; the latter is quite common and occurs as coarse, twinned 'cogwheel' crystals. Northwards from this mine, there is extensive forestry surrounding the lower slopes of the Moelwyns:

Figure 6. A 5cm quartz crystal from the Manod locality, with dendritic sulphides forming dark areas in its outermost growth-zone. Photo John Mason.

service-tracks cut in the mid 1990s revealed numerous coarsely crystalline quartz-cogwheel marcasite veins up to a few centimetres in width, emphasising the regional abundance of such mineralisation. Two decades of exposure to the weather have largely degraded these exposures.

To the northwest of Catherine and Jane Consols are the extensive remains of the Bwlch-y-Plwm Mine (SH 6287 4146). This appears to be an example of a mine that was actually developed to work the post-Acadian mineralisation. Although the official output amounts to just a few hundred tons of lead ore (Dewey and Smith, 1922), the site is of some antiquity and was probably operational prior to the mid-nineteenth century, when ore production data began to be collated. The paragenesis is rather similar to that at Catherine and Jane Consols: milky quartz with pyrite, sphalerite, chalcopyrite and galena is cut by veins of low pyramidal quartz with crystalline galena and later sphalerite; followed by calcite and marcasite.

In Cwm Pennant, post-Acadian mineralisation is found at the Blaen-y-Pennant Mine (SH 5410 5061). Pre-Acadian mineralisation, which consists of abundant pyrrhotite, with lesser chalcopyrite and minor arsenopyrite, is cut by post-Acadian veins dominated by low pyramidal crystalline quartz with pyrrhotite, galena and sphalerite, followed by calcite with pyrite and marcasite. In this case the unusual occurrence of pyrrhotite in the later veins may represent remobilisation from the abundant pre-existing material.

Britannia Mine (SH 6145 5470), on Snowdon, worked E–W- to SE–NW-striking chalcopyrite-rich pre-Acadian lodes associated with the Late Ordovician Snowdon Caldera. Post-Acadian calcite-sulphide mineralisation is well developed here. Colman and Laffoley (1986) presented the results of a detailed underground survey of the workings, in which they found calcite-sulphide mineralisation to be present in all accessible levels over a vertical distance of approximately 100 m. The calcite-sulphide veins are generally located along the foot-wall of the pre-Acadian lode, but crosscutting of the pre-Acadian mineralisation was also observed. Banded textures are common, though the banding tends to be restricted to around five centimetres of vein adjacent to the vein wall, passing outwards into a matrix-supported breccia of at least 30 cm thickness, in which marcasite crystals rim the clasts and earthy red hematite accompanies the abundant calcite.

Samples of the banded and breccia mineralisation are common on the tips. In the banded deposits, layered calcite with a rather fibrous appearance contains repeated thin bands of marcasite and sphalerite, a few millimetres in thickness. Larger, floret-like crystals of marcasite up to 5 cm across are also present (Fig. 7). Galena occurs intergrown with the other sulphides but is a minor component of the assemblage. Sphalerite contains very occasional chalcopyrite inclusions. This mineralisation is highly reminiscent of that occurring in the vicinity of the Cwm-Heisian and Gwynfynydd mines. Colman and Laffoly (1986) interpreted the calcite-sulphide mineralisation at Britannia Mine to represent a "later period of lower temperature mineralisation under conditions of lower pressure and tensional stress".

Figure 7. Marcasite floret in calcite; typical material from Britannia Mine. Photo John Mason.

LLANENGAN OREFIELD

The Llanengan Orefield is situated to the southwest of the popular seaside resort of Abersoch on the Llŷn Peninsula. The mines exploited base-metal mineralisation developed along a WNW–ESE-trending fault system, cutting sedimentary rocks of early Ordovician and, in one case at depth, Cambrian age. At the Llanengan mines, no older, pre-Acadian mineralisation has been detected. However, to the west of the Llanengan Orefield, hitherto undescribed, northeast-striking, chalcopyrite-bearing quartz-carbonate-chlorite veins, that bear a visual resemblance to the pre-Acadian lodes of Snowdonia, crop out at Porth Ysgo (SH 2086 2641). They are hosted by thick gabbroic sills, intruded into Ordovician sedimentary rocks (author's unpublished data).

Eight mines in total, locally reaching depths of up to 165 m below surface (Young *et al*., 2002) were developed along the Llanengan Orefield fault system, these being (from west to east) Porth-Neigwl (sometimes referred to as Port Nigel), Pant-gwyn, Tan-y-bwlch, Bwlch-y-tocyn, West Assheton, Assheton and Penrhyn-Du. Dewey and Smith (1922) noted that:

> "According to Mr. T. C. Nicholas, writing in 1915, the lode was then nowhere visible, and the mines had all been abandoned for over twenty years."

However, prior to that time, production was considerable, with the most productive mine, Tan-y-bwlch, yielding 8,722 tons of galena concentrates in the period between 1873 and 1886, giving 5,213 tons of lead and 29,939 ounces of silver; 4,652 tons of chalcopyrite concentrates and 447 tons of sphalerite concentrates were sold during the same period. The history of the mines is described in detail by Bennett and Vernon (2002).

The rather poor grade of the galena concentrates in the above figures, at just under 60% lead, is suggestive of ore-dressing difficulties and the often finely divided nature of the galena is confirmed by examination of veinstone remaining at the mines. However, at many sites, little viable material remained at the time of the Minescan survey in 1997 (Bevins and Mason, 1998) and a recent visit to the

district has revealed further deterioration. The site thought to be Assheton Mine (SH 3210 2618) had largely been bulldozed when visited in 1997 but it provided samples: a recent visit revealed a large area of mostly overgrown jig-tailings although limited amounts of veinstone were still present in gullies eroded by floodwater. More extensive tips remain in the Penrhyn-Du section, but it was noted in 1997 that supergene alteration there has obscured original primary mineral relationships in many samples.

Penrhyn-Du (SH 3240 2647) and the beach towards Abersoch have previously featured in the mineralogical literature because of the uncommon supergene lead and copper halides that occur, both in outcrop and in beach-cobbles derived from the veins (Hubbard, 1991; Dossett and Green, 1998; Hubbard and Green, 2005). This interesting mineral assemblage has been formed by the chemical reaction of sea-water with the primary sulphides. In contrast, however, few details have, to date, been published on the primary paragenesis of the Llanengan veins.

It is important to note that samples of unoxidised primary mineralisation are not common and that some sites have been all but obliterated, so that representative material is hard to find in many cases. This situation means that there is a risk that the full paragenesis may not be wholly represented by the material studied. However, what has been examined reveals a consistent paragenetic sequence. The mineralisation occurs both as breccia cements and, especially, as open-space fillings. Samples reveal at least two generations of chalcopyrite, galena and sphalerite, occurring in a quartz matrix. An early generation of chalcopyrite-bearing quartz is cross-cut by later crustiform-banded mineralisation with the depositional sequence sphalerite-chalcopyrite-galena. Other samples reveal later sphalerite as brown, yellow-orange or reddish-orange crystals to 4 mm in quartz-lined vugs, with galena confined to the quartz matrix. Galena also occurs commonly in a distinctive association in which disseminations of very small (predominantly <1 mm) crystals are embedded in saccharoidal quartz, something which would go some way towards explaining the poor grade of the lead concentrates, as such an ore would have been difficult to prepare into a clean concentrate, using nineteenth-century techniques.

Baryte occurs (or occurred) at most of the mines and is always a late-stage mineral, forming massive, white to pinkish-white coarse bladed crystal aggregates overgrowing the sulphide-bearing quartz, which has very locally undergone slight brecciation (Fig. 8). The baryte is in some cases pseudomorphously replaced by further quartz. There is no record of baryte production from Llanengan.

Although the main interest in terms of supergene mineralisation in the Llanengan district concerns the halides found along the coast at Penrhyn-Du, a variety of secondary minerals were recorded at Porth Neigwl Mine (SH 2942 2676) in 1997 (Bevins and Mason, 1998); these included microcrystalline linarite, brochantite, a langite-group mineral, cuprite and native copper; all were thought to be of post-mining origin. The site was considered to have further potential at the time of the original visit, though less dump material is evident there today.

Figure 8. Saccharoidal quartz with finely divided galena, overgrown by later baryte collected in 2017 from the Llanengan mines. Such material is now relatively scarce. Photo John Mason.

ABERDARON DISTRICT

Pompren Barytes Mine is 13 km to the west of the Llanegan Orefield (SH 1674 2634), at the western end of Aberdaron beach. Pompren exploited very similar (albeit apparently sulphide-free) mineralisation to that found at Llanengan. The mine was worked as late as 1914; historical details are provided by Shaw (2014).

At Pompren, baryte is common and occurs along a NW-trending fracture, the Nant Saint Fault. The mineralisation is hosted by Ordovician sedimentary rocks of the Nant Ffrancon Subgroup and the late Neoproterozoic Gwna Group. According to Wilson *et al*. (1922), the lode was up to 3 m wide, and it contained:

> "intersecting stringers of quartz and barytes, running generally north and south, the maximum width of any one stringer being rarely over a foot. The barytes occurs in pockets, which are more or less free from quartz and of good quality, but they are infrequent and small".

The waste rock appears to have been dumped, to an extent at least, onto the beach, since water worn blocks of intergrown quartz and baryte occur in some quantity along the beach-head. Samples reveal a very similar paragenesis to the material found in the Llanengan mines, to the extent that the Pompren mineralisation may be inferred to belong to the same mineralising event. Quartz, again with a rather saccharoidal appearance in many samples, is overgrown by coarse-grained, pinkish-white to white, massive to bladed baryte, some of which has then been replaced pseudomorphously by further quartz. Both quartz and baryte enclose a few sedimentary rock-clasts, with a rather bleached appearance, a feature suggestive of strong weathering. The observation that the material is strongly weathered is corroborated by the presence of manganese oxides, which commonly form mostly microbotryoidal coatings on wall-rock, baryte and quartz alike: some samples reveal thicker crusts including larger aggregated botryoids forming masses up to 10 mm across (Fig. 9). Weathering might explain the absence of sulphides: in the blocks of veinstone so far examined, irregular small cavities in quartz

Figure 9. Manganese oxides overgrow massive bladed baryte, part-pseudomorphed by quartz in a characteristic association from Pompren Mine. Photo John Mason.

may have originally been occupied by sulphide minerals.

Gibbons *et al*. (1993) record another instance of fault-hosted barium mineralisation of a similar nature, nearby on the coast north of Ynys Piod, near Porth Meudwy. Furthermore, the widespread occurrence of baryte, identified in panned concentrates collected during drainage sampling in this part of North Wales (Leake and Marshall, 1994), suggests that further concealed examples of this style of mineralisation may occur widely in the district. The exposure inland is typically poor.

DISCUSSION

Vein Classification

Post-Acadian vein mineralisation of the Lower Palaeozoic rocks of Snowdonia and the Llŷn Peninsula consistently differs from the pre-Acadian lodes in terms of its open, vuggy nature, the simplicity of its parageneses and the absence of strain-indicators. The mineralisation can be placed into three categories, based on mineralogy. The first, which is described herein as post-Acadian assemblage A, consists of galena, sphalerite and chalcopyrite associated with vuggy, low pyramidal quartz. The second, post-Acadian assemblage B, variably features manganiferous calcite (typically fluorescing pinkish-red), dolomite, quartz, galena, sphalerite, chalcopyrite, pyrite, marcasite and local late hematite and goethite. The third, post-Acadian assemblage C, consists of baryte and quartz and is limited in its occurrence, in the area under discussion, to the western Llŷn Peninsula.

Post-Acadian assemblage A is the ore-bearing assemblage at the Llanengan mines. The assemblage (or something very close to it) also occurs at Blaen-y-Pennant, Bwlch-y-Plwm, Afon Gamallt, Llynnau Gamallt and Prince Edward mines. There is also a strong similarity in terms of mineralogy (and paragenesis) between post-Acadian assemblage A and the important A2-a quartz-sulphide assemblage of the Central Wales Orefield, a major source of Pb and Zn in that district (Mason, 1997). The similarity between the Manod quartz occurrence, described above, and the Central Wales A2-d assemblage, has already been noted.

At several sites, assemblage A is overgrown by assemblage B, establishing their relative ages. Assemblage B is however highly variable. It always includes quartz, calcite, pyrite and marcasite, but the other constituent minerals are not ubiquitous. Assemblage B so strongly resembles the 'post-ore' stage of the Llanrwst Orefield (Haggerty, 1995) that it is difficult to resist the interpretation that the two are cogenetic.

One thing that many occurrences of assemblages A and B, and indeed the Llanrwst Orefield mineralisation, have in common is their proximity to, or development along, important mainly N–S-striking faults. This is particularly evident in the Dolgellau Gold-belt, where a concentration of well-developed ENE-trending veins carrying assemblage B is situated close to the NNW-striking Trawsfynydd Fault. It may well be the case that the enhanced extensional stresses set up in the elongated slivers of crust between such faults, when they were active, caused the opening up of the fracture-fissures in which the post-Acadian mineralisation was deposited.

Assemblage B has a possible counterpart in Central Wales, where the A2-c assemblage of Mason (1997) is calcite-dominated, crustiform-banded and carries sphalerite, galena, minor chalcopyrite and late pyrite and/or marcasite. Many localities in North and Central Wales feature marcasite-dominated mineralisation as the final stage of epigenetic mineralising activity. However, the later Central Wales mineralisation features more stages and more complexity than the post-Acadian veins of North Wales. As an example, the A2-b stage of Central Wales, which is widespread in the western part of that orefield, consists of coarse-grained chalcopyrite, ullmannite (NiSbS), and galena, occurring as crustiform bands in coarse-grained quartz. This assemblage has not been recognised anywhere north of the Bala Fault.

The relative ages of assemblages B and C are unknown, since they are nowhere in contact with one another and the reason for the apparent absence of baryte in post-Acadian vein mineralisation, across the rest of Snowdonia, is unknown. Late white baryte is present at some mines in the Llanfair Talhairn district (Haggerty and Bottrell, 1997), around 20 km to the northeast of the Llanrwst Orefield in northeast Conwy. Furthermore, Silurian-hosted vein mineralisation at Pennant Mine near St Asaph in Denbighshire (SJ 0877 7535), a further 15 km to the ENE of Llanfair, includes abundant baryte and also witherite, occurring in much greater abundance than at any of the mines that worked the veins of the nearby Pennine-type Halkyn–Minera Orefield (Bevins *et al*., 2010). Further baryte occurrences in Lower Palaeozoic rocks, that were either historically tried or worked, are near Ruthin and Llangollen (Wilson *et al*., 1922).

This baryte distribution pattern, with an emphasis on the eastern side of Wales (but with some significant occurrences in the far west) is not an effect local to North Wales. It is part of a wider pattern, as the following list of known localities with significant barium mineralisation (Fig. 10) demonstrates.

