Mineralization of England and Wales

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Chapter 7

South-west England

R.F. Symes

INTRODUCTION

The most intensively mineralized region in the British Isles is the metallogenic province of South-west England. The area comprises the whole of Cornwall and much of western Devon, and as such was one of the great mining districts of the world. The region is often referred to as 'Cornubia', and is a peninsula roughly 200 km by 40 km in size. The topography of the peninsula is dominated by masses of granite topped by granite tors and associated rock debris, standing out above open moorland. The region is renowned for the former production of copper and tin; however, the mining province is polymetallic so that some 15 different metals have been extracted, along with barite and fluorite. Estimated production figures show that some 2.5 million tons of tin metal and 2 million tons of copper have been produced, together with major amounts of lead, arsenic and iron.

Mining in the region has an almost continuous history starting as far back as the Bronze Age. However, the heyday of the mining industry occurred within the 18th and 19th centuries, being aided by major engineering initiatives such as the development of steam-driven beam engines for mine pumping. During the 20th century the industry slowly declined, and with the recent closure of the South Crofty Mine, in 1998, the industry is now dormant.

Earlier published studies and unpublished GCR site reviews (L. Haynes, pers. comm.) provided the background to the choice of reference sites, shown on Figure 7.1. A very extensive literature exists related to the aspects of ore genesis, mineralization and mining history. Important overviews are provided by Alderton (1993), and Scrivener (2006). Details and images of the minerals present in South-west England are given in Embrey and Symes (1987).

Geological setting

The geological evolution of South-west England is primarily linked to a series of basins which developed in Devonian and Carboniferous times, and extended in an easterly direction for some 800 km, into the Rhenohercynian Zone in Germany. Sedimentation in the area was probably greatest in Devonian times, and the area was one of varying environmental conditions so that three main facies can be recognized. To the north lay the so-called 'Old Red Sandstone Continent' with sediments accumulating in fluviatile, lacustrine or deltaic environments. They consist mostly of poorly sorted sandstones and conglomerates, interbedded with marls and siltstones. The near-shore marine facies, farther to the south, consists of coarse-grained sandstones and shales with some bedded limestones, often coralline- or crinoid-rich. Deep-water sediments, which accumulated farther to the south again, now comprise shales and some limestones, containing corals and cephalopods. Adjacent to the northward-advancing Variscan Front, turbidity currents led to the accumulation of sandstones, sometimes associated with volcanic activity. The Carboniferous rocks of South-west England have long been known as the 'Culm Measures'. Detailed information on the sedimentary and tectonic evolution of these basins of sedimentation, which include (from south-west to north-east) the Gramscatho, Looe, South Devon, Tavy, Culm and North Devon basins, is provided in Durrance and Laming (1982, 1997), and Selwood *et al*. (1998). To the miners of South-west England all of these sedimentary rocks were known as 'killas'.

The Devonian and Carboniferous strata of South-west England were deformed during the Variscan Orogeny, which culminated in late Carboniferous times, when many basement faults were inverted and the basin-fill sediments were uplifted, which heralded a change in environmental conditions in Permian times. These fault movements were mostly completed before the emplacement in latest Carboniferous to earliest Permian times of five major granite bodies, which collectively comprise the Cornubian Batholith. This magmatic episode was associated with a major mineralizing event, spanning many tens of millions of years, and which was complex and multi-phase. The distribution of the granite bodies, coupled with the structures developed during the Variscan Orogeny, was to have a profound influence on the character and extent of that mineralizing episode, and controlled the distribution of the mineral lodes themselves.

Granites

The granites of South-west England extend from Dartmoor in Devon westwards through Cornwall, to the Isles of Scilly. The surface

