Frongoch Mine

[SN 722 744]

Introduction

Frongoch (Figure 5.91) is one of the largest old mines in the Central Wales Orefield and is as important in mineralogical terms as it is historically. The mine worked lead-zinc-dominated mineralization belonging to the late (A2) group of assemblages of the Central Wales regional paragenesis (Mason, 1994, 1997; Green *et al.,* 1996), occurring along a major fracture system, the Frongoch Fault (Davies *et al.,* 1997). In addition to a number of interesting features revealed by the primary mineralization, Frongoch Mine is of particular note for its complex suite of secondary minerals, produced both by pervasive deep weathering of the mineralization *in situ* and also by post-mining geochemical processes operating within old mine tips. A number of extremely rare secondary minerals occur within this post-mining suite, including the second reported world occurrence of the new mineral bechererite, a complex zinc-copper basic sulphate-silicate (Green *et al.,* 1996; Rust *et al,* 2004), the rare zinc-bearing supergene mineral brianyoungite (Cotterell *et al.,* 2003), redgillite, and the new lead-bearing thiosulphate mineral steverustite (Cooper *et al., 2009).*

Frongoch Mine was a noteworthy site early in its history, being one of very few Central Wales mines to receive a mention by Greg and Lettsom (1858). At the time, it was merely known as 'a mine near Devil's Bridge', but the 'brilliant hair-brown' pyromorphite crystals, for which the mine was mentioned by Greg and Lettsom (1858), are diagnostic. Brown pyromorphite is rare in Britain compared to the commonplace green variety, and Frongoch is the only Welsh locality where it has been found in anything exceeding trace amounts. Thus, the site has long attracted amateur mineralogists seeking the occasionally fine pyromorphite (and cerussite) specimens.

In more-recent years, hard-core extraction operations have resulted in the excavation of the old dumps along and below the lode outcrop, revealing intensely altered sulphide-rich material. Within these deep excavations, many fine, albeit micro-crystalline, specimens of caledonite, susannite and a large variety of other rare supergene species have been recovered (Green *et al.,* 1996). Comprehensive suites of this material are preserved in the collections of the National Museum of Wales and the Natural History Museum.

Frongoch was known as a lead mine by the mid-18th century (Bick *et al.,* 1986), although production was relatively small until the 19th century, when the mine eventually became one of the greatest producers of lead and zinc in the Central Wales Orefield. The mine, as one of the Lisburne mines, controlled and . leased by the eponymous Lord, attracted several major 19th-century operators. Between 1825 and 1834, it was controlled by the Williams family of Scorrier, who were followed between 1834 and 1878 by John Taylor and Sons, who were extremely successful in their development and exploitation of the deposit, frequently producing in excess of 1500 tons of galena concentrates per annum, an impressive figure considering that a large number of Central Wales mines never exceeded this figure in their entire working life. In the period 1834 to 1903, sales of 50 669 tons of galena concentrates, yielding 38 071 tons of lead and 19 014 oz of silver, were recorded (Jones,1922). Galena was only desilvered intermittently, the yield never exceeding 5 oz per ton of lead ore (Burt *et al.,* 1986).

By the latter quarter of the 19th century, the increasing importance of zinc resulted in reworking of the walls of Taylors' lead stopes under the management of John Kitto; this, coupled with previous sphalerite production, resulted in a total of 50 856 tons of sphalerite concentrates being sold up to 1903. Subsequently, further tonnages of sphalerite and minor galena were recovered in an ambitious project which involved transporting the mine waste, by aerial ropeway, a distance of *c.* 2.5 km to a new mill which was installed on the banks of Afon Ystwyth. Further intermittent exploration, but without any major production, took place in both pre- and post-Second World War years: the last major venture involved the drilling of a deep borehole in 1971. Since then, many of the remaining tips have gradually been removed for hard-core, although remnant areas are still surprisingly rich in massive sphalerite.

Frongoch Mine is a Scheduled Ancient Monument on the basis of the fine collection of buildings, including a 19th century Cornish engine-house, which stood on the site. However, the chimney of the engine house collapsed in hurricane-force winds in late January 1990 and now little remains of the other buildings. Recently, spoil tips at Frongoch Mine have been relocated a short distance by the Countryside Council for Wales on conservation grounds (Figure 5.92).