South of the Bala Fault, barium mineralisation is encountered in the Llangynog Orefield, at Galltymain near Meifod, in the Newtown and Welshpool districts, and between Newtown and Knighton, at the Felindre Mine (Wilson *et al*., 1922; Bick, 1978; Hall, 1993). To the east of Newtown and Welshpool lies the historically important baryte-producing district of southwest Shropshire. Further south along the Welsh border, Dolyhir Quarry near Kington features intermittently exposed barium mineralisation associated with a Cu-Pb-As-dominated base-metal sulphide assemblage (Cotterell *et al*., 2011). In the Central Wales Orefield, baryte-witherite mineralisation is almost entirely limited (with two very minor exceptions) to the far east of the district, where it occurs in abundance at a cluster of mines in the Llanidloes district (Bick, 1977; Mason, 1997).

Well to the southwest of the Central Wales Orefield, however, barium mineralisation reappears in earnest, in the district just to the east of Carmarthen. Several trials and mines were once at work in this area, where baryte is a common late-stage mineral, overgrowing chalcopyrite, sphalerite and galena, in quartz (Bevins and Mason, 1997; Hall, 1993), in a remarkably similar overall paragenesis to the Llanengan veins. Unfortunately, the ravages of time and development have served to obscure many of these workings, such as Vale of Towy (SN 4377 1999).

Age of Mineralisation

Radiometric dating of post-Acadian mineralisation in the Lower Palaeozoic rocks of Snowdonia and the Llŷn is, with the notable exception of the Llanrwst Orefield, non-existent. At Llanrwst, dating of the ore-stages indicates mineralisation spanning the Carboniferous; a 'post-ore' stage is clearly later but remains undated.

Elsewhere in Wales, there is plenty of evidence for phases of post-Acadian vein mineralisation persisting into at least early Jurassic times. Galena from the Halkyn–Minera Orefield has an average Triassic model age of 240 Ma (Fletcher *et al*., 1993). Analyses of galena from similar Pb-Zn mineralisation in the Carboniferous limestone of South Wales have produced model ages that average around 200 Ma, a value consistent with field evidence, which indicates that at least some of that mineralisation has an early Jurassic age (Fletcher, 1988). How that tectonic and hydrothermal activity is represented in the older rocks of Wales is a problem that remains to be fully unravelled.

Probable post-Carboniferous lead mineralisation is certainly known from Central Wales, where Pb isotope analyses of galena collected from each lead-bearing stage (Swainbank *et al*., 1992; Fletcher *et al*., 1993; Mason, 1997) have indicated that, for the later (A2) mineralisation, episodic mineralising activity was taking place from the early Carboniferous (the major A2-a mineralisation, 360–330 Ma) through to the Permo-Triassic (A2-b and A2-c). Further galena analyses, undertaken for the OXALID archaeological database (Stos-Gale and Gale, 2009), independently replicated these results, so it is unlikely that the post-Carboniferous model ages represent analytical error.

These Pb isotope data indicate that either there was an episode of mineralisation in Central Wales during Permo-Triassic times, or that these later phases of mineralisation also occurred in the Carboniferous but were deposited from well-travelled fluids that somehow sourced lead of a more radiogenic nature from distal crust, a scenario considered by the author to be less likely.

To summarise, available isotopic data therefore show that North Wales was affected by a major Late Devonian to Late Carboniferous regime of regional extension, fluid flow, metal transport and ore deposition. Data from other parts of Wales show that further, post-Variscan extensional tectonics accompanied by regional hydrothermal activity affected some districts into Mesozoic times, perhaps linked to subsidence during the development of sedimentary basins in areas adjacent to the Welsh Massif. How widely this later activity is represented in the post-Acadian mineralisation of North Wales is a question whose answer is yet to be determined.

Genesis

In terms of a genetic model for the Snowdonia and Llŷn mineralisation, the only previous detailed work on this area involved the Llanrwst Orefield. It is therefore important to consider the results of that research (Haggerty and Bottrell, 1997) in a regional context. Fluid inclusion data indicate that the fluids responsible for the main, early Carboniferous phase of Pb-Zn mineralisation in the Llanrwst Orefield were highly saline calcic brines, with up to 26 wt% NaCl equivalent, and temperatures of 140 to 190°C. The pyrite- and pyrrhotite-bearing Lower Palaeozoic host rocks were interpreted to be the major source of sulphur during the main phase of mineralisation, although during the later, marcasite-dominated stages, the fluids became markedly enriched in ^{34}S. This change was interpreted to indicate that ^{34}S-enriched sulphur was added into the system via either seawater or evaporitically-concentrated groundwater, finding its way in during the waning stages of mineralisation, when the hydrothermal system began to collapse.

Haggerty and Botterell (1997) noted that the timing of mineralisation tended to dictate against the involvement of a metamorphically derived fluid, since peak regional metamorphism had already occurred. They commented that the rocks would have long since become dehydrated through metamorphic fluid release, with any residual fluids being consumed by retrograde reactions. Instead, the mineralising fluids at Llanrwst were likely to be highly evolved brines, a hypothesis supported by fluid inclusion and isotopic data, and their original source would either be surface or formational water in post-Acadian sediments. They noted that the latest Devonian and early Carboniferous were times of major, regional extensional tectonics, during which reactivated old faults and new fractures would both have provided a linked, high-permeability network, so that such fluids could penetrate deeply into the underlying Lower Palaeozoic rocks. The siting of the Llanrwst Orefield along splays from the major Conwy Valley Fault was, they suggested, no coincidence in that context.

James (2011) makes a similar point with respect to the later (A2) mineralisation of Central Wales: he considers that by the early Carboniferous, that orefield's host rocks were likely to have contained an essentially open networked fracture system, over depths in excess of 5–7 km, that would have created a temperature contrast of at least 150°C from convecting cell base to top (i.e., the areas from which metals were being scavenged and where they were being deposited, respectively), and that temperatures extant at depth would render metallic ions far more soluble in the scavenging fluids.

In the rest of Snowdonia and the Llŷn, the common spatial association between post-Acadian vein mineralisation and regional-scale faults has already been noted. The mineralisation has likewise affected areas whose metamorphic, structural, and metallogenic histories imply that the Lower Palaeozoic rocks had already been largely dehydrated by the time the veins were emplaced. Epizonal rocks and widespread pre-Acadian lodes characterise much of Snowdonia, although interestingly these older lodes appear to be absent from the Llanrwst district. On the Llŷn Peninsula, however, not only is metamorphism in the Lower Palaeozoic rocks of relatively low-grade, at late diagenetic to low anchizone facies, but in addition, pre-Acadian lodes are not widely documented. These differences imply that, whereas some areas may have still had limited potential as fluid sources, in others that possibility had been eliminated by the time of the post-Acadian mineralisation. Therefore, it is highly likely that the involvement of externally derived hydrothermal fluids was required in most, if not all cases.

Haggerty and Bottrell (1997) point out that the extensive and important base-metal mineralisation of the Irish Midlands, which has a Lower Carboniferous age, was formed from fluids that had descended deep-seated fractures and had interacted extensively with the underlying basement rocks, before convective ascent took them back up to the sites of major mineralisation. They saw the Llanrwst district as a possible analogy. The Lower Palaeozoic rocks underlying the Pb-Zn deposits of the Irish Midlands certainly contain locally-abundant veining, thought to represent fossilised feeders to the orebodies. Everett et al. (1999) describe such veins as falling into three groups: type 1 veins consist of hematitic calcite with quartz ± pyrite; type 2 veins consist of quartz and calcite ± sphalerite, galena, chalcopyrite, pyrite and local baryte; type 3 veins are dominated by ankerite, ferroan dolomite and quartz ± sphalerite and pyrite. There are clearly some similarities in terms of mineralogy, between these Irish feeder-veins and the post-Acadian veins of North Wales.

Although the Irish Midlands are highly distal to the mineralised district discussed here (Navan is some 200 km away from the heart of Snowdonia), it is important to bear in mind the scale of the Irish Midlands mineralised province. Navan is 140 km from Silvermines, another deposit of the same class. Leach *et al*. (2010) comment on the vast sizes of the some of the hydrothermal systems responsible for Mississippi Valley Type (MVT) Pb-Zn mineralisation provinces, of which the Irish Pb-Zn deposits fall into a subclass. They suggest that the overall hydrothermal system that was responsible for the Irish deposits was operative over about 8,000 square kilometres. Given that much of the post-Acadian Welsh mineralisation that has so far been dated falls into a similar time-frame as the ore-deposits of the Irish Midlands, one has to consider the possibility of an even more extensive geological tract, throughout which regional-scale tectonic conditions favoured widespread early Carboniferous hydrothermal activity.

The fluids responsible for depositing the Irish Pb-Zn mineralisation were originally evaporatively concentrated Lower Carboniferous seawater. A source for that is readily available for the Llanrwst orefield, given the palaeogeography at the time: it is thought the seas of the North Wales Carbonate Platform covered the area, at least episodically (Davies *et al*., 2004; Juerges *et al*., 2015) and the arid, tropical climate would certainly have encouraged evaporative processes. However, if one takes the accepted view of the palaeogeography at the time, sourcing such fluids for the rest of the district becomes more problematic, as central and northwest Wales are thought to have been fully emergent. Although the vast extent of MVT hydrothermal systems is widely acknowledged, just how far can fluids travel, away from their source, in such a system, and what driving force could facilitate such travel? These are key questions that need to be addressed.

If the palaeogeography is correct, what do we know about the topography of Snowdonia at the time? The early Carboniferous sedimentary rocks of northeast Wales include basement beds that are probably Chadian in age: these consist of red beds including breccias and conglomerates, in which most of the clasts consist of proximal Silurian rocks (Davies *et al*., 2004). The large volumes of terrestrial clastic sediment, that one might expect if the Wales–London–Brabant High was a major, sediment-shedding upland area, are thereafter absent from the sequences. Such an absence could be due to the Lower Carboniferous sea having transgressed further west than thought, but with any sediments deposited upon its floor having since been removed by erosion. Alternatively, the topography could have been subdued: in combination with the hot arid climate, major clastic sedimentary systems would be unlikely to develop. Seasonal rains might, however, be accommodated in temporary playas along topographic lows: such environments would certainly be capable of generating hypersaline brines, though whether they would satisfy the needs of a metal-transporting hydrothermal system is debatable, since due to the relatively low solubility of most metals, such systems require vast volumes of fluid in order to form ore deposits. A similar problem has been raised by James (2011) with respect to the later (A2) ore deposits in Central Wales.

The evidence for later mineralising events in parts of Wales, up into early Jurassic times, raises interesting questions with respect to the role of actively subsiding offshore sedimentary basins from the Permian onwards. Such basins, typically areas of steep geothermal gradient, are a potential source for hydrothermal brines, but drive mechanisms are required for fluid flow up into the older uplifted massif. In any case, a more pertinent line of

enquiry would be to first undertake a wider programme of radiometric dating of the post-Acadian veins of North Wales, in order to establish just how old these deposits are, prior to attempting to construct mechanisms for their emplacement.

CONCLUSIONS

This documentation of the post-Acadian vein mineralisation in the older Lower Palaeozoic rocks of North Wales reveals paragenetic consistencies that suggest regional phases of hydrothermal activity coupled with episodic extensional stress-regimes operating across the whole area. An important early Carboniferous phase of mineralising activity coincides temporally with the regional MVT mineralisation of the Irish Midlands, and the post-Acadian veins of North Wales could feasibly be related, although hydrothermal fluid-sources pose problems with respect to the accepted palaeogeography of the time. Episodic extensional tectonics, accompanied by hydrothermal fluid activity, again affected parts of Wales during the Permo-Triassic and early Jurassic, producing the important Pennine-type mineralisation found in northeast and southern Wales. Lead isotope data from some of the later Central Wales mineralisation suggests hydrothermal circulation was active in that district during the Permo-Triassic, too. However, with respect to the undated later post-Acadian veins of North Wales, further work is required in order to determine whether they are entirely related to the early Carboniferous phase of activity or if they, too, include veins formed under this later tectonic regime. A more detailed, paragenetically orientated fluid inclusion and stable isotope study of both the later (A2) Central Wales mineralisation and the post-Acadian veins of Snowdonia and the Llŷn is required, before such questions can be answered.

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ANDRADITE-BEARING SKARN-LIKE MINERALISATION AND A SUSPECTED PALAEOGENE DYKE FROM COED Y BRENIN, NORTH WALES

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Skarn-like mineralisation, dominated by andradite garnet, occurs in a riverbed section on the Afon Mawddach in Coed y Brenin, near Dolgellau in central Gwynedd. Andradite is associated with chlorite, calcite, ferroactinolite, epidote, hematite, magnetite, pyrite and chalcopyrite. The occurrence is hosted by a highly altered mafic-intermediate sill, one of a widespread suite of minor intrusions within the Middle to Late Cambrian sedimentary rocks of the district. Sills of this composition are regarded as relatively early in the sequence of magma-fractionation and intrusion that accompanied the Rhobell Volcanism during early Ordovician (Tremadoc) times. The section also features a series of later, leucocratic, altered microtonalite sills, again of Rhobell affinity, and a thin, uncleaved melanocratic dyke, the properties of which indicate that it may belong to the Palaeogene suite of dykes that crop out in North Wales. In the immediate vicinity, field investigations have located Rhobell-related intrusive rocks that, atypically for the district, are relatively unaltered. These include a tonalite sill containing previously unrecorded cognate cumulate blocks and a spectacular mafic body, known to nineteenth-century geologists as the 'magnificent uralite porphyry', the last descriptions of which appeared in the literature in the late 1920s. Several other styles of mineralisation are hosted by the sills, including well crystallised actinolite and epidote–clinozoisite-bearing veins, described here in detail for the first time.

INTRODUCTION

Coed y Brenin Forest is a large (36 km^2) expanse of mixed, deciduous and coniferous woodland that is situated to the north of the market town of Dolgellau, in the centre of the county of Gwynedd. The forest covers the foothills of both the Rhinog range to the west and the mountain massif of Rhobell Fawr to the east. Within the forest the terrain is deeply dissected by the valleys of the Afon Wen, Afon Mawddach, Afon Gain and Afon Eden. The bedrock geology is dominated by sedimentary rocks of Cambrian to earliest Ordovician age, overlain unconformably by early Ordovician volcanic rocks of the Rhobell Volcanic Group. Cogenetic intrusive rocks occur widely, varying in size from sills and dykes less than a metre thick to large sheeted intrusive complexes cropping out on a kilometre scale.

Metalliferous mineralisation is widespread. The intermediate Afon Wen Intrusive Complex, situated less than a kilometre to the east of the Mawddach Valley, hosts the well known, drillcore-defined but unworked Coed y Brenin porphyry-copper deposit. Investigated by Riofinex in the late 1960s and early 1970s, the deposit contains at least 200 million tonnes of mineralised rock carrying >0.3 wt% copper (Rice and Sharp, 1976). The mineralisation occurs within altered, sheared and fractured intermediate intrusive rocks and consists of disseminations and veinlets of pyrite and chalcopyrite, with later centimetre-scale quartz-carbonate veins that in places carry pods of chalcopyrite, tennantite and bornite. Many of the core-logs from the boreholes, including descriptions of the mineralisation encountered, are now available online (British Geological Survey, 2018).

Molybdenite occurs in the same area and was frequently noted in the Riofinex boreholes. In most occurrences, molybdenite forms thin smears along joints, but coarser-grained examples are known from quartz-calcite veins. Samples of the latter type, found by JSM in the 1990s in mineralised float, consist of chalcopyrite-bearing altered igneous wall-rock, cut by sulphide-poor quartz-calcite veins to a few centimetres in width. The veins contain scattered coarse-grained aggregates of molybdenite, exceptionally to 5 mm, and localised areas of coarsely crystalline pyrite.