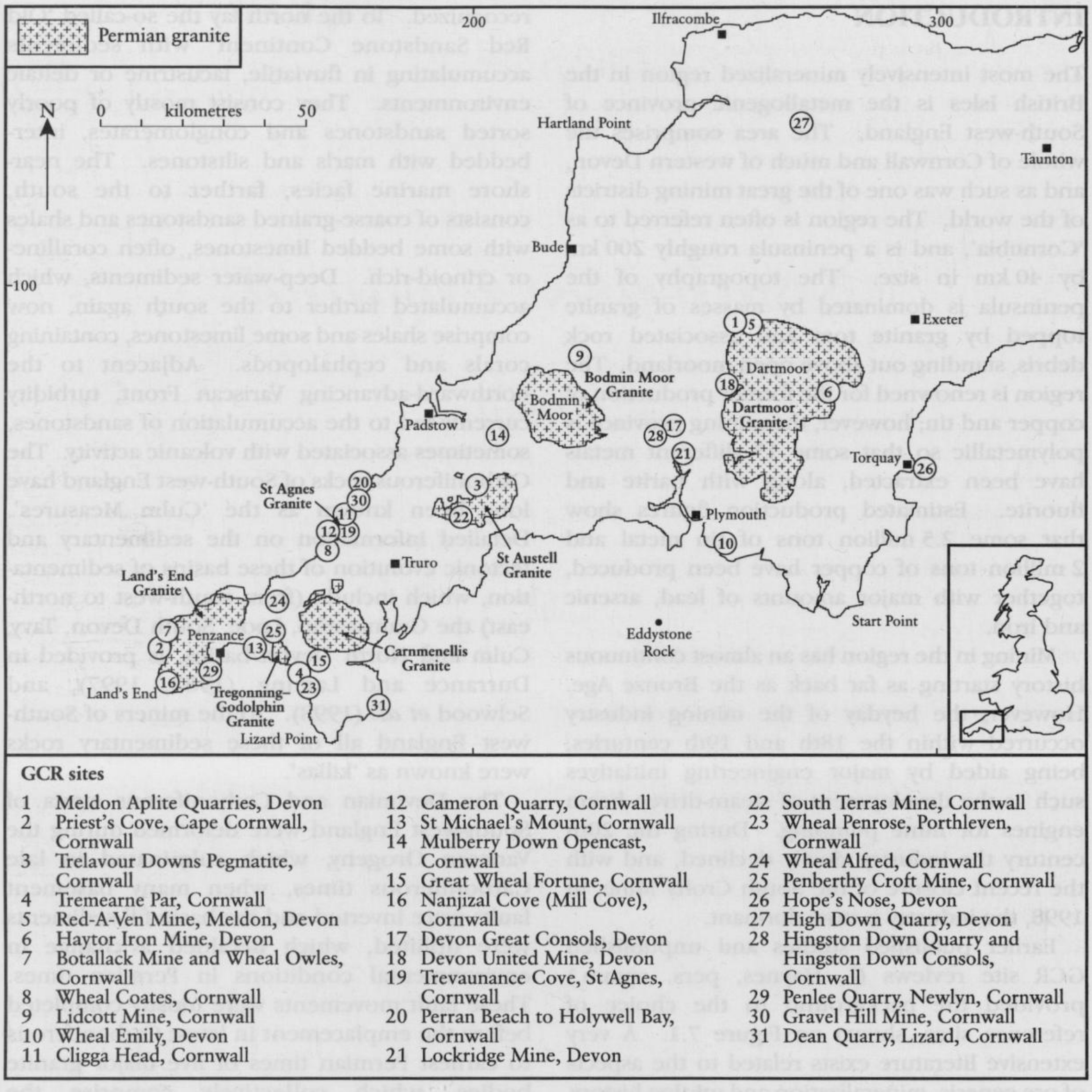


Figure 7.1 Map showing the locations of the GCR sites in South-west England.

expressions of the granites in Cornwall are the Land's End, Tregonning–Godolphin, Carnmenellis, St Austell and Bodmin Moor plutons. The different intrusions are connected at depth, as demonstrated by geophysical evidence and also the occurrence of minor cusps of granite between, and close to, the major bodies. All the granites have well-developed contact metamorphic aureoles. The granites are noted for their high contents of radioactive elements, in particular Th and U. The economic importance of these rocks goes beyond their use as building stone, especially to their association with the metalliferous and non-metalliferous mineral deposits.

Several different varieties of granite have been determined, and are classified on the basis of petrographic and geochemical characteristics. A much simpler classification is based on the key contrasting petrogenetic elements, identifying three major types, namely: (1) biotite granites; (2) tourmaline-rich granites; and (3) topaz granites. Further studies of compositional variations have been made utilizing geochemical means, which has led to a classification based on major- and minor-element concentrations, especially of the volatile elements F, B and Li. A series of the main granitic types has been defined, as shown in Figure 7.2.