Description

The Frongoch Fault, or Lode, is a major ENE–WSW-trending fracture cutting grey mudstones and turbiditic sandstones belonging to the Devil's Bridge Formation (Cave and Haim, 1986) of Llandovery age. Formerly (Jones, 1922), these strata were referred to as the 'Frongoch Formation', named after the mine. There are few good exposures of this structure, but at the eastern end of the mine, a large open-cut reveals stopes up to 5 m wide dipping away steeply to the south; some sphalerite remains in places along the poorly defined footwall. It was commented by Jones (1922) that most of the sphalerite tended to be associated with the foot-wall of the lode, while the galena-rich part of the lode took the form of two essentially parallel bands separated by a zone of barren ground. Jones (1922) also commented that the mine, which was eventually sunk to a depth of 142 fathoms (*c.* 260 m) below adit-level, still had considerable potential at depth, particularly for sphalerite.

The mineralization occurring along the Frongoch Lode belongs to the 'Late Simple' or A2 group of assemblages in the Central Wales Orefield paragenesis (Mason, 1994, 1997). At least five assemblages are present, although, due to later brittle deformation, original textures have been obscured to an extent. The sequence of primary mineral assemblages is:

1. coarse sphalerite overgrown by quartz overgrown by galena (A2-a assemblage)
2. chalcopyrite overgrown by ullmannite overgrown by galena in a silicic fault-gouge matrix (A2-b assemblage)
3. open-space growths of galena, fibrous sphalerite and quartz, overgrown by pyrite and marcasite plus quartz (?A2-c/f assemblages)
4. coarsely crystalline quartz containing dendritic sulphide inclusions and minor chalcopyrite (A2-d assemblage)
5. pervasive pyrite-marcasite net-veining with minor quartz (A2-f assemblage)

Of these, assemblage 1 is the most abundant, but has been re-brecciated severely in most samples and tends to consist of fragments of the constituent minerals in a 'muddy' sphalerite/ quartz matrix, this material commonly occurring in large blocks on the dumps. Assemblage 2 is relatively minor, and where unoxidized consists of < 5 mm spots of chalcopyrite, 2–4 mm twinned ullmannite cubes, and < 10 mm cubo-octahedra of galena in a quartz or silicic gouge matrix. The fibrous sphalerite of assemblage 3 is present as part-spheroids up to 10 cm in radius. The coarsely crystalline quartz of assemblage 4 is characteristic of this generation of Central Wales Orefield mineralization, with growth-zoned crystals, often with dark dendritic sulphide inclusions, exceptionally reaching 8 cm on edge. Pyrite-marcasite net-veining of earlier assemblages is relatively rare, in comparison to sites such as Cwmystwyth (see Cwmystwyth Mine GCR site report, this chapter), where it contaminated Pb-Zn ores to the extent that they were unsaleable in the worst cases.

The Frongoch Lode runs sub-parallel to the major, post-metallogenic Ystwyth Fault (Jones, 1922), which crops out *c.* 2 km to the south of the mine. The two structures dip toward one another and it is probable that, at great depth, the Frongoch Lode is 'faulted out' in an analogous situation to that affecting the Comet Lode at Cwmystwyth (see Cwmystwyth Mine GCR site report, this chapter). It also appears that some of the movements along the Ystwyth Fault affected the Frongoch structure, as large blocks of loose, uncemented crush-rock, consisting of cataclastic quartz and sulphides, are common on the dumps at Frongoch.

Secondary mineralization is most pervasively manifested in the tips along the outcrop of the lode, where the host grey shales have been deeply leached to yellowish and pinkish shades. Goethite and bright-red, earthy hematite commonly coat fracture surfaces in this leached mudrock, and are accompanied by abundant cerussite and locally by brown pyromorphite. Cerussite forms massive veins up to 2 cm in thickness, twinned crystals up to 3 cm, and has also been observed as reticulated 'snowflake' groups covering large hand specimens (Green *et al.,* 1996). It is sufficiently abundant that it was probably worked as a lead ore.

Pyromorphite, locally overgrown by cerussite, occurs most commonly as prismatic crystals with pinacoidal terminations which exceptionally reach up to 2.5 cm in length. Rarely, crystals show strong development of the hexagonal pyramid, and sub-parallel sheaves of acicular crystals have been recorded (Green *et al.,* 1996). Pyromorphite varies in colour from rare colourless crystals to the more usual brown and occasionally purple-brown; two specimens in the collection at the National Museum of Wales feature pyromorphite crystals which have thin green outer zones and brown cores. More characteristic (for the Central Wales Orefield) green micro-crystalline pyromorphite crusts, overgrowing cerrusite, also occur especially towards the western end of the sett near to the boundary with Wemyss Mine. The crusts occasionally feature small tabular crystals of vvulfenite, notably showing hopper structure in some specimens.

Associated with cerussite, where oxidation of galena is less pervasive, is a mineral belonging to the bindheimite group of lead-antimony oxides.