At higher structural levels in Coed y Brenin, phreato-magmatic explosion breccias form a series of pipes in the sedimentary rocks. Within some of the breccias, sulphides are abundant. Pyrite dominates such assemblages, but chalcopyrite is also present and some pipes are significantly enriched in As, Sb, Ag and Au, one example having been worked at the Glasdir Mine (SH 7402 2230), for copper and gold. The implication of this metalliferous mineralisation, at multiple structural levels, is that a major hydrothermal system was active on a regional basis during the Rhobell volcanism. For details of key study sites related to the porphyry-copper and related deposits, the reader is referred to Bevins *et al*. (2010).

Coed y Brenin is situated within the famous Dolgellau Gold-belt, historically one of Britain's most important

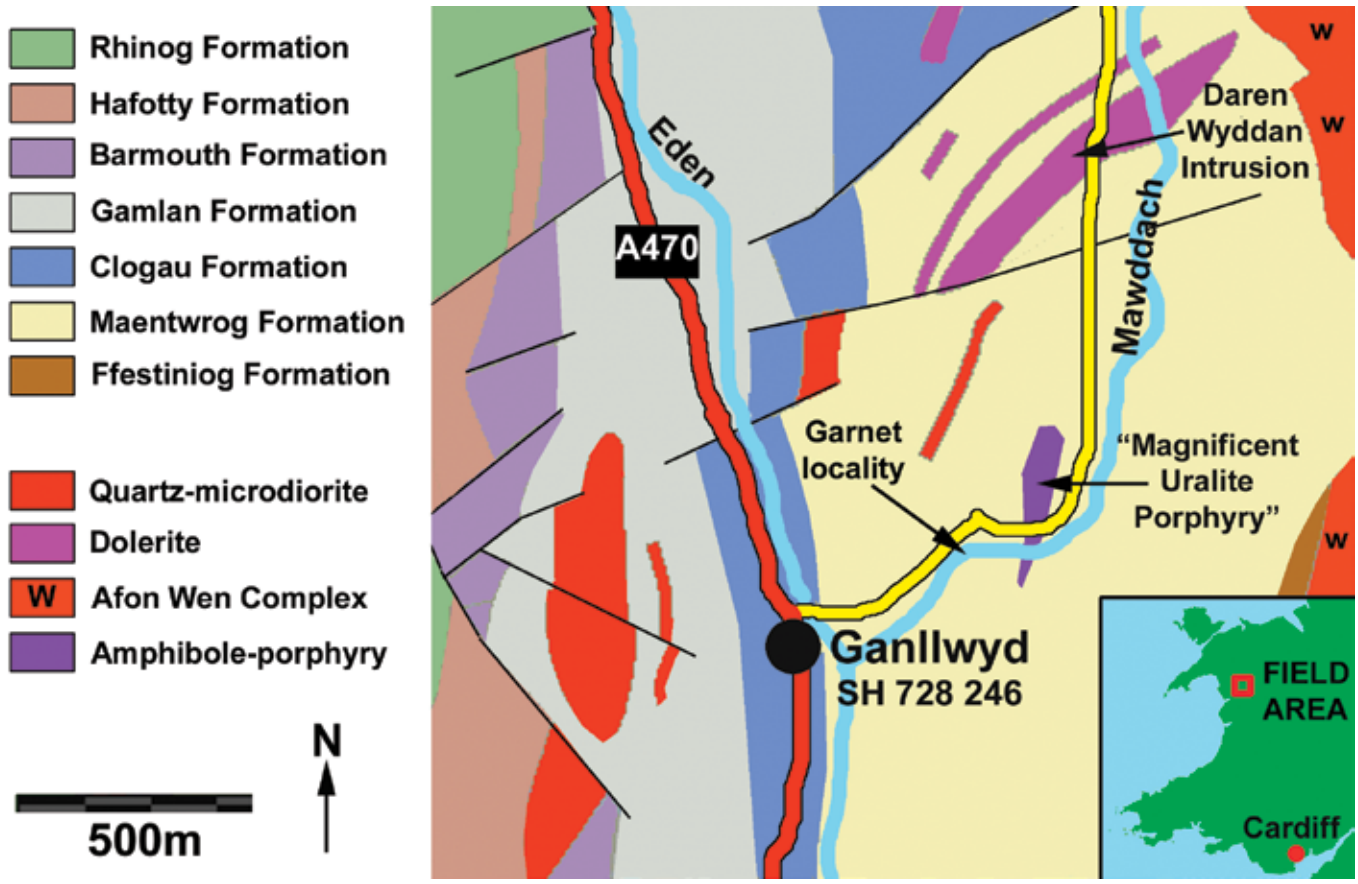

Figure 1. Location and geological map. Geology redrawn from BGS Harlech sheet (135) and the amphibole-porphyry marked in from the Old Series maps that agree best with recent mapping.

gold-producing provinces. The Gold-belt mineralisation manifests itself as a swarm of southwest–northeast- to northwest–southeast-striking milky quartz-carbonate-sulphide lodes, ranging from thin veins to multi-metre thickness bodies, transecting all of the Cambro-Ordovician sedimentary and intrusive igneous rocks. Metals and semi-metals present in the lodes variably include iron, copper, zinc, lead, cobalt, nickel, silver, gold, arsenic, antimony, bismuth and tellurium. Gold is of localised occurrence within the lodes but where it does occur, high-grade 'bonanzas' have been located and worked (Hall, 1990). The district has a long and colourful history of gold mining and efforts to locate further rich pockets of ore have continued intermittently to the present day.

The paragenetic mineralogy of the Gold-belt lodes was described by Mason *et al*. (2002). The lodes pre-date the mid-Devonian Acadian deformation of the district (Mason et al., 1999; Platten and Dominy, 1999), as best demonstrated by coastal exposures near Fairbourne, where complex and highly photogenic folding and boudinage of the quartz-sulphide veins is displayed (Bevins *et al*., 2010). Polished and thin sections invariably reveal extensive recrystallisation of both sulphides and quartz. The Gold-belt mineralisation best fits with the 'orogenic gold' class of deposits (Groves *et al*., 1998).

The bedrock occurrence of andradite-bearing skarn-like mineralisation described herein was discovered by ML, during mineral exploration in 1998–99, following the observation, atypical for the district, of abundant euhedral garnet crystals in panned heavy mineral concentrates. The concentrates were obtained from underwater gravels situated close to bedrock, along a section of the Afon Mawddach, situated below the steep afforested slopes of Cefn Deuddwr, upstream of the village of Ganllwyd (Fig. 1). Investigation of the submerged bedrock underlying the gravels revealed thin garnetiferous veining within highly chloritic zones in a heavily altered sill, and a limited number of specimens were recovered.

More recently, fieldwork (in 2013 and again in 2017–18) by JSM has resulted in the nearby rediscovery (see Appendix 1) of an intrusion, referred to in the nineteenth century as the "magnificent uralite porphyry" (e.g. Forbes, 1867; Readwin, 1879), which was lost to science following the planting of Coed y Brenin in the 1920s and 1930s. The last descriptions of the rock were given by Andrew (1910), and Cox and Wells (1927).

A second composite intrusion, cropping out 0.6 km to the north and located during the same fieldwork, is also relatively unaltered and features tonalite that contains hitherto undescribed cognate cumulate blocks, similar to those catalogued from the Rhobell Volcanics (Kokelaar, 1986). These finds have presented new opportunities to investigate the intrusive rocks of the district using modern methods and a detailed petrological and geochemical study is currently underway.

The possible presence of a Palaeogene dyke, crossing this district, was inferred from aeromagnetic data by Allen *et al*.

(1979). The discovery, during the recent fieldwork, of an uncleaved, melanocratic dyke, at a new outcrop apparently created during improvements to a badly dilapidated anglers' footpath, is therefore of considerable interest.

This fieldwork, combined with background research, has, in addition, potentially solved a long-standing problem regarding the provenance of some fine epidote–clinozoisite specimens in the Griffith John Williams Collection, acquired in 1927 by the National Museum Wales, Cardiff. An account of the outcrop geology and vein mineralisation in these rocks is provided herein. In all, five generations of vein mineralisation are recognised, three of which are described for the first time.

GEOLOGICAL SETTING

The Lower Palaeozoic strata that make up much of Wales were deposited within the marine ensialic Welsh Basin, situated within the eastern sector of the Avalonian micro-continent, between the southern margin of the Iapetus Ocean and the northern continental margin of Gondwana, deep in the Southern Hemisphere (e.g. Woodcock and Strachan, 2012). The Cambrian history of the Welsh Basin was dominated by clastic sedimentation but by the early Ordovician, Avalonia had rifted away from Gondwana and begun moving northwards. This change in tectonics led to the onset of southward-directed subduction of Iapetean oceanic lithosphere beneath Avalonia. Evolving activity along the subduction zone, lying to the northwest of Avalonia, had major consequences during Ordovician times, in terms of volcanism, sedimentation and tectonics throughout Wales.

In the Coed y Brenin district, situated on the eastern flank of the positive fault-bounded block known as the Harlech Dome, the sequence records developments from the mid-Cambrian through to Early Ordovician (Allen and Jackson, 1985). The lower part of the sequence belongs to the Harlech Grits Group, represented in the Mawddach Valley by the its uppermost member, the Gamlan Formation, which consists of grey silty mudstones with centimetre-scale pods of micritic quartz-spessartine rock ('coticule'). Close to the junction of the Gamlan Formation with the overlying Mawddach Group, there is a coarse quartzo-feldspathic sandstone, known as the Cefn Coch Grit, which forms a prominent marker-horizon.

The Mawddach Group contains the rest of the Cambrian and earliest Ordovician sedimentary rocks of the district. In the Mawddach Valley, it comprises the Clogau and Maentwrog Formations, and to the east it also includes the overlying Ffestiniog Flags and Cwmhesgen Formations. The Clogau Formation is dominated by dark grey to black, organic-rich and sulphidic hemipelagite, recording a long-lived and widespread instance of marine hypoxia or anoxia, where reducing conditions dominated at the sea floor. Such lithologies also occur in the overlying Maentwrog Formation, but are interbedded with turbiditic sandstones, siltstones and mudstones. Shallowing is recorded by the Ffestiniog Flags Formation, deposited in an intertidal environment and consisting of silty mudstone intercalated with beds of coarse, quartzose sandstone. The Cwmhesgen Formation is divided into the dark mudstones of the Dolgellau Member and the paler mudstones of the Dol-cyn-afon Member. Both of these latter units contain thin beds of reworked tuff.

Gradual shallowing in the late Cambrian culminated in early Ordovician (Tremadoc) times with a phase of uplift, emergence and folding along a north–south axial trend. Folding was focused in its intensity within the eastern parts of the district and was a precursor to the onset of island arc-type volcanism that produced the unconformably-overlying Rhobell Volcanic Group and the accompanying subsurface intrusions. Eruptive and intrusive activity was particularly concentrated along a north–south zone of significant, east–west orientated crustal extension, termed the Rhobell Fracture (Kokelaar, 1979; Kokelaar *et al*., 1984). Smaller intrusions, associated with the same episode of volcanism, occur widely throughout the Cambrian strata of the Harlech Dome and are especially concentrated in the younger formations belonging to that system.

The Rhobell Volcanic Group crops out extensively to the east of the Mawddach Valley, making up a broad tract of rugged country dominated by the mountain of Rhobell Fawr, although the eruptive centre is considered to have been situated to the west of the present-day outcrop (Kokelaar, 1979). It was concluded by Kokelaar that a mafic to felsic (basalt to dacite) sequence of magmas was originally erupted, as products of a fractionation sequence in a deep (sub-crustal) magma chamber. However, following the cessation of volcanism, further uplift and significant erosion removed the intermediate to felsic erupted components. Clasts of intermediate to felsic eruptive rocks occur in the basal conglomeratic grits (Garth Grit Member) of the overlying Allt Lwyd Formation, of Arenig age, a unit that marks the resumption of marine sedimentation across North Wales (Kokelaar, 1986).

Arc-type volcanic activity was a precursor to far more widespread volcanism of a mainly back-arc bimodal character, across North Wales, in the Middle to Late Ordovician (Kokelaar *et al*., 1984). Following the cessation of volcanism, turbidite sedimentation continued into the Silurian until the Welsh Basin effectively silted up. The sedimentary environment had become terrestrial by the Early Devonian and sedimentation was finally terminated in the Middle Devonian by the Acadian Orogenic Event, caused by the collision of another fragment of Gondwana with the southern margin of Avalonia (Woodcock *et al*., 2007). During this deformation, shortening occurred across the Welsh Basin, accompanied by folding, uplift and the imposition of cleavage. The area may have remained land, constituting a sediment source, ever since.

The post-Acadian tectonic evolution of North Wales was dominated by crustal extension. Offshore fault-controlled basins, featuring both marine and terrestrial sedimentary sequences, variably of Carboniferous to Oligocene age, record an intermittent pattern of subsidence and sedimentation. In the Palaeogene, the opening of the North Atlantic Ocean was marked by the development of several major igneous centres in the northwest of Britain. Volcanism

in that region was intense, with associated intrusive activity occurring widely. In North Wales, intrusive rocks of this age are represented by a swarm of northwest-trending mafic dykes, examples of which crop out most commonly on Anglesey.

FIELD GEOLOGY OF THE MAWDDACH VALLEY

All of the localities described here are situated within a 1.5 km long section along the Afon Mawddach and on the steeply sloping sides of its valley (Fig. 1). On its western side, from Cefn Deuddwr northwards to the upstanding, craggy outcrop of Daren Wyddan, exposure is intermittently good. Along the eastern side, extensive and thick glaciogenic deposits cloak the slopes, obscuring much outcrop, although forest roads high above the valley do provide several sections. The river itself presents several sections with good exposure, away from major alluvial benches. Its generally north–south course forms an oblique to absolute strike-section (Fig. 2). Gorges are common, some being difficult to access without specialist techniques. These remain unexamined.

Fieldwork presents some challenges in Coed y Brenin. Positioning oneself precisely on maps, once away from tracks or footpaths, can prove troublesome. Global positioning systems are not particularly accurate in this district and fixing grid references, using online resources, requires care. Old-series six-inch Ordnance Survey maps, available from the National Library of Scotland (2018), published in the late nineteenth century prior to the afforestation (e.g. Ordnance Survey, 1888), have proved surprisingly useful in that they have features like ruined buildings, stone walls and sheep-folds, still detectable on the ground beneath the forest canopy, but not necessarily included in later map revisions. Finally, it should be noted that fieldwork is much easier during the winter months, when the vegetation has died down.

The most interesting part of the Mawddach section is in the 300 m downstream from the Pont Cae'n-y-Coed footbridge at SH 73383 25104, where exposure is mostly continuous. The strike-section (Fig. 2) is immediately downstream from the bridge, but after approximately 100 m, the river swings around to an east–west course, providing an uncommon and useful short dip-section along which the exposure is near-continuous. The lower part of this dip-section is where the andradite-bearing assemblage was discovered and beyond it there lies another, mostly inaccessible gorge, part of which has been studied at times of very low river-flow, but which would become dangerous if even a heavy shower were to break out over the surrounding hills. The more accessible sections are reached from either side of the river by narrow footpaths, used primarily by anglers.