The origin of the biotite granites which dominate the Cornubian Batholith is generally thought to be due to partial melting of lower crustal metapelites (see Stone 1975, 1984; Stone and Exley, 1986), but there may well be a mantle contribution. Once generated, the magma became enriched in H_2O, Li and B as it crystallized, leading to a hydrous mineral assemblage and Li-mica and tourmaline granites. The biotite granites and varied tourmaline granites are usually seen as a cogenetic suite, although the origin of the topaz granites is still not clear. The possibility of a further episode of lower crustal melting has been proposed (Stone, 1992). Manning and Hill (1990) suggested that a residual S-type granite source was involved in a second episode of partial melting. Isotopic dating techniques (Rb-Sr and U-Pb) give relatively consistent results in the range 300–250 Ma, which suggest that the main stage of granite magmatism was between 290 Ma and 270 Ma (see Darbyshire and Shepherd, 1985; Chen *et al.*, 1993; Chesley *et al.*, 1993). The variations in mineralogy and texture of the granites are represented in this volume by the **Meldon Aplite Quarries**, **Priest's Cove**, **Trelavour Downs Pegmatite** and **Tremearne Par** GCR sites.

The granites have contact thermal aureoles, although their mineralogy is relatively restricted because of the rather monotonous siliceous nature of the country rocks. However, where calcareous rocks are present in the vicinity of the granites, interesting assemblages are developed. The development of skarns at the **Red-a-Ven Mine** GCR site at Meldon, on the northern margin of the Dartmoor Granite, has led to the formation of the rare tin silicate mineral malayaite, while the bedded copper deposits found at the Belstone Consols and Ramsley mines also lie on the northern margin of the Dartmoor Granite. South-west of Bovey Tracey, at the **Haytor Iron Mine** GCR site, magnetite was worked in stratiform deposits from thermally metamorphosed sandstones and shales. Good examples also occur within the sedimentary and greenstone rocks of the **Botallack Mine and Wheal Owles** GCR site area. At this locality, shales, pyroclastics and lavas have been replaced by skarn assemblages of garnet-magnetite-axinite containing tin- and copper-bearing minerals. At Grylls Bunny, near Botallack, such skarns have been invaded later by boron-bearing fluids to produce a series of 'floors' (flat-lying sheets) of quartz-tourmaline rock carrying some cassiterite.

Pegmatites and aplites typically occur as late-magmatic features of granitic rocks, and are exceptionally well-developed in South-west England. The pegmatites are rich in coarse-grained quartz, feldspar and mica. Most of these pegmatites comprise assemblages of K-feldspar, quartz and tourmaline, although albite is some-

Type	Variety	Pl:Or	Plagioclase type (vol%)	Micas	Accessories[a]	Occurrence
A	basic microgranite	Pl > Or	Olig – And (amount varies)	Bi >> Musc	Hb	as inclusions in B
B	coarse-grained megacrystic biotite granite	Or > Pl	cores An 25–30 (22%) rims An 8–15	Bi > Musc	T	dominant variety
C	fine-grained biotite granite	Or > Pl	An 10–15 (26%)	Musc > Bi	T	dykes, etc., cutting B
D	megacrystic Li-mica granite	Or = Pl	An 7 (26%)	Zinn	T	modified or transitional into B (only St Austell)
E	aphyric Li-mica granite	Pl > Or	An 0–4 (32%)	Zinn	T, To, Ap, Fl	cuts B, C, D (St Austell, Tregonning–Godolphin)
F	fluorite granite	Pl > Or	An 4 (34%)	Musc	Fl, To	alteration of E? (St Austell)
G	aphyric Li-mica leucogranite	Pl >> Or	An 0 (?)	Lep	T, To	roof differentiate (St Austell, Tregonning–Godolphin)

Pl:Or plagioclase:K-feldspar ratio.
[a]Accessories only listed if volume is 1% or greater.
Ap apatite; Bi biotite; Fl fluorite; Hb hornblende; Lep lepidolite; Musc muscovite; T tourmaline; To topaz; Zinn zinnwaldite.