This occurs commonly as pale- to canary-yellow crusts, which are typically less than 1 mm thick but cover large areas of veinstone. It is often found in cavities in quartz containing relict masses of corroded galena, and additionally forms resinous cubic pseudomorphs after ullmannite.

Cerussite, pyromorphite and the bindheimite-group mineral, plus small amounts of malachite, aurichalcite, rosasite and hemimorphite, constitute the in-situ formed supergene assemblage. The remainder of the supergene minerals reported from Frongoch Mine belong to the post-mining, basic sulphate-dominated supergene suite. In this suite of minerals occur a number of assemblages whose mineralogy has been directly influenced by local geochemical conditions. Galena alters firstly to micro-crystalline anglesite, which occurs quite commonly as small (< 1.5 mm) transparent crystals, of a tabular or blocky morphology. Anglesite is commonly associated with secondary covellite, which forms thin micro-crystalline films on the galena, and occasionally with native sulphur, which occurs as yellow-green, rounded crystals up to 3 mm, with a typically resinous lustre. Galena is also replaced by cerussite, which is commonly black due to numerous relict galena inclusions, and very rarely contains small dendritic masses of native silver (Green *et al.,* 1996).

Further oxidation of the galena, particularly in the presence of minor chalcopyrite, has resulted in the development of what has been termed a 'Leadhills-type suite' of secondary minerals (see Green *et al.,* 1996). This assemblage comprises susannite (which is unusually common at Frongoch), linarite, caledonite, hydrocerussite, lanarkite and mattheddleite. Previous unconfirmed reports of leadhillite (Bevins, 1994) probably refer to susannite, the only mineral of the leadhillite-group confirmed by X-ray diffraction investigations (Green *et al.,* 1996). All of the species present occur as micro-crystals less than 2.5 mm across or smaller (in the case of mattheddleite). Susannite tends to form pseudohexagonal, tabular to blocky crystals varying from colourless to yellowish, brownish and bluish shades. Caledonite forms characteristic bright sky-blue sprays of acicular to prismatic crystals with well-developed terminations. The limited paragenetic information obtained from this suite indicates that the sequence linarite–susannite–caledonite–mattheddleite is typical; lanarkite is only known from two specimens (in the S.A. Rust private collection), while hydro-cerussite appears to occur in a number of positions in the paragenetic sequence.

Linarite is also present as a decomposition product of chalcopyrite, occurring as blue, bladed crystals up to 2 mm, and as fine-grained external coatings, with brochantite, on small sulphide fragments within deeper parts of the dumps. Recent analyses (Green *et al.,* 1996) have shown that some linarite specimens show significant substitution of selenium for sulphur, placing them within the linarite-schmiederite solid solution series. Recently, a new lead-bearing thiosulphate mineral, steverustite, has been described from the dumps at Frongoch Mine (Cooper *et al.,* 2009).

Within the assemblage produced by chalcopyrite decomposition, native copper is occasionally observed as dull, pointed crystals up to 1 mm, associated with cuprite, and superficially replaced by basic copper sulphates. These comprise langite, as euhedral pseudo-hexagonal and blocky, blue-green crystals up to 1 mm, and wroewolfeite, as blue-green, acicular to prismatic crystals up to 0.5 mm. The extremely rare mineral lautenthalite occurs very rarely as emerald-green, tabular to bladed crystals up to 0.7 mm, often forming epitaxial overgrowths on prismatic wroewolfeite. Both langite and wroewolfeite are replaced locally by brochantite. Associated with these copper sulphates is the 'undescribed mineral' recorded also from Esgairhir Mine (Rust and Mason, 1988) and Eaglebrook Mine (see Eaglebrook Mine GCR site report, this chapter), now determined to be the new mineral redgillite (Pluth *et ed.,* 2005). At Frongoch Mine, as at other localities, it forms minute groups of intense, light-green, divergent, lath-like crystals.

Given the amount of sphalerite occurring at Frongoch Mine, it is perhaps surprising that supergene zinc minerals are only superficially developed and, with the exception of minor amounts of hemimorphite, are largely confined to the post-mining suite. Most Central Wales Orefield sphalerites contain trace amounts of cadmium (Khan Kakar, 1971), and its presence at Frongoch is belied by the occurrence of an as yet undifferentiated cadmium sulphide, which is occasionally conspicuous on freshly broken, part-weathered sphalerite as typical canary-yellow coatings. Recently, however, the rare zinc-bearing supergene mineral brianyoungite related to hydrozincite, first described by Livingstone and Champness (1993) from Brownley Hill Mine in Cumbria, has been reported from Frongoch Mine, occurring as spherulitic aggregates of pearly white lath-like crystals up to 0.5 mm across (Cotterell *et al.,* 2003).