Alternating thin sandstones, siltstones and dark, pyritic mudstones of the Maentwrog Formation make up the country-rock along the dip-section. The sedimentary sequence, which dips at 40–60° to the ESE, is intruded by

Figure 2. A N–S strike-section in Maentwrog Formation sandstones and siltstones, below Pont Cae'n-y-Coed, Afon Mawddach.

Figure 3. Positive bedrock feature formed by a 'greenstone' sill with Maentwrog Formation sedimentary rocks forming its hanging wall. Outcrop is several metres in height. Afon Mawddach, just past the start of the dip-section below Pont Cae'n-y-Coed.

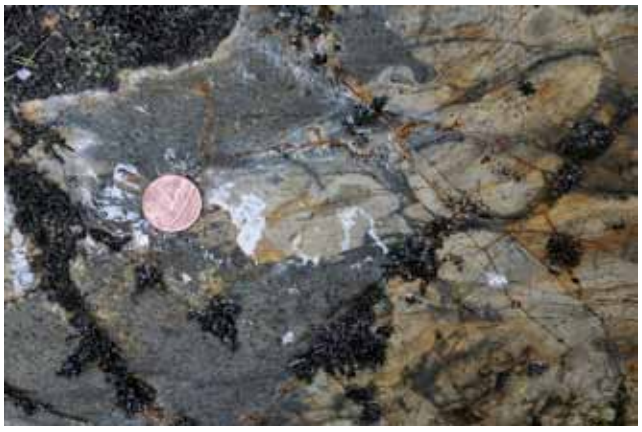

Figure 4. Irregular contact between 'greenstone' (L) and pale buff Maentwrog Formation sedimentary rocks (R). The sequence dips steeply towards the camera. Afon Mawddach, lower part of section at SH 73164 25000.

Figure 5. Sharply contorted bedding in Maentwrog Formation mudstones and siltstones in the hanging wall of a thin 'greenstone' intrusion (contact concealed beneath pine needles on the left). Exposure situated above river and road, close to edge of clear fell, at SH 73156 25154.

at least twelve sills of mafic through to intermediate–felsic composition, up to 10 m or more in thickness (Fig. 3). The contact effects of the sills, on the surrounding sediments, are limited to weak hornfelsing, that in the field can only be discerned to penetrate for a few tens of centimetres out from sill margins. Irregular contacts, featuring flame-like bodies of igneous rock extending out into the sediments (Fig. 4) and local, sharp contortions to bedding (Fig. 5), are consistent with Allen and Jackson (1985: p. 58), who made the suggestion that some sills, hosted by strata in the Maentwrog and younger formations, may have been emplaced into unlithified and possibly wet sediment.

Most of the intrusive rocks exposed throughout the district, including those along this section, are of a pale to mid-grey or greenish grey colour (Fig. 6). The nondescript nature of these rocks has led to their local name, 'greenstones', having been adopted widely in much of the older geological literature (e.g. Andrew, 1910). All of the 'greenstones' in the Gold-belt have suffered pervasive, variably potassic or propylitic hydrothermal alteration, resulting in the loss of primary features in many cases and the replacement of feldspar and ferromagnesian minerals with a variable, calcite-chlorite-sericite-quartz dominated

Figure 6. Typical, rather featureless sample of 'greenstone' from the Mawddach Valley.

assemblage. Millimetre-scale spots of pyrite, pyrrhotite and chalcopyrite are commonly observed, especially in the more silicic rocks. Despite the alteration, rocks of originally mafic and intermediate–felsic composition may be distinguished in the field with practice, especially with respect to the appearances of both fresh fracture faces and weathered surfaces, the more felsic sills having smoother fracture surfaces and the more mafic rocks having irregular, often rather pitted weathered surfaces.

Geochemical data were obtained from a sample suite of these intrusive rocks, collected by JSM in the late winter of 2013 for Acadia University, Nova Scotia. These data (Sandra Barr, *personal communication*) show that the rocks variably contain 46–65 wt% SiO_2, although there is some uncertainty with regard to the proportion of silica that was added (or lost) during alteration. Incompatible elements, such as Zr, widely regarded as being relatively immobile during most types of alteration, provide a better guide to the original nature of the altered rocks. In the case of the Coed y Brenin intrusives, Zr concentrations are interpreted to track the progression of the fractionation sequence. Intrusive rocks containing 35–45 ppm Zr, similar levels to the basalts of the Rhobell Volcanics (Kokelaar, 1986), represent the most mafic end of the compositional range, whereas in the later more felsic intrusives, 60–65 wt% SiO_2 and 90–110 ppm Zr are typical.

In sharp contrast to the severely altered 'greenstones', the 'magnificent uralite porphyry' (Fig. 7), henceforth referred to as the amphibole-porphyry, is a relatively fresh rock that is often strikingly crowded with randomly orientated, large (up to 3 cm), lustrous, euhedral phenocrysts of dark-brown–black amphibole. The rediscovery of this rock, by JSM in 2017 (Appendix 1), involved a hunt that was inspired by its nineteenth century name and the knowledge born from experience that none of the 'greenstones' could in any way be described as 'magnificent'.

In its once-concealed outcrop upon a storm-devastated and now cleared hillside (SH 73318 25126), the amphibole-porphyry forms a body of unknown but considerable thickness. Only its lower contact is visible, slanting steeply upwards along the eastern side of the outcrop, where crags to a few metres in height are flanked by awkward and steep blocky scree. The strong hydrothermal alteration that is typical of the 'greenstones' is limited in its extent to a metre or so above the contact, where the rock has a bleached appearance and the progressive chloritisation and sericitisation of the amphibole phenocrysts is evident. On the western side of the outcrop, the contact is largely obscured by glaciogenic overburden. The hillside is a dip slope that flattens out further up and the upper contact of the amphibole-porphyry has been lost to erosion. At the lower contact exposures, anomalous dips, compared to the regional east to southeast norm, are recorded in the sediments of the Maentwrog Formation. An exposure near the top of the dip-slope reveals sediments striking east–west and dipping to the south. A second exposure near the base of the outcrop has sediments which dip westwards, into the hill. The anomalous dips suggest that local folding has accompanied emplacement, a feature also exhibited at the contacts of some other sill-like bodies in the district (Fig. 5).

Powder X-ray diffraction (PXRD) analysis at the National Museum of Wales (NMW X-3576) has shown that the amphibole phenocrysts are magnesiohornblende or pargasite. Chemical data obtained by energy-dispersive X-ray spectrometry on a scanning electron microscope (SEM-EDS) on the rough surface of a carbon-coated crystal fragment suggests that despite the fresh appearance, there is local, partial alteration to actinolite, marked by a sharp drop in the concentration of aluminium. The 'uralite', which is clinopyroxene replaced by actinolite, forms slightly smaller phenocrysts, which form depressions on weathered surfaces. These mafic minerals are accompanied by smaller (typically 5–10 mm), altered phenocrysts of white plagioclase feldspar, giving the rock a highly distinctive, speckled appearance.

The same intrusion is also exposed in the river section immediately to the south at SH 73274 24988, where both contacts are present, and the intrusion is ten metres across the strike. However, the best outcrop, on the northern side of the river, is difficult of access, due to the deep and

Figure 7. A small boulder of the 'magnificent uralite porphyry' at its main outcrop.

often fast-flowing water surrounding it and the sheer bank above. Hornblende crystals do occur in this rock and may be discerned through binoculars. On the more accessible southern side of the river, the exposure is rather vegetated and the rock has undergone severe local alteration, although relict phenocrysts may still be discerned. Nevertheless, the exposures provide useful information about the contacts. The lower contact is steep and there is contortion of bedding in the host rocks. Between the upper contact of the amphibole-porphyry and the host Maentwrog Formation, there is a heavily altered sill, a few metres in thickness, of pale microtonalite, which indicates the intrusion is of a composite nature.

Fieldwork in 2013 and 2017–2018 has located further relatively unaltered intrusions in this vicinity. For example, just under a kilometre to the north of the amphibole-porphyry, at Daren Wyddan (forest track section at SH 73282 25865 to SH 73268 25641), another composite sill crops out. The lower parts consist of heavily altered 'greenstone', but fresher gabbro and microgabbro form the middle. The upper part of the sill features a separate large sheet of porphyritic tonalite and microtonalite, these being distinctive highly leucocratic, feldspathic rocks with fresh-looking, lustrous amphibole phenocrysts.

Age relationships between the components of the Daren Wyddan intrusion can, to a great extent, be discerned in the field. The tonalites form cross-cutting veins in mafic rocks and they also contain mafic xenoliths (Fig. 8), including gabbro, microgabbro and material very similar in appearance to the amphibole-porphyry. More rarely, the tonalites contain cognate cumulate blocks (Fig. 9), up to a few centimetres in diameter. The cumulate consists of clustered 1–4 cm dark phenocrysts, lying compositionally between magnesiohornblende and pargasite (NMW SEM-EDS data), accompanied by clinochlore, plus minor pyrrhotite (NMW X-3584). Similar cumulate blocks are well known from the eruptive rocks of the Rhobell Volcanic Group (Kokelaar, 1979; 1986). Some of the Rhobell basalts also conspicuously feature large, fresh euhedral black phenocrysts of pargasitic amphibole (Fig. 10).

Figure 8. Xenoliths of dark-green–grey dolerite in leucocratic, feldspathic tonalite, Daren Wyddan intrusion.

The presence of further, concealed, outcrops of amphibole-porphyry is indicated from isolated to clustered angular blocks in glacial drift elsewhere in Coed y Brenin, at locations that mean their source must have been well to the north of the known outcrop, when Quaternary ice-flow orientation is taken into account. An apparently similar intrusion was also intersected in one of the westernmost boreholes drilled by Riofinex Ltd to investigate the porphyry-copper mineralisation. In borehole CB38 (British Geological Survey, 2018) (depth 122 m), collared some 750 m ESE of the amphibole-porphyry outcrop, the core log records chloritic "diorite" with coarse, often euhedral hornblende crystals to 2.5 cm, between 50.9 and 62.2 m. Unfortunately, only a selection of the Coed y Brenin borehole cores now remain and CB38 is not among them (Tim Colman, *personal communication*). Although it has not been possible to locate any surface expression of the rock intersected in CB38, that is hardly surprising, since the eastern slopes of the Mawddach Valley are extensively cloaked in thick glaciogenic deposits.

Finally, another hitherto-undescribed intrusion crops out at approximately SH 73145 25004, on the north bank of the Mawddach, where an old trackway, down to a ford

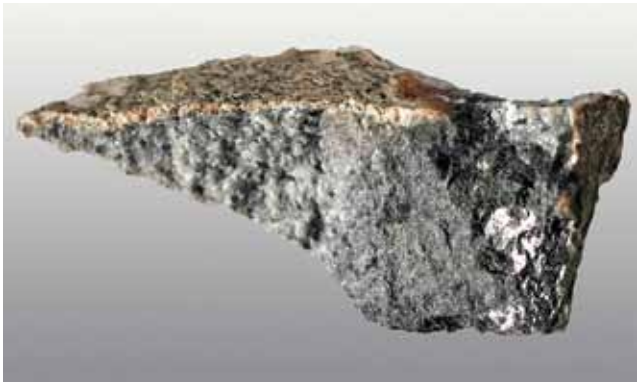

Figure 9. A cumulate xenolith in the leucocratic tonalite of the Daren Wyddan intrusion. The RH half of the sample is all cumulate, with the margin of the 3 cm diameter xenolith having a clinochlore-coated rind: the lustrous cleavages are pargasite.

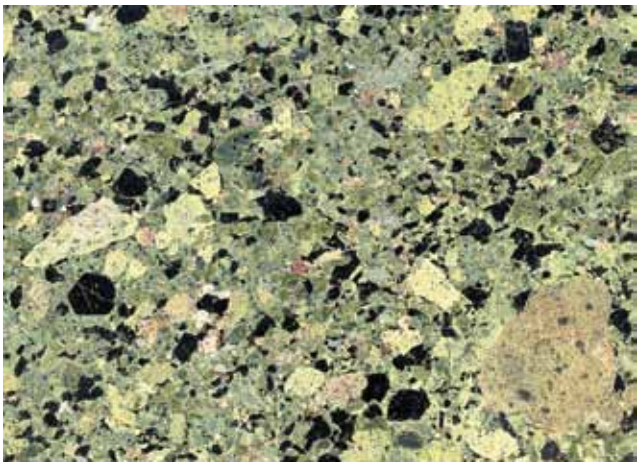

Figure 10. Polished slab of Rhobell Volcanic Group lava-breccia with whole and broken euhedral black pargasite phenocrysts to c. 15 mm. The green colour of the matrix is due to epidotisation: such texture and colour is typical of the Rhobell Volcanics.

marked on old-series Ordnance Survey six-inch maps, is still used as a path by anglers. When this section was visited in late 2017, the path was extremely boggy in places, but another visit in the spring of 2018 revealed that it had been drained and much mud had been removed, creating a fresh exposure at the riverside. Here, steeply dipping, thinly bedded Maentwrog Formation sediments are cut by a highly discordant dyke, up to 0.6 m in width and intermittently exposed along 7 m of strike-length, the fresh exposure being at the western end of its outcrop. Beyond this point, the dyke disappears beneath thick overburden, so that its full extent cannot be determined.

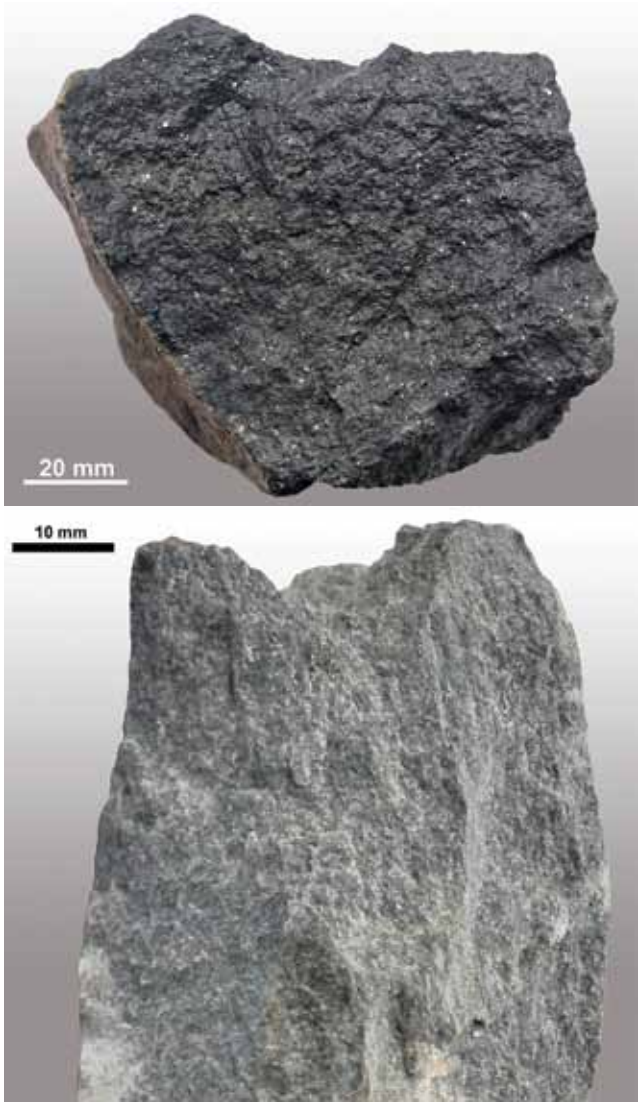

Figure 11. a) Hand specimen of the melanocratic dyke-rock of potentially Palaeogene age. The mineralised vesicles are clearly visible (upper image). **b)** for comparison, a hand specimen of a cleaved Rhobell-related dyke from just upstream of Pont Cae'n-y-Coed (lower image).