Figure 7.2 Main granite types of South-west England. Based on Exley (1983), Stone *et al.* (1988), and Alderton (1993).

times present. Such a variety of coarse-grained granitic rocks can be seen at the contacts with country rocks ('killas') as at Megilligar Rocks, at the **Tremearne Par** GCR site. Usually poor in cassiterite and wolframite, such rocks often contain a minor assemblage of interesting accessory minerals. At Megilligar Rocks triplite and a range of phosphate minerals have been formed (George *et al.*, 1981). Similarly a range of minor accessory minerals have formed within the Meldon Aplite, exposed at the **Meldon Aplite Quarries** GCR site (Kingsbury, 1970).

Fine-grained quartz-feldspar porphyry intrusions (usually dykes but sometimes sills and typically associated with the granites), so-called 'elvans', are another important feature of the orefield, often being intimately associated with the mineralization, for example at the Wherry Mine, near Penzance (Russell, 1949). The elvans generally follow the same trend as the mineralized lodes, and in some cases can be seen to have controlled the distribution of the mineralizing fluids, as for example at the **Wheal Coates** GCR site. The elvans are texturally recognizable by the presence of quartz and feldspar phenocrysts set within a fine-grained rhyolitic groundmass. The dykes (or sills) usually have chilled margins against country rocks and may be of considerable width (up to 50 m in thickness) and length, and often cross-cut the major coarse-grained granite varieties. They are important to the understanding of the origin of the orefield, and acted as leaders to the miners. They may represent feeders for subaerial volcanism of dacite-rhyolite-type, and also spatially and genetically may be associated with intrusive breccias (Goode, 1973). Limited available age data seem to agree with field observations that the elvans were amongst the last of the magmatic rocks to be emplaced (Hawkes *et al.*, 1975).

Dykes, sills and bosses of altered basic igneous rocks, chiefly dolerites, the so-called 'greenstones', intrude the Devonian and Lower Carboniferous rocks of both Cornwall and Devon. On the coast, where the best exposures are found, the dolerites are sometimes associated with pillow lavas, and because of the hardness of the rocks form conspicuous headlands, such as Trevose and Botallack Head. These rocks are often worked in large aggregate/ballast quarries, such as at Meldon. The dolerites in Meldon (BR) Quarry have been dated at 296 ± 12 Ma. However, examples can be seen which pre-date the major phases of folding whilst others post-date the folding. Some mineralization in South-west England has been linked to contemporary volcanism, such as the **Lidcott Mine** GCR site, and the epithermal mineralization at the **Wheal Emily** GCR site.

Mineralization

The South-west England orefield is spatially associated with the intrusion of the high-heat-production (HHP) granitic Cornubian Batholith, intruded into the Upper Palaeozoic (essentially Devonian and Carboniferous) shale–sandstone sequence at about 280 ± 10 Ma (Darbyshire and Shepherd, 1985). Mineralization appears to have been a multi-stage process, possibly spanning the period 280 Ma to 255 Ma, beginning with early greisen development, followed by the main-stage event. It is believed that magmatic, hydrothermal and tectonic processes were all operative during the main-stage event and that mineralization was focused in the roof zone and at the margins of high-level plutons. Deep, extensional fractures allowed for the release of magmas which generated the K-rich feldspar porphyry dykes and also metalliferous magmatic fluids. The main-stage events gave rise to vein lodes containing tin and tungsten mineralization and copper-arsenic-iron, sometimes in a zonal configuration. Following the main-stage event there was further radiogenically driven hydrothermal convection throughout Mesozoic and Tertiary times. Leaching of the killas and the then consolidated granite within convection cells provided metalliferous fluids which precipitated in essentially N–S-trending faults, the so-called 'cross-courses'. Some lead mineralization is also thought to have been derived from brines expelled from adjacent Mesozoic sedimentary basins.

Formation of greisen-bordered vein structures is an important feature of the Cornubian Batholith, and may be the earliest and highest-temperature (< 400°C) assemblages of the main mineralization episode. Alteration of granite to a greisen assemblage of quartz, white mica and in places topaz is a common feature. These are often found at the marginal and apical parts of smaller granite plutons. The greisen alteration commonly encloses small veins of quartz with cassiterite and/or wolframite and minor sulphides. Examples are seen at the **Cligga Head**, **Cameron Quarry** and **St Michael's Mount**

GCR sites. At several localities greisen-bordered veins form sheeted complexes within granite, many of the veins being so closely spaced that the pervasive alteration has left no fresh granite. These often form large low-grade ore deposits worked in open pits, as at the **Mulberry Down Opencast** and **Great Wheal Fortune** GCR sites.