Post-mining hemimorphite occurs as individual grey-white botryoids and thin botryoidal crusts, often-overgrowing susannite, and is one of the latest minerals in this assemblage. Hydrozincite also occurs as part of the post-mining mineral assemblage, as crusts of white, lath-like crystals, which are commonly associated with hemimorphite.

Where sphalerite has oxidized in the presence of copper cations, a variety of minerals, some extremely rare, have formed. Namuwite occurs very rarely as pale blue-green, pseudohexagonal platy crystals and rosettes up to 0.5 mm. Ramsbeckite occurs rarely as typically emerald-green, pseudo-orthorhombic crystals up to 0.7 mm, on schulenbergite, which itself forms light blue-green rosettes of thin platy crystals up to 0.7 mm, and which are easily confused with namuwite. All three species may occur on altered sphalerite, or with the other post-mining species on quartz-dominated veinstone.

The newly described mineral bechererite (Geister and Rieck, 1996) occurs as morphologically striking but characteristic colourless to pale-green or ice-blue, inverted cone-like crystals. It is associated with namuwite, susannite, hemimorphite and corroded cerussite. The distinctive crystals exceptionally approach 1 mm in length but are usually, like the type material, no more than 0.25 mm in size. Frongoch Mine is one of a number of Central Wales Orefield localities where this mineral has been noted as a component of the post-mining supergene assemblage (Green *et al.,* 1996; Rust *et al.,* 2004).

Recent important discoveries include the second British occurrence of cesàrolite (Cotterell, 2007), and the first Welsh occurrences of corkite and himsdalite (Cotterell and Todhunter, 2007).

In such post-mining assemblages, highly local influences on geochemistry can produce particularly unusual minerals. Frongoch Mine is no exception to this general observation, and a small area of dump overlain by collapsed masonry, which was partly removed in the early 1990s, produced specimens of two minerals whose development appears to have been affected by the juxtaposition of lime mortar debris with sulphide-rich dump material. In this area, elyite was found rarely as minute, pale-violet masses of lath-like crystals in small cavities in galena with hydrocerussite and cerussite. Nearby blocks contained cerussite, which had been corroded, with the development of amorphous masses and equant octahedra of bright-red litharge up to 0.5 mm. Rarer, minute areas of a powdery yellow phase associated with the litharge have been tentatively identified as massicot (Green *et al.,* 1996).

Interpretation

The primary mineralization at Frongoch Mine is not unusual in the overall Central Wales Orefield context, having many features similar to that seen to better advantage at the Cwmystwyth Mine GCR site. However, the development of abundant, uncemented (and therefore post-mineralization) crush-rock, derived from the Pb-Zn-rich lode-filling, is of particular interest as it is strongly indicative of considerable tectonic activity along the Frongoch Fault, which is probably related to movement along the parallel and major tectonic lineament, the Ystwyth Fault. The fact that the Frongoch and Ystwyth faults dip towards one another would tend to preclude normal movements along both faults simultaneously, and it is possible that such severe cataclasis of part of the mineralization along the Frongoch Fault could have been caused by wrench movements along the Ystwyth Fault, which would be more likely to have caused concurrent movement at Frongoch. Curiously, however, there is little evidence for such severe mechanical deformation within the mineralized fractures at Cwmystwyth Mine, 7.5 km to the east of Frongoch Mine and in close proximity to the Ystvvyth Fault.

The secondary mineralization at Frongoch may be divided logically into pre- and post-mining assemblages. The pre-mining assemblage, occurring in considerable quantity and associated with severely leached mudstone wall-rocks, was probably formed over a protracted period of intense deep weathering (see Llechweddhelyg Mine GCR site report, this chapter; Mason, 2004), but is chiefly remarkable for the occurrence of brown pyromorphite. Few other occurrences of brown pyromorphite are documented in Britain, two notable examples being at the Barrow and Force Crag mines in Cumbria (Green *et al.,* 1997), specimens from the latter site strongly resembling those from Frongoch Mine. The reason for the colour is unknown: Green *et al.* (1996) commented on two similarities between the Force Crag and Frongoch pyromorphites, specifically that both occurrences are often developed on a siliceous matrix and that both orebodies carry abundant ferroan sphalerite.