The dyke has a sinuous course, striking at 160° where it emerges from the bank at the western end of the exposure. Eastwards, it turns to 140° and then 110° before abutting against a screen of hornfelsed Maentwrog Formation at the foot-wall of a sill of microtonalite, which it has failed to penetrate: although at first sight the dyke appears to have been faulted-out, closer examination indicates this is not the case. The dip is vertical to steeply northeast on the contacts. Well jointed chilled margins occur and are 3–4 cm in width. The dyke is relatively soft compared to its Maentwrog Formation host and has been eroded preferentially, so that in places it forms the base of a natural shallow trench. Erosion surfaces are weathered to rusty hues.

When freshly broken, the dyke-rock is fine-grained, dark grey to almost black (Fig. 11a), and is speckled with minute white, almost perfectly spheroidal vesicles, up to 3 mm in diameter but mostly less than half that size (Figs 12 and 13). Some vesicles are hollow whereas others are fringed with thin, sectile crystals of a chlorite-group mineral (NMW X-3597), stood on edge and packed together, thereby displaying a distinctively fibrous appearance in cross-section. Many vesicles are also filled by white to colourless calcite, overgrowing the chlorite (NMW X-3596). Whole-rock PXRD (NMW X-3594) indicates a mineral composition dominated by labradorite and augite in a ratio of approximately 3:1, with minor secondary minerals. The rock is completely different in appearance to any other intrusion, known to the authors, in the Coed y Brenin district.

The vast majority of the dykes and thinner sills in the Harlech Dome, including a narrow east–west altered basalt dyke cropping out on both banks of the river immediately upstream from Pont Cae'n-y-Coed, display cleavage (Fig. 11b) and other indicators of strain, such as flattened vesicles. In the case of the newly discovered dyke, the rock

Figure 12. Close-up of calcite-filled vesicles.

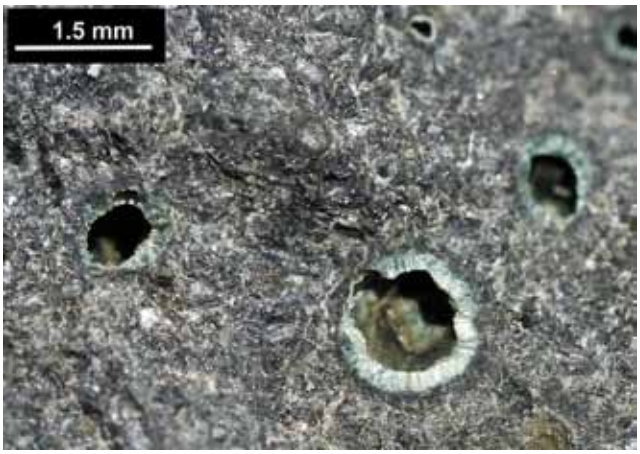

Figure 13. Close-up of chlorite-fringed vesicles.

is uncleaved and the vesicles show no sign of strain-related deviation away from their spheroidal morphology. These observations suggest that the rock probably post-dates the mid-Devonian Acadian deformation. The only post-Acadian intrusive igneous activity to affect the north of Wales was the injection of the northwest-trending, Palaeogene mafic dyke-swarm, most notably across Anglesey but also in northern Snowdonia. The dyke-rock certainly bears a strong visual similarity to other known Palaeogene dykes in North Wales and that, along with its uncleaved nature, leads the authors to provisionally affiliate the dyke to that episode of intrusive activity. However, the authors equally accept that such a status requires confirmation, via radiometric dating. If confirmed, this dyke would be one of the southernmost members of the swarm: others are known from northern Shropshire (Thompson and Winchester, 1995).

Regional aeromagnetic data, discussed by Bevins *et al*. (1996), suggest that dykes of Palaeogene age could indeed occur much further to the south of known outcrops in North Wales. They note that a linear magnetic anomaly indicates such a dyke ("Dyke A") may be at or close to surface, in the country just to the east of Porthmadog, and extending southeast into the northern Rhinogydd. Some 3.5 km to the southeast of the newly discovered outcrop, a second linear, northwest–southeast aeromagnetic anomaly near the village of Llanfachreth has been confirmed by four ground traverses (Allen *et al*., 1979). The authors interpreted the anomaly, through its reversed magnetic field signature, to indicate the presence of a Palaeogene dyke. A northwest–southeast line drawn between these two anomalies passes straight through this dip-section on the Afon Mawddach.

VEIN MINERALISATION

In addition to the porphyry-copper mineralisation, five categories of vein mineralisation are found in this district. Listed in order of abundance, from very rare to widespread, they are:

1. The relatively localised garnetiferous assemblage hosted by the altered sills;
2. Thin and again relatively localised veins, dominated by coarse, fibrous actinolite, apparently hosted exclusively by the amphibole-porphyry;
3. Quartz-clinochlore ± epidote ± clinozoisite ± albite ± calcite ± ferroan dolomite veins, hosted by miscellaneous sills;
4. Crustiform, undeformed, vuggy quartz-carbonate-marcasite-dominated veins;
5. The Dolgellau Gold-belt lodes.

Of these, only the last two categories have been described (Mason *et al*., 2002; Mason, 2018b). In the district under discussion, Gold-belt lodes are common and worth a brief mention. They are mostly narrow, centimetre-scale structures, cutting all of the Cambro-Ordovician sedimentary and intrusive rocks. Quartz-dominated, they may be weakly to highly sulphidic, especially with respect to pyrite and arsenopyrite. A wider and well mineralised lode was worked for gold via levels and opencuts at the Cefn Deuddwr Mine (SH 72925 25101), the remains of which are situated along a steep afforested hillside, high above the river dip-section. Although the size of the tips indicates that a substantial amount of work was done, the recorded output was only 8 oz of gold from 5 tons of lodestuff (Hall, 1990).

The crustiform assemblage (Category 4) likewise cuts all Cambro-Ordovician sedimentary and intrusive rocks and is again regional in its occurrence. In contrast to the Gold-belt lodes, the open, vuggy nature of this mineralisation and its lack of deformation both indicate that it post-dates the Acadian events. Texturally similar mineralisation occurs across North Wales and is clearly related to crustal processes in Carboniferous and more recent times (Mason, 2018b).

The Garnetiferous Assemblage (Catagory 1)

The key locality for this assemblage is at SH 73148 24999. It is permanently underwater and when the samples were collected it was only accessible by wading, at times of low river flow. Even in such conditions, the collection of the samples in 1999 was an awkward process, as anybody who has attempted to use a hammer and chisel underwater will testify.

An unusually intense flash flood, caused by a severe thunderstorm, occurred throughout the Mawddach catchment in the summer of 2001. During this extraordinary event, the river here rose rapidly by some 5 m (and by ~10 m at the sharp bend in the gorge upstream). As a consequence of the flood, the locality was buried beneath alluvium of up to boulder-size. Large, now rotting tree-trunks that cross the lower part of the anglers' path down to the locality were left here by the flood waters (Mason, 2018a). Due to that rearrangement of boulders, the whole force of the river now flows across the locality discovered in 1999. The site has not been accessed since the thunderstorm rearranged the bed of the river.

The host sill, exposed along 14 m of the river's north bank, is one of the most heavily altered examples known to the authors in the district. It is a pale- to medium-grey rock with irregularly distributed darker green-grey spots, and where mineralised it feels distinctly talcose to the touch. Several WNW- to NW-striking fractures, shears and breccia zones dissect the outcrop and one truncates the part of the outcrop that is above normal river levels. Downstream, in the northern wall at the start of the gorge proper, this fracture is seen to throw the sill, on its northern side, against sedimentary rocks to the south, although the amount of displacement is not known. In a hollow in the north bank of the river, carved out by flood-waters, the sill is again heavily fractured and here it carries quartz-pyrite-arsenopyrite-chalcopyrite-sphalerite-veining of Gold-belt type, locally brecciated and cemented by vuggy, post-Acadian type quartz. The inferred Palaeogene dyke should theoretically be only a few metres northwards, into the bank, at this spot and it, too, seems to have utilised part of the same band of fracturing.

Garnetiferous mineralisation occurs in the river along an irregular, close-spaced set of joints, in some cases only a centimetre or two apart and chiefly trending 060° and 100°. It is the 060° trending joints that are most heavily

mineralised. In the vicinity of this mineralisation, the host sill is so altered that, due to its relative softness, it forms a negative bedrock feature. This is in contrast to most of the Rhobell-related intrusive rocks in the river section, which although hydrothermally altered, still tend to be harder than their host Maentwrog Formation sediments, and form positive features (e.g. Fig. 3).

Whole-rock geochemistry of the host sill suggests it was originally of mafic-intermediate composition, with 54.66 wt% SiO_2 and 64 ppm Zr. Fresher mafic rocks with similar Zr levels (e.g. from Daren Wyddan), contain a little less SiO_2, suggesting that minor silica addition may have occurred as part of the host-sill alteration.

The mineralised joints in the garnetiferous part of the sill range in thickness from a fraction of a millimetre to 20 mm, the wider examples constituting thin veins, which are laterally impersistent, pinching out into dark green-grey chloritic selvages over 10–30 centimetres of strike length. Similar selvages also extend out from the veins, occurring as droppers at fairly steep angles, but these also pinch quickly (Figs 14 and 15). The mineralisation appears to represent both narrow open-space fillings and progressive replacements of the host-rock inward from the surfaces of its numerous joints.

Post-depositional movement along the wider joints is minor but has resulted in local cataclasis of the mineralisation and host-rock into soft grey clay, filled with loose crystals of garnet and other minerals.

Figure 14. A typical sample of the chloritic substrate, part-weathered (ochre coloration), with areas of euhedral andradite garnet. Specimen JM2522, 86×65 mm.

Figure 15. The side of specimen JM2521, showing heavily altered 'greenstone' with the chloritic host to the mineralisation present as a band along the top, with fairly steep chloritic selvages occurring as 'droppers', especially to the RHS, but pinching quickly. Rather indistinct darker spots are visible here and there. For scale, the label is 15mm in length.

Minerals

The minerals making up the garnetiferous assemblage are described in paragenetic order in the following text. A suite of samples from the occurrence, collected in 1999, is preserved in the Mineral Collection at the National Museum Wales, Cardiff, with the accession numbers NMW 99.40G.M.1–12.

Quartz, SiO_2

Quartz forms slightly contorted and fractured milky white veins up to 10 mm in width, occasionally with minor pyrite, although it is not ubiquitous: only three out of nine specimens held by JSM include quartz. Only in one of these (JM2522) is any useful paragenetic information provided: a joint cuts both the host rock and a quartz vein and both host and quartz are overgrown by garnets. The quartz is perhaps related to the Gold-belt vein mineralisation, which is developed in the close vicinity, adjacent to the river bank.

Clinochlore, $Mg_5Al(AlSi_3)O_{10}(OH)_8$

Clinochlore is the most abundant species in the assemblage and is common as dark green to almost black selvages, cutting the altered igneous rock, and forming a substrate upon or within which other minerals have crystallised. Small (1–2 mm) indistinct chloritic spots, of a similar colour, also occur within the host rock (Fig. 15): it is uncertain whether these represent regressed thermal spots or crude replacements of small phenocrysts.

Magnetite, Fe_3O_4 and Hematite, Fe_2O_3

Magnetite, confirmed by PXRD analysis (NMW X-1225), forms scattered black octahedral crystals, no more than 1 mm in size and covering areas to 3 cm^2. Magnetite is locally associated with isolated platy, steel-grey specular hematite rosettes to 2.5 mm, both phases occurring embedded in or sat upon chlorite.

Pyrite, FeS_2 and Chalcopyrite, $CuFeS_2$

Pyrite occurs as euhedral pyritohedra up to 1.5 mm across and is associated with chalcopyrite, which forms sparsely scattered sphenoidal crystals of a similar size. Both species are spatially associated with magnetite.

Ferroactinolite, $\square Ca_2(Mg_{2.5–0.0},Fe^{2+}_{2.5–5.0})Si_8O_{22}(OH)_2$

Common white and brown to yellowish green acicular to prismatic crystals, up to 2 mm in length but mostly much smaller, forming extensive, matted impregnations within chlorite, have been identified by PXRD analyses (NMW X-1222, 1224 and 3579) as a member of the amphibole group, with the best match being ferroactinolite. Two SEM-EDS

analyses of unpolished carbon-coated acicular crystals support the PXRD data. Alteration of amphibole to a white, as yet unidentified clay mineral is common.

Epidote, $Ca_2(Al_2,Fe^{3+})(SiO_4)(Si_2O_7)O(OH)$

Minute prismatic crystals with a vitreous lustre and a variably yellow to green colour, occurring associated with amphibole, especially where the latter is altered, have been identified by PXRD analysis (NMW X-3580) as epidote.

Andradite–Grossular, $Ca_3Fe_2(SiO_4)_3$–$Ca_3Al_2(SiO_4)_3$

Garnet is locally common but only occurs in the wider parts of the veins, where it was clearly one of the last minerals to crystallise. It may occur on or in amphibole or chlorite. The garnet forms bands of conspicuous euhedral crystals, exceptionally to 4 mm but more commonly 0.5–1 mm, which vary in colour from pale yellow through orange to deep red-brown. Crystals are translucent to transparent, often rich in amphibole and probable epidote inclusions (Fig. 16) and commonly display highly modified faces. Smaller crystals are often much better formed than their larger counterparts. The richest occurrences in the wider parts of the veins manifest themselves *in situ* as rare bright yellow-orange ribs to >10 mm in width and several centimetres in length and breadth; however, due to minor post-depositional movement such material commonly consists of loose garnet crystals in a friable clay matrix which disintegrates upon removal. However, a number of matrix specimens were recovered, the best of which, with areas of garnet crystals to several square centimetres in extent, constitute the finest known Welsh examples of garnet-group minerals (Figs 17 and 18).

Initial PXRD (NMW X-1226) of a yellow crystal in September 1999 indicated a garnet-group mineral consistent with andradite or grossular, but with a marginally better fit with andradite. Follow-up analysis, in January 2018, using a modern X-ray diffractometer (NMW X-3578) revealed that for another powdered sulphur-yellow crystal both andradite and grossular diffraction peaks are present in the approximate proportion An70:30. Chemical data obtained by SEM-EDS from an unpolished carbon-coated single yellow crystal is consistent with almost pure end-member andradite. However, in thin section, distinct internal growth zones are observable (Fig. 16). Many crystals have orange cores and yellow outer zones, so that the possibility exists that these internal zones are grossular in composition.