The formation of Fe-rich tourmaline (schorl) is a widespread and distinctive feature of the Cornubian Batholith granites, occurring as small veins, grains or rafts (large masses). The latter development is especially associated with late-stage pegmatites, as at Porth Ledden, Cape Cornwall. Tourmaline veining is very common in and around the granites, and mineralized veins are often associated with tourmalinization of the wall-rocks. Cassiterite is a minor constituent of the Wheal Remfry breccia, and is a feature of such intrusive tourmaline breccias elsewhere in Cornwall. Tourmalinization is well seen at the **Nanjizal Cove** and **Priest's Cove** GCR sites.

In South-west England faulting has played a major part in determining the pattern of lode development of the main-stage mineralization event, veins often being related to normal faults. This pattern, providing channels for hydrothermal mineralizing fluids, developed during folding of the country rocks during the Variscan Orogeny, and subsequently during intrusion and cooling of the Cornubian Batholith granites.

The most important economic concentrations of Sn-W, Cu and As occur in the hydrothermal veins, which are somewhat later than the greisen-dominated systems. There is usually evidence of a protracted history of vein formation, with episodes of fracturing, brecciation and mineralization, while phases of deuteric activity were widespread within the Cornubian Batholith, causing alteration to wall-rocks and veins, and leading to phases of sericitization, hematization and tourmalinization. The general paragenetic sequence of ore minerals in South-west England is shown in Figure 7.3.

The lodes are generally narrow structures but can vary considerably in width. They are commonly near-vertical or steeply dipping, although some important lodes have a more gentle dip, for instance the Great Flat Lode, Camborne, has an average dip of 40°. In general the regional strike is ENE–WSW-trending, changing to east–west in east Cornwall and Devon. The mines of the **Devon Great Consols** GCR site worked the largest main-stage sulphide lode in the region, being proven for almost 4 km and varying from 2 m to 10 m in width. The lodes are not uniformly rich in metallic ores, and their content varies considerably both laterally and in depth. In general they tend to be richest at changes of strike, at vein intersections, and in the steeper sections of lodes. Often the contacts with host rocks are not clear. Mineralized fault-breccias are often formed. The nature of some veins from Cornwall is shown in Figure 7.4. Main-stage copper-arsenic mineralization is well seen at the **Devon United Mine** GCR site.

Early workers recorded that the tin and copper mineralization in South-west England tended to occur closer to the granite than the other metals. Davey (1925), and Dines (1934) proposed models in which fluids migrated outwards from emanative centres in the granites to produce the classical interpretation of lateral and vertical zoning of the ores and gangue minerals. The metals formed into a series of roughly concentric zones around the granite bosses, as seen for example at the **Wheal Coates** GCR site, while at the **Trevaunance Cove** GCR site the relationship between N-dipping tin lodes and S-dipping copper lodes is exposed. However, it is now realised that this scheme is too simplified for the whole orefield, although it is still seen as a classic early interpretation.

In Cornwall in particular there was an episode of post-granite polymetallic (Pb-Zn-Ag-fluorite) mineralization occurring in N–S-trending cross-course veins, excellent examples of lead-bearing veins being well-exposed at the **Perran Beach to Holywell Bay** GCR site. Cross-course veins at the **Lockridge Mine** GCR site were renowned for their silver contents. Such veins at the **South Terras Mine** GCR site are of special interest for their contents of U, Co and Ni, while the **Devon United Mine** veins contain high contents of Cu and As. These developed in a period of crustal extension, the north–south regional fractures providing excellent conduits for the circulation of the metal-rich fluids. Often the vein infill is associated with a complex history of fracturing, brecciation and mineralization. Fluid-inclusion temperatures generally fall in the range 80°–180°C. Recent research seems to indicate that the N–S-trending veins owe their origin to metalliferous brines derived from sedimentary basins, as determined by Gleeson *et al.* (2000) at the **Wheal Penrose** GCR site.