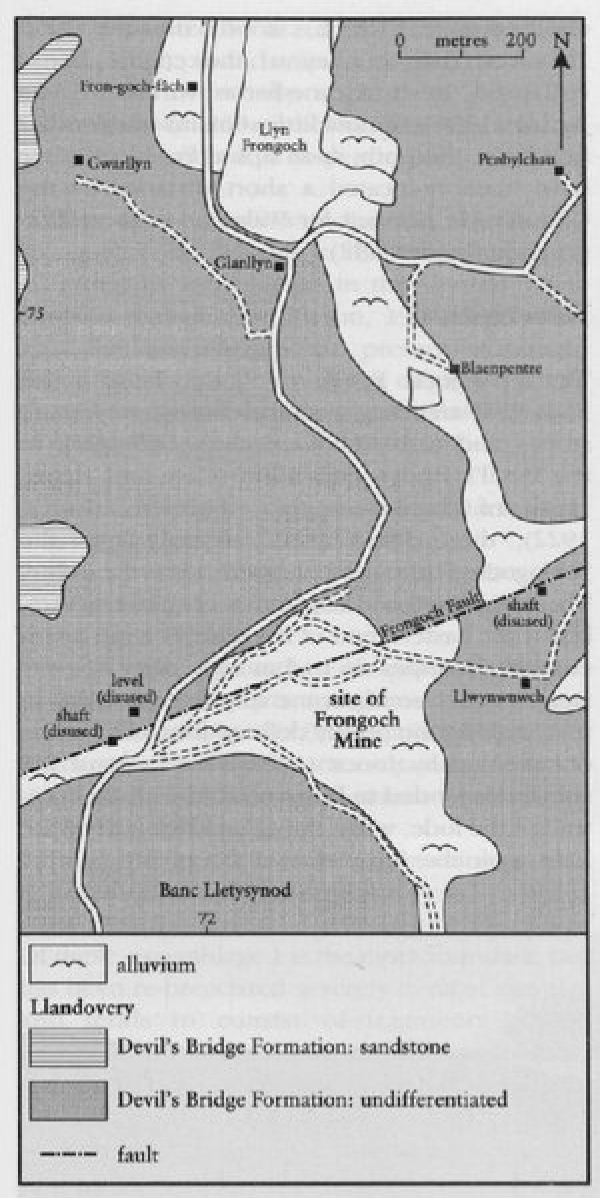
The origin of colour variation in pyromorphite is not entirely understood and cannot be explained merely by arsenate substitution for phosphate, or calcium substitution for lead, although in the latter case, greyish pyromorphites from Broken Hill, New South Wales, were shown by Inegbenebor *et al.* (1992) to contain enhanced levels of calcium. At Broken Hill, brown pyromorphites were commonly found by Inegbenebor *et al.* (1992) to be of near-phosphate end-member composition, a feature reflected by IR spectrography of Frongoch pyromorphite, which shows no arsenate present, regardless of whether it is green or brown (G. Ryback, pers. comm.). The colour variation of Frongoch pyromorphite remains, therefore, to be explained.

The post-mining supergene mineralization at Frongoch Mine is the result of removal of sulphide-rich rock from deep mine-workings and its transfer to the surface environment, where the sulphides are relatively unstable; as such, it is a partly anthropogenic process, although the weathering of such material to produce the post-mining assemblage is an entirely natural process. Mineral assemblages with an anthropogenic element in their origin have recently been the subject of controversy, a situation complicated by the fact that minerals such as susannite may occur in entirely natural, part- and wholly-anthropogenic situations. Thus, the 'Leadhills-type' mineral association present in the post-mining assemblage at Frongoch Mine, occurs *in situ* and in quantity at Leadhills (Livingstone and Sarp, 1984), in the Caldbeck Fells, Cumbria (Cooper and Stanley, 1990), and also in weathered slags (Green, 1987). Recently, it has been decided (Nickel, 1995) that supergene compounds occurring as a result of the weathering of metalliferous slags are not, strictly speaking, minerals, as they have formed by the weathering of a totally anthropogenic substance. At present, although fresh sulphide material brought to surface by mining activity has an anthropogenic component, compounds formed by its weathering are accepted as minerals. However, it is anticipated that the debate as to what constitutes a mineral will continue, perhaps citing sites such as Frongoch Mine.

Conclusions

Frongoch Mine is famous as one of the few localities in Great Britain where well-crystallized, brown pyromorphite, the coloration of which remains poorly understood, is well exposed. As well as the secondary mineralization which formed *in situ,* due to deep weathering of sulphides, there also exists an extensive suite of post-mining minerals, including some extremely rare mineral species, whose genesis and status are at present contentious.

References



(Figure 5.91) Map of the Frongoch Mine GCR site. After British Geological Survey 1:50 000 Sheet 178, Lianilar (1994).

(Figure 5.92) Photograph of re-located spoil at the Frongoch Mine GCR site. (Photo: R. Mathews.)