Further isolated occurrences of garnet, including an emerald-green crystal, also identified by PXRD as andradite (NMW X-1403), were noted (by ML) in the early 2000s, in panned heavy mineral concentrates obtained from the Afon Mawddach up to 1.4 km upstream. Such discoveries suggest that this section of the river may feature further, as yet undetected, instances of garnetiferous bedrock mineralisation, although, of course, glacial transport from a more distal source cannot be ruled out.

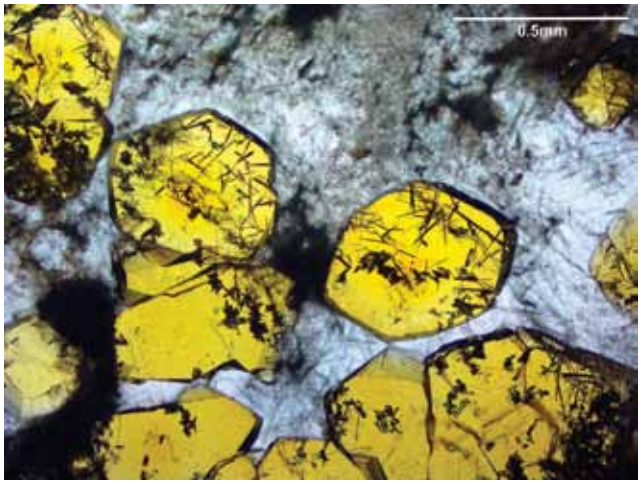

Figure 16. Photomicrograph, in plane-polarised light, of a thin section through garnet-rich material, impregnated with resin. Note the darker cores to some garnet crystals and the abundant inclusions of bunched and radiating amphibole needles.

Figure 17. Andradite crystals to 3 mm across on highly altered matrix. Specimen JM2514.

Figure 18. Small but well-formed druse of andradite on highly altered matrix. Individual crystals reach about 1 mm across. Specimen JM2525; photo, David Green.

Calcite, $CaCO_3$

Calcite, confirmed by PXRD (NMW X-1223) occurs as localised, millimetre-scale white to colourless cleavage-domains that clearly enclose andradite.

The Actinolite-Bearing Assemblage (Catagory 2)

Actinolite, $\square Ca_2(Mg_{4.5-2.5},Fe^{2+}_{0.5-2.5})Si_8O_{22}(OH)_2$, occurs within uncommon, narrow, planar sub-parallel joint-filling veins, less than 5 mm in width, cutting the amphibole-porphyry. Specimens, obtained from fallen blocks below the hillside outcrop, consist of flat-lying 2–5 cm long, plumose sprays of lustrous, dark green, fibrous actinolite, in which 1–2 mm cubic pyrite crystals are embedded (Fig. 19). Actinolite is surrounded by clinochlore and a little quartz is also present. The identities of these phases were confirmed by PXRD (NMW X-3575). The few specimens collected from this assemblage are among the best examples of actinolite known from Wales.

The Epidote–Clinozoisite-Bearing Assemblage (Catagory 3)

Milky quartz veins, carrying fibrous to prismatic epidote–clinozoisite, variably accompanied by clinochlore, albite, ferroan dolomite and calcite, occur widely in the district. The veins are exclusively hosted by intrusive rocks and they are particularly common in parts of the Afon Wen Intrusive Complex. The veins are mostly narrow, centimetre-scale structures although some more massive examples, up to 0.5 m in width, crop out in places. Samples reveal three types of vein textures:

1. Veins in which the epidote–clinozoisite crystals are randomly orientated to sub-parallel or radiating (Fig. 20) and embedded in massive quartz or calcite or both;
2. Arrays of parallel fibre-veins;
3. More rarely, well-crystallised epidote–clinozoisite or albite, or both, projecting into planar voids.

In the first type of texture, the epidote–clinozoisite is often mildly deformed, with crystals being bent and multiply fractured. Fine specimens of epidote (by North Wales standards) can be found where enclosing calcite has weathered away (Fig. 21).

Although there is clearly further potential for fine specimens of this assemblage, areas that are or were until recently afforested tend to have a thick moss cover, draped over outcrops and associated boulder fields alike. At Daren Wyddan, a boulder exposed along a new forestry haulage-road, at approximately SH 73468 25894, yielded some well-developed, colourless, bladed crystals to nearly 10 mm, consisting of nearly pure clinozoisite, confirmed by PXRD (NMW X-3583).

An interesting and unsolved problem is that in the mineral collection at the National Museum Wales, there are three old specimens of ‘epidote’ in the G. J. Williams (GJW) Collection, acquired by the Museum in 1927. The accession numbers of these specimens are NMW 27.111.

Figure 19. Well formed, flattened sprays of actinolite to several centimetres lining a joint in the amphibole-porphyry.

Figure 20. Small specimen consisting of radiating aggregates of clinozoisite crystals to 7 mm, with albite (pink) and manganese oxides (black), a common combination in veins cutting the Afon Wen Intrusive Complex at Moel Dol-frwynog (SH 74417 25095).

Figure 21. A vein of epidote crystals up to 18 mm long on quartz in altered greenish diorite. The epidote was enclosed by calcite, but the calcite has been removed by weathering. Loose but clearly local float from the eastern upper slopes of the Mawddach Valley (SH 74012 26142).

GR.301, 302 and 303. Specimen 301 (GJW no. M 22) has a rectangular handwritten label with the corners clipped, stating, "Epidote? Daran Belydr Dolgelley". 302 (GJW no. M 23) has a typed label: "EPIDOTE; Daran Belydr, Nr. DOLGELLEY"; and 303 (GJW no. Me 65) has a diamond-shaped handwritten label that reads "Epidote Daran belydr Ganllwyd Dolgelley".

A search of old maps (National Library of Scotland, 2018) and of the List of Historic Place-names website (Royal Commission on the Ancient and Historical Monuments of Wales, 2018) has not found this place name. There is a Dol-Belydr in pasture land to the northeast of Trawsfynydd, too far from Ganllwyd for association with the latter to be realistic, since Williams, as Assistant Inspector for Mines and Quarries in North Wales, was highly familiar with the district and would not have made such an error. The only place name prefixed by 'Daran' or 'Daren' in the district is Daren Wyddan, which is only 1.4 km from Ganllwyd.

Daren translates from Welsh as rocky hill, which fits with the local geography. Wydden translates as trees and on the Old Series OS six-inch map (Ordnance Survey, 1888), that pre-dates Coed y Brenin's planting, a cluster of trees is marked on part of Daren Wyddan, whereas the surroundings are rough pasture. Belydr is Welsh for rays, the implication being that Daren Belydr might refer to a rocky hill that catches the sun at a certain time of day. Daren Wyddan, steep, craggy and south-facing, would satisfy that requirement if its shroud of conifer forestry were to be removed. It is therefore hypothetically possible that Daran Belydr was an alternative local name for Daren Wyddan and the Ordnance Survey, when working in this district, went with the latter name rather than the former.

The specimens in question show coarse (1–2 cm), brown to murky green prismatic to fibrous epidote–clinozoisite crystals forming sprays and intergrowths embedded in quartz. A PXRD analysis of 27.111.GR.302 (NMW X-3586) gave a pattern closer to epidote than to clinozoisite. This particular specimen (Fig. 22) includes some matrix that bears a very strong resemblance to the tonalitic component of the Daren Wyddan intrusion. It is strongly suspected, on the above evidence, that Daran Belydr is Daren Wyddan and that there exists further potential for well crystallised epidote–clinozoisite in the vicinity; although the terrain makes fieldwork difficult.

DISCUSSION

The discussion naturally divides into two subsections: firstly the garnet-bearing assemblage (Category 1), and secondly the actinolite and epidote–clinozoisite assemblages (categories 2 and 3).

Garnetiferous Assemblage

The mineralised joints, cutting the highly altered sill in the underwater river section, preserve evidence for the invasion of the host rock by hot fluids that deposited a mineral assemblage consisting of andradite, amphibole, epidote, magnetite, hematite, pyrite and chalcopyrite. This association is characteristic of calcium-iron exoskarns, developed through thermal metamorphic or metasomatic processes in high-temperature environments (e.g. Meinert, 1992).

There can be little doubt that the intrusive rocks along this section have undergone forms of alkali metasomatism. Allen *et al*. (1979) consider the hydrothermal alteration of the intrusive rocks of Coed y Brenin in some detail. They describe local potassic alteration, related to the porphyry-copper mineralisation and only affecting Rhobell-related intrusives. A more widespread Na-metasomatism subsequently affected both Rhobell-related and later Ordovician igneous rocks. In a pattern consistent with this, within the altered sill hosting the garnets, Na_2O is strongly elevated at 5.17 wt%, whereas CaO and K_2O are depleted (concentrations of 1.79 and 0.19 wt%, respectively). This type of alteration has been shown by the 2013 geochemical dataset to occur widely in the Harlech Dome, replicating the results of Allen *et al*. (1979).

Interestingly, the altered amphibole-porphyry, cropping out on the southern bank of the Afon Mawddach only 150 m upstream, has undergone potassic alteration: it carries 3.68 wt% K_2O, with just 0.94 wt% CaO and 0.48 wt% Na_2O. Preliminary results on samples of the relatively fresh amphibole porphyry cropping out on the hillside (Andreas Hahn, *personal communication*) indicate that this potassic alteration has involved an approximately tenfold increase in K_2O and a correspondingly large decrease in CaO, and that Na_2O has declined by some 75%. In the full 2013 dataset (23 analyses), the altered porphyry and altered garnet-bearing sill are, respectively, the most potassic and sodic rocks of the whole sample suite. The fact that the potassic alteration appears to have survived the later Na-metasomatism event would suggest that both alteration types attacked the same minerals and converted them to secondary products of a less reactive nature.

Emplacement of a skarn-like mineral assemblage, at this single locality, was long regarded by the authors as problematic in its genesis. A source of calcium for

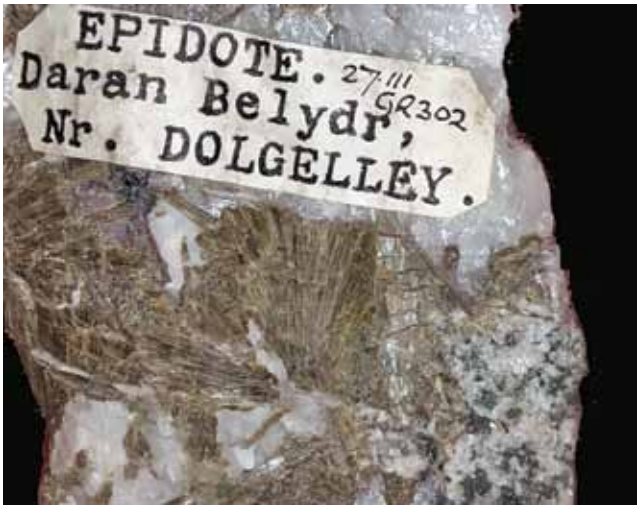

Figure 22. Epidote–clinozoisite in quartz, with old, 38mm long label. Part of National Museum Wales specimen NMW 27.111. GR.302, collected by G.J. Williams. Note the area of matrix on the lower RHS; this is very similar to the highly feldspathic tonalites of Daren Wyddan. Photo Tom Cotterell.

incorporation into the garnet is not the main problem: the pervasive alteration of most mafic intrusives includes the replacement of calcic plagioclase by a fine-grained mixture of albite, calcite, clinozoisite and sericite (Allen and Jackson, 1979). Calcite is therefore readily available in these rocks. However, the high heat-flow required to generate such a mineral assemblage is harder to explain.

Furthermore, the Dolgellau Gold-belt has, compared to many parts of North Wales, seen an atypically high volume of detailed geological and mineralogical investigation over the past two centuries. Such work has been on a commercial basis, with respect to both the porphyry copper deposit and gold lodes, and of an academic nature, with a significant number of PhD studies having been undertaken. Miles of underground drivages, made in search of gold and other metals, have been studied, both by contemporary geologists and mineralogists at the time the mines were at work, and by collectors and researchers, in the years since the mines closed. Propylitised sills are abundant throughout the Gold-belt, but the skarn-like mineralisation is apparently limited in its bedrock occurrence to this single described locality. That such mineralisation may have been overlooked elsewhere therefore seems rather unlikely.

A more probable interpretation is that the mineralisation is indeed very localised. Its relatively recent discovery could simply be due to the fact that, whereas other parts of the Harlech Dome have been subjected to detailed modern geological mapping, this particular small area has received less attention since the planting of Coed y Brenin in the 1920s and 1930s. Abnormally, for the wider district, relatively fresh intrusions of Rhobell-related igneous rock occur in the same area. The fact that these highly distinctive rocks have gone undescribed between 1927 and the writing of this paper, some ninety years later, supports such a contention.

Are the occurrence of an inferred Palaeogene mafic dyke and skarn mineralisation, within just metres of one another, cause or a coincidence? The emplacement of such a dyke, involving the movement of very hot mafic magma, would certainly cause high local heat flow in rocks that would, away from joints and other fractures, have been essentially dehydrated thanks to burial-related metamorphism and the imposition of Acadian cleavage. The host-rocks were probably not far (possibly <1 km) from the surface at the time of dyke emplacement: the Welsh uplands have apparently remained an eroding sediment source since at least the Late Cretaceous (e.g. Woodcock and Strachan, 2012). Therefore, the rocks would have been relatively cool and brittle when the dyke was intruded. That the emplacement of the dyke was accompanied by hydrothermal activity is evidenced by its abundant calcite-filled and chlorite-fringed vesicles. Furthermore, the already fractured and shattered nature of some of the adjacent host rocks would have facilitated the movement of high-temperature hydrothermal fluids in the immediate vicinity of the dyke.

Many descriptions have been written with respect to the Palaeogene dykes on Anglesey, of which one of the most interesting was by Henslow (1822), who provided a very detailed account of the albeit much larger (40 m wide) and now legally protected Plas Newydd Dyke, near Llanfairpwllgwyngyll, and its contact effects on the host Lower Carboniferous sedimentary rocks (mudstones, calcareous mudstones and impure limestones). Thermal alteration effects extend out into some of the mudstones to a distance of nearly 11 m. Within 3 m of the contact, these rocks had been converted to a hard, cherty or even flinty lithology. Henslow (1822) described euhedral to anhedral garnet crystals, now known to be grossular (National Museum Wales, 2018), in the alteration assemblage:

> "Some large crystals of the dodecahedron with truncated edges, seven-tenths of an inch in diameter. Facets well defined, possessing a resinous lustre and olive brown colour. These are embedded in a mass of crystalline matter of the same kind, and the whole attached to some hardened shale".

Archer and Elliot (1965) described finely amygdaloidal olivine-dolerite dykes of Palaeogene age, encountered in underground workings at the Parc and neighbouring lead-zinc mines in the Llanwrst Orefield, in the lower Conwy Valley of North Wales. The dykes were observed to cut the metalliferous lodes, but did not displace them. Contact effects, where the wall-rock was tuff, included shattering with addition of chlorite veins, associated with acicular to prismatic pyroxene and rare suspected cordierite. Where the dykes crossed the quartz-calcite-galena-sphalerite-marcasite-bearing lode, small honey-yellow crystals of andradite occurred on a joint face cutting the lode, and joints in wall-rock alongside another dyke carried pale brown andradite. The dykes themselves were not mineralised (with the exception of amygdale fillings) and the authors suggested contact metamorphism to have been the source of the garnets and other minerals.