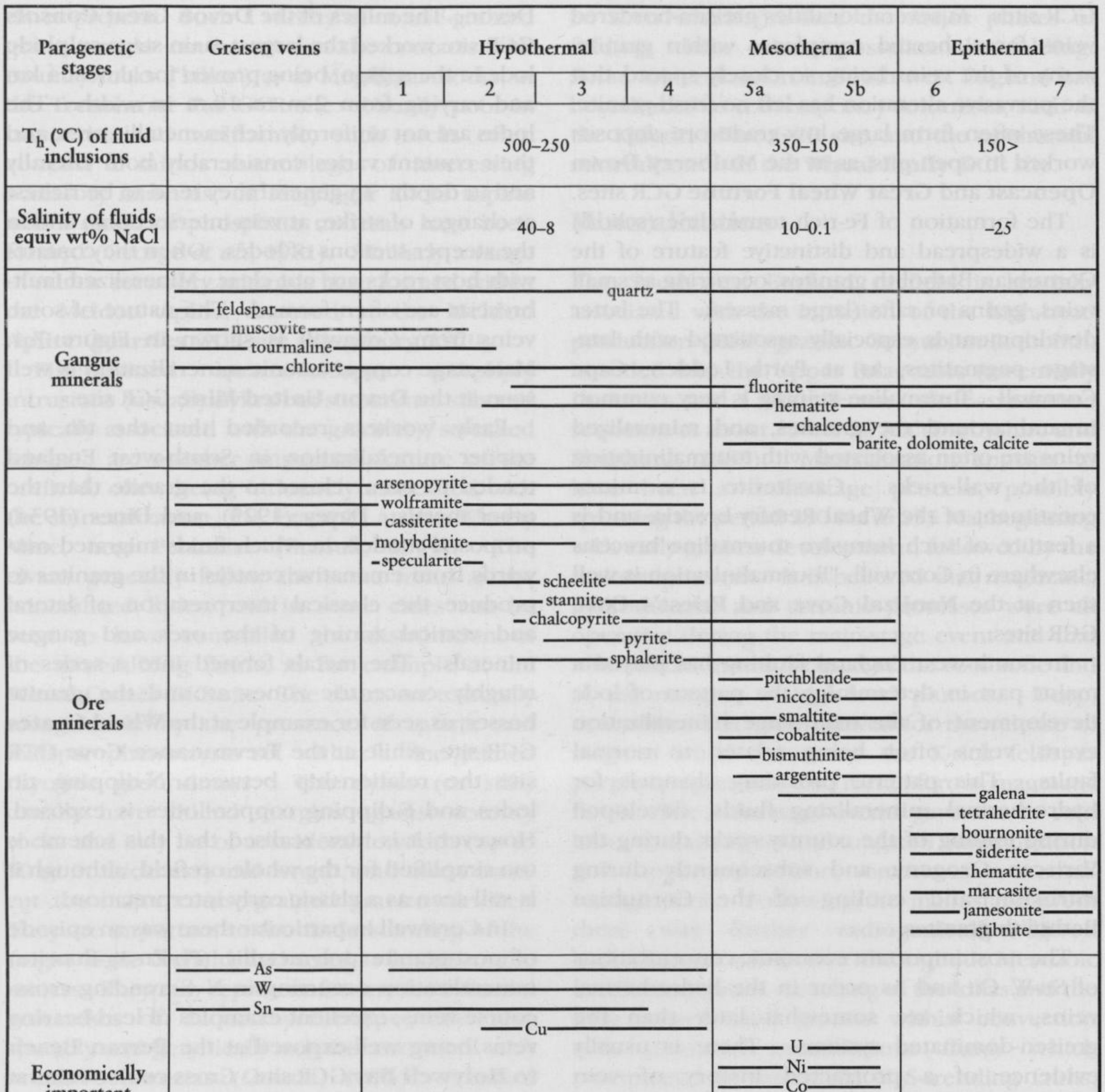


Figure 7.3 **General paragenetic sequence of ore minerals in South-west England. Based on Hosking (1964), Edmonds *et al.* (1975), and Stone and Exley (1986).**