It is therefore clear that these Palaeogene intrusive rocks are associated with contact-metamorphic haloes, albeit variable in extent and nature. It is also clear that further analytical work is required to properly establish whether the skarn-like mineralisation was generated when the mafic dyke was emplaced, or whether it belongs to a much older episode of mineralising activity: as ever, field observations are a precursor to a fuller understanding of events.

Actinolite- and Epidote–Clinozoisite-Bearing Assemblages

With respect to the actinolite-bearing, joint-hosted assemblage in the amphibole-porphyry and the more widely occurring epidote–clinozoisite-bearing veins in sills, a pre-Acadian origin seems likely. Although one would not expect such mineralisation, hosted by highly competent thick sills, to be intensively deformed, evidence for mild deformation is certainly preserved in these veins, in the form of bent, fractured and healed crystals.

The component minerals of these veins, actinolite, epidote, clinozoisite, albite and clinochlore, are characteristic of lower greenschist facies vein assemblages in metabasites. Such veins are therefore considered to be metamorphic segregations formed during the burial-related

metamorphism of the rocks, which across this part of North Wales reached the epizone greenschist grade (Robinson and Bevins, 1986). The veins may also be related to the apparently diachronous 'regional veins', as described from Ordovician and Silurian sedimentary rocks in the Welsh Basin by Fitches (1987). Fitches (1987) noted that a conspicuous feature of the regional veins is the close correlation between their mineralogy and that of their host rocks. If that observation applies to veins hosted by sedimentary rocks, it should equally apply to veins developed within igneous hosts. In a deeply buried basinal sequence such as that of North Wales, metamorphic dehydration reactions under epizonal conditions would be adequate to generate the modest quantities of hydrothermal fluids required: the strong correlation between vein mineralogy and the nature of the host rock would certainly imply locally derived fluids with a strong element of lateral secretion.

Age-constraining of this generation of veins is not straightforward, since although an epizonal mineral assemblage is involved, the point at which that metamorphic grade was attained, in the Harlech Dome, remains undefined. However, there is evidence to suggest that peak metamorphism may have been reached early in the Upper Palaeozoic. In their discussion, Robinson and Bevins (1986) suggest, with cited supporting evidence, that peak regional metamorphism in the Welsh Basin occurred prior to Acadian compressive deformation. Soper and Woodcock (2003) imply a burial maximum in Lower Devonian times, when the district was deeply buried beneath a thick Lower Old Red Sandstone overburden, long since removed by post-Acadian erosion.

The fibre-veins and planar void linings, again dominated by epidote–clinozoisite, have important differences in structural terms. Vein textures indicate crystallisation within incrementally opening tensile fractures. Although these textures have not been examined *in situ*, the fact that the fibre-veins and planar voids are parallel and that the crystals projecting into the planar voids were clearly the last to form, suggest that these structures may be late orogenic features with respect to the Acadian deformation. Whereas the larger intrusions are not noticeably deformed, such incrementally opening tensional structures could have developed during vertical extension, following uplift and late-orogenic exhumation of the sequence due to rapid erosion.

In the Alpine and Variscan orogens of Europe, such veins, known widely as alpine-type fissures, have been studied in detail and they are widely recognised to have developed along post-peak metamorphism, late-orogenic exhumation pathways. The deposition of their contents is partially to wholly attributed to lateral secretion from adjacent wall-rocks (e.g. Wagner and Cook, 2000). The Lower Palaeozoic rocks of North Wales are well known for their alpine-type fissure assemblages, most of which have been recorded from mid-late Ordovician igneous rocks. However, some albite samples from the Afon Wen Intrusive Complex are in textural terms very similar to specimens from, for example, Manod Quarry near Blaenau Ffestiniog (Bevins *et al.*, 2010), although the crystals from Coed y Brenin are much smaller.

CONCLUSIONS

The Mawddach Valley, within the Coed y Brenin district, preserves evidence for a sequence of igneous intrusion and hydrothermal activity, with some relatively unaltered intrusions providing unusually good constraints with respect to age relationships. The sequence reflects fractionation in a magma chamber, at a probable sub-crustal level, generating melts of an increasingly silicic composition. The later, dioritic to dacitic rocks are directly associated with the Coed y Brenin porphyry-copper deposit, implying the establishment at the time of their intrusion of a regional meteoric to magmatic hydrothermal system at high crustal levels. The ongoing intrusion of the more silicic rocks, within an active hydrothermal system, led to strong hydrothermal alteration of many of the intrusions. Burial-related and/or regional, Acadian metamorphism led to the formation of veins containing minerals typical of lower greenschist facies conditions and of late-orogenic exhumation. An exoskarn-like garnetiferous mineral assemblage of very local occurrence may be genetically related to the emplacement of a nearby melanocratic dyke, the properties of which, especially the absence of evidence for tectonic strain, make it possible to hypothesise that it is of Palaeogene age.

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APPENDIX 1

The Rediscovery of the Magnificent Uralite Porphyry

The existence of a boulder train of amphibole-porphyry along the Mawddach and now known to be downstream of the key exposure, was known to JSM and ML for many years, but its source outcrop proved elusive. Tracking down its location involved piecing together a jigsaw and provides an instructive tale. The task also revealed why the rock has not featured in more recent writings on the district, although accounts of it are scattered through the nineteenth-century literature: for example, Forbes (1867) stated:

> "The very characteristic rock-species diabase does not even seem to have been recognized by the Survey, notwithstanding that it would be probably impossible to find better opportunities of studying it in all its variations of texture, crystallization, and mineral composition than in the immediate vicinity of Dolgelly. The coarse-grained varieties, with the

felspar especially prominent, are quarried on the Towan road just beyond the town; the more chloritic ones are well seen in the rocks between Llaneltyd and Tyn-y-Groes; calc-diabase occurs in the mountain-side immediately above Penmaen Pool; the schistose, close-grained, and compact varieties occur everywhere; and, lastly, the magnificent Uralite porphyry, as it has been termed, forms hills alongside of the river Mawddach before coming to Tyddynglwadis".

"Tyddynglwadis" clearly refers to Tyddyn Gwladys, a mine named after the farm, now ruined, on which it is situated. The Tyddyn Gwladys Mine is something of an oddball in the Dolgellau Gold-belt as its sulphide assemblage contains unusually high levels of Ag and Sb, in the form of tetrahedrite, pyrargyrite and other minerals, illustrated in Mason *et al*. (2002). These minerals occur as microscopic intergrowths associated with galena, chalcopyrite and sphalerite and must have been fiendishly difficult to separate using nineteenth-century technology, as detailed by Hall (1990), although Tyddyn Gwladys was always regarded as a silver-lead mine.

Although Forbes therefore gave a vague location for the amphibole-porphyry, Phillips (1877), with some contradiction, wrote:

"An instructive example of the changes which sometimes take place in crystalline rocks, and in which their quarry-water is probably an important agent, is afforded by the "uralite porphyry," or uralitic dolerite of the Mawddach valley near Dolgelly. An outcrop of this rock is seen near the summit of a hill immediately north of the road a mile below Tyn-y-groes".

Tyn-y-groes is a prominent inn on the roadside of the A470, 1.6 km south of Ganllwyd. Since "a mile below Tyn-y-groes" puts one in a NE–SW-trending section of the Mawddach Valley, with no obvious summit anywhere immediately north of the road, it is thought that Phillips may have confused place-names, but not rocks. The rediscovered outcrop is almost exactly a mile below Tyddyn-Gwladys, lies immediately north of the road, and forms a summit-like feature, the latter two attributes in agreement with Phillips (1877). However, in terms of its now-known position on the map, the location clearly matches that given by Forbes (1867), whose greater familiarity with the district is obvious from his writings.

	I	II
Water (hygrometric) %	0.34	0.37
Water (combined) %	2.88	2.74
Silica %	46.73	46.51
Carbonic anhydride %	trace	trace
Phosphoric anhydride %	trace	trace
Alumina %	19.28	19.33
Ferric oxide %	2.86	2.72
Ferrous oxide %	7.57	7.73
Manganous oxide %	trace	trace
Lime %	10.76	10.81
Magnesia %	6.98	7.15
Potassa %	0.38	0.30
Soda %	1.96	2.08
Total %	99.74	99.74

Table 1. Analyses of the amphibole-porphyry from Phillips (1877).

Phillips (1877) did present two analyses of this rock, reproduced in Table 1, and which are remarkably consistent with the emerging data coming from the recent and ongoing investigations of the amphibole-porphyry.

Andrew (1910) gave some details of the petrology of this rock and the location of its key outcrop was last described by Cox and Wells (1927), when samples were collected by a party on an Easter field-meet based in Dolgellau:

"Those interested in igneous petrology were able to obtain excellent specimens of hornblende diorite-porphyry from blocks which had rolled from the heights of Cefn Deuddwr above".

That report was only tracked down in late summer 2017 and it immediately identified the immediate area in which to look. The forestry on the steep hillside of Cefn Deuddwr was for years impenetrably dark and dense, with no hint of the interest concealed within. During early 2014, however, the situation changed when a series of violent gales wreaked havoc across North Wales. The winds devastated the hillside at Cefn Deuddwr, flattening the trees in great swathes. In the years that followed, the trees were removed and the main outcrop was finally located in September 2017, armed with the information in the Cox and Wells (1927) report. It can therefore be stated that both literature-searching and bad weather contributed directly to the rediscovery.

Matley and Wilson (1946) stated that they did not re-examine the rock although they were clearly aware of it. Allen and Jackson (1985) did not mention the rock. The reason for it having been effectively lost to science, for many decades, seems to have been the planting of the Coed y Brenin forest in the late 1920s and 1930s. Very tellingly, Matley and Wilson (1946) stated:

"Considerable areas are now being transformed to forest by the Forestry Commission, greatly to the disadvantage of the field geologist, who finds the spaces between the young trees an almost impenetrable tangle of brambles. For this reason detailed mapping of certain areas has had to be omitted".

When attempting to examine areas of Coed y Brenin (or indeed any forestry) that have been clear felled for longer than about five years, and are rapidly regenerating, it becomes very easy to empathise with that statement.

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"MINERALS OF THE ENGLISH MIDLANDS"

By Roy E. Starkey

Published in September 2018 by British Mineralogy Publications

15 Warwick Avenue, Bromsgrove, Worcestershire, B60 2AH

With 432 pages and 943 illustrations, colour throughout; 276 mm × 218 mm in the softback version, slightly larger in hardback; priced at £35 softback and £50 hardback, plus postage and packing; available from the author at the above address or via https://britishmineralogy.com; ISBN 978-0-9930182-2-0 for the hardback and 978-0-9930182-3-7 for the softback.

Many members of the Russell Society will be aware that Roy Starkey has been researching a volume on the minerals of the English Midlands. For your bookshelf? The short answer for anyone with an interest in British mineralogy is 'yes'. For those who would like a detailed review, read on.

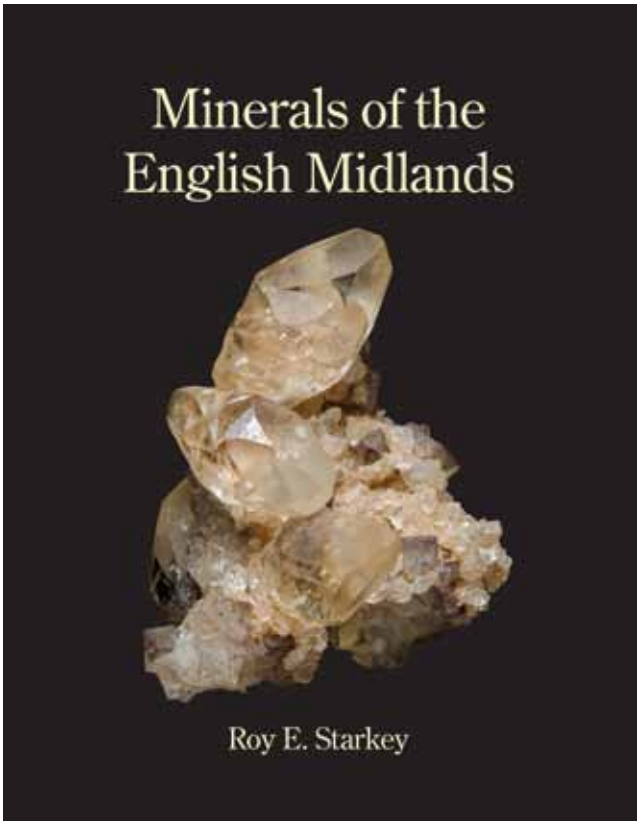
Recent topographic descriptions of the mineralogy of the British Isles fall into two categories. Some produce an alphabetic listing of the species known from the study area. Richard Bevins' *A Mineralogy of Wales* is a familiar example. Others focus on species of collector interest. The first of the modern topographic studies of the British Isles, which described the counties of Cornwall and Devon, took this approach; *Minerals of the English Midlands* also lies squarely in this category.

After the success of *Crystal Mountains – Minerals of the Cairngorms*, Roy decided to paint a larger and more complex canvas. That canvas consists of fourteen counties in the approximate centre of England, namely: Cheshire, Derbyshire, Gloucestershire, Herefordshire, Leicestershire, Nottinghamshire, Rutland, Oxfordshire, Shropshire, Staffordshire, Warwickshire, West Midlands and Worcestershire. This region extends a little further from north to south than it does from east to west and has Birmingham at its approximate centre. In the west it runs the whole of the way along the Welsh border. The southern boundary is almost entirely north of the M4 motorway. The eastern boundary runs up Oxfordshire and Northamptonshire and then roughly along the line of the A1. The northern boundary lies along the border with Yorkshire and Lancashire, which is where many would argue northern England begins.

Four introductory chapters set the scene. The first describes the topography and provides a historical sketch of the industry and natural resources of the Midlands. In the next chapter the geology of the area is summarised, beginning in the Precambrian and ending with the impact of people in the recent past. The major mineral deposits are described in a geological context. A one-page introduction to the 'mineral chapters', which are arranged alphabetically by county, completes the first part of the book. In this the author notes:

> "... if your pulse races a little as you turn a page, I shall have succeeded, at least in part in my endeavour".

Minerals of the English Midlands is a substantial volume. Rather than describe each chapter in detail, a few interesting, quirky or surprising stories are noted herein. These give a flavour of the text and a guide to the content.



Beginning in Cheshire, where salt mining is the major story, attention is drawn to the copper mines at Alderley Edge. Currently, the area is more famous for its association with wealthy footballers than minerals, but 'The Edge' preserves some of the earliest evidence of copper mining in the Britain. Several pages of specimen photos are included, many drawn from the collection of the author or Russell Society President, Steve Warren. Mention is made of the nearby workings at Mottram St Andrew, where mottramite occurs as black botryoidal crusts on sandstone (a particularly fine specimen is illustrated as a full-page photo in Figure 92). The 'mottramite story', and its association with the isolation of the element vanadium, is told in detail.

Derbyshire is the jewel in the crown of Midlands mineralogy and the 87 pages of description could be a book in their own right. Here there are accounts of the calcite, fluorite and galena specimens for which the Peak District is famous; decorative oakstone, and bizarre brainstone baryte; classic phosgenite and matlockite; rare sweetite and ashoverite; historic 'Buxton Diamonds' and of course Blue John. There are a selection of photos of the wonderful lead

minerals found in Permian dolostones near the Derbyshire–Nottinghamshire border at Whitwell Quarry. Most of the figured specimens, in the Derbyshire chapter are from museum collections. And not just the well known iconic pieces from Britain's great collections; the author has visited numerous local museums and included specimens from many lesser known localities. The selection of photos of matlockite, phosgenite and related species from Bage Mine occupies seven full pages. There are numerous images of Derbyshire calcite, including the strange 'axe head' twins from Bonsall Moor. As a beginning collector I had doubts about Derbyshire calcite: the county has produced fine specimens but do they really belong in the same category as the fantastic pieces from west Cumbria? Not always, but the remarkable specimen on the front cover of *Minerals of the English Midlands* from Ladywash Mine stands with the finest calcite from anywhere in the world. At the end of the chapter photos of specimens are gathered together from unknown locations in the county, they include remarkable smithsonites the like of which have not been seen in modern times. Each poses an unanswered question, which future research may unravel.

Gloucestershire is best known to mineralogists as one of the world's premiere sources of the strontium sulphate celestine. My attention was drawn by a series of specimens of iron ore from the Forest of Dean in the Woodward Collection at the University of Cambridge. The 'brush ore' dusted in carbonate rhombs is particular attractive, as is a broken goethite stalactite in the Russell Collection at the Natural History Museum. Equally remarkable are the lustrous stalactitic goethite specimens from Bury Hill in the collection of Bristol Museum and Art Gallery. This is one of a number of localities that may be unfamiliar to collectors. I had certainly not come across it before. Mention must be made of the calcite-lined cave infills encountered at Hampstead Farm Quarry near Chipping Sodbury. On occasion, spectacular 'crystal caves' lined with crusts of euhedral calcite crystals, sprinkled or coated with golden pyrite, with contrasting banded bright pink and white barium-rich celestine have been (and still are) found at the quarry.

Herefordshire is not known for its minerals and only merits three pages. The most interesting occurrence is of millerite from near the village of Gorsley Common, which is further described by Roy Starkey and Tom Cotterell in this journal.

Leicestershire is second only to its northern neighbour Derbyshire in terms of mineralogical interest. In terms of mineral diversity it may be the premiere county in the English Midlands. It is introduced with a photo of the priory church of St Mary and St Hardulph, which overlooks Breedon Hill Quarry, a locality that is familiar to many Russell Society members. The facing page has a map which provides an outline of the county (together with adjoining Rutland). County maps, on which the principal localities are marked, accompany each of the chapters. It is hard to know where to begin in Leicestershire such is the mineralogical variation. The minerals of Croft Quarry are described in seven pages, including five completely given over to specimen photographs. In the description of Bardon Hill Quarry there is a photo of a gold specimen found by the late Bob King and now in Franz Werner's collection. New Cliffe Hill Quarry became famous in the 1990s for a remarkable and varied suite of copper minerals (it is the type locality for bobkingite). A two-page photographic spread celebrates this mineralogical diversity. Newhurst Quarry is known for various unusual supergene minerals; I was particularly taken by the platy off-matrix wulfenite crystals in Neil Hubbard's collection. Russell Society members will be pleased to see an excellent selection of fine specimens recently found on field trips to Breedon Quarry and Cloud Hill Quarry. These have similarities to specimens from Earl Ferrer's Lead Mine, of which Leicestershire collectors speak in hushed tones. It is the classic mineral site in the county and with more than five pages of text and seven of specimen photos gets deservedly full coverage. A galena (Figure 516) from the Russell Collection at the Natural History Museum is second only to the cover specimen in my fantasy Midland collection. The Leicestershire chapter is rounded off by the story of the Barwell Meteorite, which fell to earth on Christmas Eve 1965.

Northamptonshire and Nottinghamshire are not known for specimen minerals. The major story in Nottinghamshire is the mining of gypsum from Triassic rocks of the Mercia Mudstone Group. However my attention was caught by a wulfenite crystal in a cavity in dolomitic Permian limestone from the north end of Annesley Railway Tunnel, near Kirkby-in-Ashfield. The site was described by Tom Deans in the early 1960s and the specimen, as with many of the fine and interesting pieces illustrated in the book, is from the collection of Sir Arthur Russell. Iron mining was important in Northamptonshire until comparatively recently and my attention was caught by a short vignette which describes how 'Sundew', a giant dragline excavator, walked from Exton to Corby in the summer of 1974. This short aside is one of my favourite stories and includes a wonderful contemporary photo.

Oxfordshire, has an abundance of gypsum. A considerable number of specimens are figured and there is a fascinating account of the growth of crystals with a note on 'gypsum farming'. The speed at which crystals have been observed to grow is interesting, a well formed hand specimen may require just a few weeks. Slightly less savoury, though equally fascinating, are the vivianite nodules from the New Sewage Works at Cassington in the collection of the Oxford University Museum of Natural History. Anthropogenic vivianite is well known at such locations.

In Shropshire a return is made to vein minerals, which are found in the West Shropshire Mining Field. The quality, size and crystallographic variety of the primary minerals, particularly calcite, from Snailbeach Mine must be seen to be believed. This now rather forgotten mine has also produced excellent galena, harmotome and witherite. Many of the best examples are once again from the Russell Collection at the Natural History Museum. Nearby Wotherton Mine stands out for its baryte specimens which were brought to the attention of mineralogists by the dealer Samuel Henson. They include specimens from the collection of

the noted crystallographer Charles Otto Trechmann, also at the Natural History Museum. Contemporary collectors will appreciate an account of the minerals of Llynclys Quarry, where Carboniferous limestones have produced a variety of species including rich crystalline malachite on altered chalcopyrite. A beautiful crystalline malachite from Eardiston Mine in northeast Shropshire is one specimen that sets the pulse racing, as does the remarkable edingtonite collected by Allan Mortimer at Squilver Quarry in July 2004.

Mention Staffordshire to a mineralogist and thoughts immediately turn to Ecton Hill. A large specimen of scalenohedral calcite, covered in chalcopyrite crystals in the collection of John Cooke stands out as one of the most sculptural of the figured specimens in the whole book. Gypsum and anhydrite are the major minerals of economic interest; the story of Fauld Mine and the massive explosion in 1944 which produced a crater 250 m across and 35 m deep is told. A few specimens are figured from the formerly important coal and ironstone mines, but in common with many other Coal Measures sites in the British Isles (see the article by Richard Bateman and co-authors in this journal), relatively little has been preserved.

The same is true of Warwickshire's manganese mines, the story of which is told in detail. The best of the few specimens that have survived are in the Royal Cornwall Museum and the Oxford University Museum of Natural History. They are very well crystallised and it is surprising that so few were saved. Judkins Quarry is probably the best known contemporary mineral locality in Warwickshire; it produced a variety of species including bornite, calcite, chalcocite, chalcopyrite, galena, mottramite, sphalerite and vanadinite. The chalcopyrite pseudomorphs after acicular chalcocite, and mottramite specimens, are well known to collectors and three pages are given over to photos.

The West Midlands came into being in 1974 and is Britain's second most populous county. Although most collectors will be hard pressed to think of a single site, a considerable number of interesting specimens are figured. The prehnite and pectolite from Pouk Hill near Walsall are surprisingly good, though very few specimens survive. One of the top spots in my fantasy Midlands mineral collection is occupied by a remarkable yellow baryte from Dudley Port, originally in the collection of Dr John Percy (1817–1889). There is also a nice gallery of clay ironstone nodules, unloved but important specimens from the collection of Dudley Museum.

The last county in our alphabetic list, Worcestershire, is also the home of British Mineralogy Publications. The story of salt extraction in the area around Droitwich, and of salt magnate John Corbett, is fascinating. It is copiously illustrated with contemporary photos, production came to a poetic end in 1972 (page 345). Unfortunately, as in a number of such industries, very few actual specimens have survived. Agates are widespread in the Midlands, and they feature in about half of the chapters. Those from Marlbrook Quarry, a gravel pit near Bromsgrove, are particularly noteworthy. Beautifully banded in shades of pale blue and deep red, the quality of the better specimens must be seen to be believed. They fully deserve the three full pages of colour photos that have been allocated.

The final chapters of *Minerals of the English Midlands* are devoted to collectors and collections, mineral dealers and decorative stones. Thumbnail sketches of the lives and interests of important collectors with links to the Midlands are arranged in chronological order. Notes on the mineral collections at 28 important museums and institutions with Midland-related material are included. There are numerous mentions of dealers in the county chapters and eight pages are given over to the more important of these (ending with our very own Don Edwards). The final chapter gives just a flavour of the more important decorative stones from the English Midlands: alabaster, Ashford Black Marble and Blue John.

> In an epilogue, the author notes:
> "Collectors in the Midlands have been very fortunate to make many interesting and important discoveries over the past fifty years or so, recovering numerous specimens which Sir Arthur Russell would have been pleased to add to his collection".

A few are illustrated opposite the editorial in this issue of the journal.

Is *Minerals of the English Midlands* for your bookshelf? The paper and binding of my copy are excellent, the fonts are clear and legible and the images well reproduced. The writing is clear and succinct and the information supported by copious references. An index enables anyone with a research interest to look up a particular mineral, locality or personality. Analyses of cost per page and cost per photo will show that *Minerals of the English Midlands* represents good value for money. It is an essential volume for anyone with an interest in British mineralogy. My pulse rose more than once while writing this review and for that reason alone it gets a wholehearted recommendation.

David Green

"MOUNTAIN MOVERS: MINING, SUSTAINABILITY AND THE AGENTS OF CHANGE"

By Daniel M. Franks. Published in September 2015 by Routledge

194 pages. ISBN: 978-0-415-0415-71171-5 (paperback)

I start this review by emphasising what this book is NOT. It is not about mountains in the sense of topographically high and remote places where one would hike or climb; it's about the mining industry which 'moves mountains' to extract valuable commodities. Primarily it's about the people involved in and affected by this industry. It is not a light read; it is not a book that you can skim through, or browse the photographs (there are very few), or open at a random page to be enlightened. It is a serious, complex, deep book, global in scope and spanning a lifetime of experience at the cutting edge of conflict, corruption and policy development in the extractive industry. That said, the narrative is engrossing and enlivened by the author's first-hand accounts of visits to remote regions and his conversations with key actors and 'movers' in the mining and petroleum industries.

As Daniel Franks says early in the Preface, our society ('civilisation' if you wish) is incredibly reliant on the products of the mining and hydrocarbon extraction industries, yet we very readily blame industry for the environmental and social consequences of our own consumption. Franks confronted this paradox early in his life, and saw no contradiction in supporting Greenpeace and Friends of the Earth while he studied geology at university. Mining undoubtedly has a bad reputation as an asset-stripping, greedy and corrupt industry that has blighted countries that had the misfortune to be endowed with mineral resources. Franks' book is an account of the reform process which spread globally through the extractive industry starting in the 1990s as, under pressure from society and government, it began to embrace the concepts of sustainability and equitable development. Following the Preface and list of abbreviations, Franks provides an introduction to the Global Mining Initiative and the Mining, Minerals and Sustainable Development Project, in a chapter with the tongue-in-cheek title 'Breaking new ground'. Following this are chapters addressing human rights, damage to the environment, resource development, conflict and financial transparency. The final chapter on 'mountain movers' looks at the regulatory processes that have shaped reform and the interactions between the various agents of change.

A vital feature of the book is that we get to know the people who have initiated the reforms and overseen their implementation. Only someone immersed in the reformation process would have the insight, and transcripts of candid conversations, to write such an account. Frank's book is a tribute to "the dedication of a remarkably diverse range of mountain movers" and to the initiative and drive of those prepared to break the established mould. The most engrossing sections are narratives in which the author has been directly involved, such as the Esmeralda ship replica built by the consortium working the Collahuasi porphyry copper deposit in northern Chile. On the subject of 'blood diamonds' we are startled by supermodel Naomi Campbell's unexpected gift from Charles Taylor, then President of Liberia, of a pouch of rough diamonds. A gift that she wisely declined!

Daniel Franks is very much an expert witness to the transformation the mining industry has undergone since the 1990s. For example, he and Rachel Davis (then a legal advisor to the UN Secretary-General's Special representative on Business and Human Rights) interviewed 45 professionals in the industry to understand the costs of conflict with local communities and the ways that this problem was being approached. We learn of the surprising cost of conflict to the mining industry, with one estimate indicating that two-thirds of the market value of companies is a function of stakeholder engagement, and only one-third relates to the value of the gold (or other commodity) in the ground.

While overall Frank's book is well written and accurate, I have a few niggles about acronyms and abbreviations, of which there are many: the list occupies 3 pages. 'Washington Consensus' is referred to on page 71 but not explained and not included in the index. The abbreviation FSG appears on page 80 but not in the list of abbreviations. As well as the list of abbreviations, it might have helped to list the personnel mentioned in the book along with their affiliations and roles, as I found it difficult to keep track of who's who. The environmental impact of artisanal mining is covered briefly (pages 55–56), too briefly in my opinion and more could have been said about reform in the non-corporate mining sector. However, I congratulate the author on his detailed 'paper trail' of footnotes to each chapter. This is a valuable asset for anyone wishing to explore further any aspect covered in the book.

Although "many in the industry have been slow to recognise that the extraction of resources is as much a 'social project' as a technical one", nevertheless remarkable progress has been accomplished since the Global Mining Initiative was formulated 20 years ago. In conclusion, Franks reflects positively on these achievements while urging that there is still much to do. We look forward to a second edition that extends the narrative beyond the 2014 cut-off for publication of the first edition. A new edition could consider how the dramatic political developments of recent years and the shift away from the carbon economy have influenced the extractive industries in their pursuit of social and environmental accountability and a good governance 'ecosystem'.

Norman Moles

NOTES FOR CONTRIBUTORS

TYPESCRIPTS

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 and that all necessary permissions have been obtained and, where appropriate, acknowledged by the authors. Material accepted for publication should not be published elsewhere in the same form without the consent of the Editor. The submitted material should normally relate 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.

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, electron beam analysis). 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., or (Fig. 1), etc. Figures must have descriptive captions, and the scale must be indicated either on the photograph or by specifying the 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. 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-resolution electronic files will be required for publication.

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 official list of mineral names and formulae is regularly updated and available at: http://ima-cnmnc.nrm.se/imalist.htm.

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, 'n.d.' in tables must be defined (as 'not determined' or 'not detected'). The following abbreviations may be used without explanation: XRD = X-ray diffraction; XRF = X-ray fluorescence; EPMA = electron probe microanalysis; EDS = energy-dispersive X-ray spectrometry; WDS = wavelength-dispersive X-ray spectrometry; SEM = scanning 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)' or 'as stated in 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 should be cited in the text, thus: (Ann Brown, *personal communication*) or (Ann Brown, *personal communication*, 1992). 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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