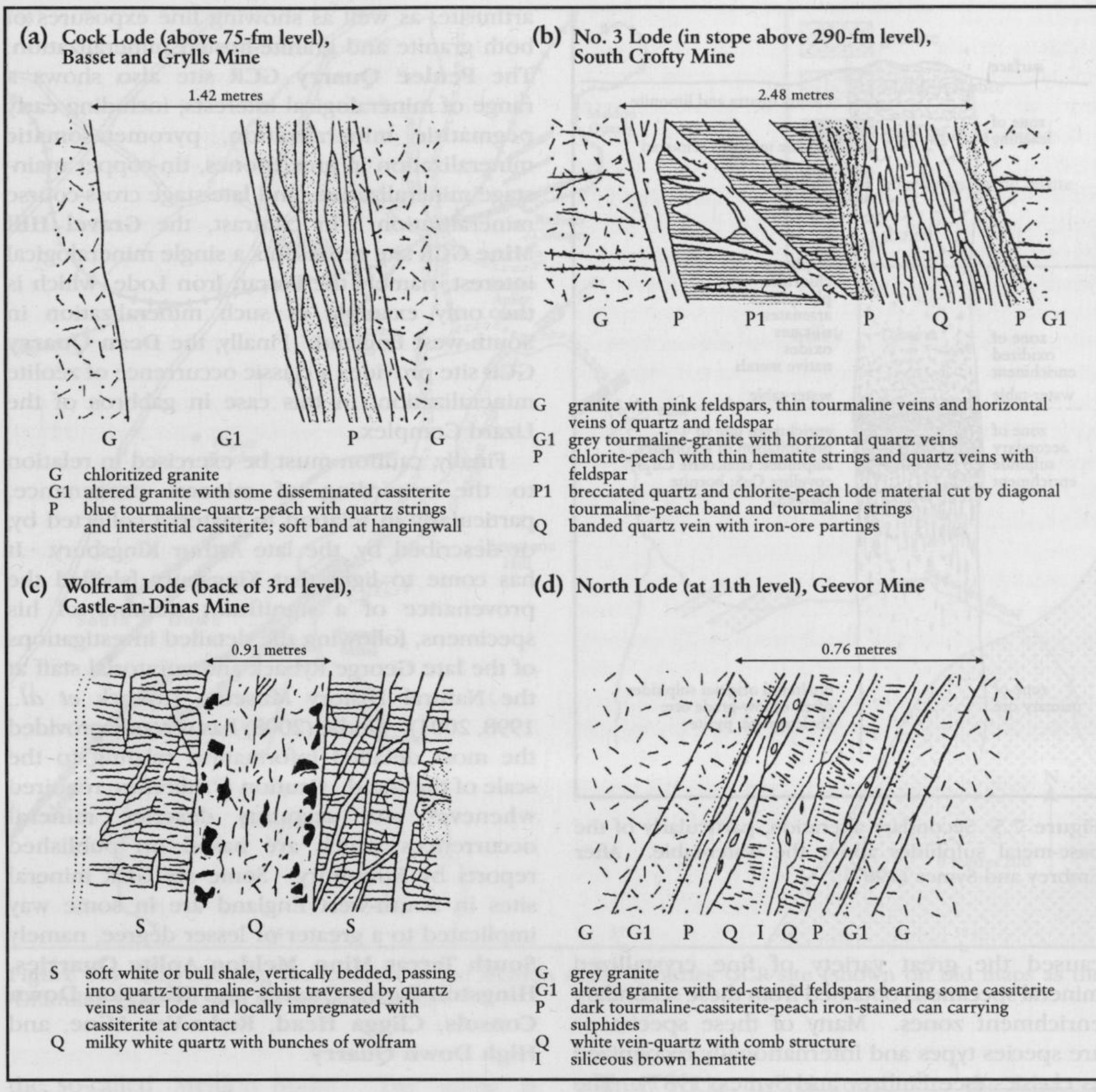


Figure 7.4 Some variations of composite 'normal' lodes in Cornwall. Based on Edmonds *et al.* (1975), and Dines (1956).

Secondary alteration, particularly of the base-metal sulphides above the water-table (see Figure 7.5), was extensive throughout the ore-field region. With only a few exceptions, however, these zones of leaching and enrichment (oxidation and reduction) have been removed by erosion or worked out by mining activities. Famous secondary enrichment deposits were found associated with the Wheal Gorland–Wheal Unity mining area, and many fine mineral specimens have been collected.

The changes took place by the action of downward-percolating surface waters, causing leaching of the primary ore and the formation of iron oxide gossans close to surface. Soluble sulphide minerals, such as chalcopyrite, were leached, the metals transported and re-deposited as oxides or sulphides in the zone of secondary enrichment below the water-table, and chlorides, sulphates, arsenates and phosphates above. It is these low-temperature supergene processes in the South-west England orefield that have

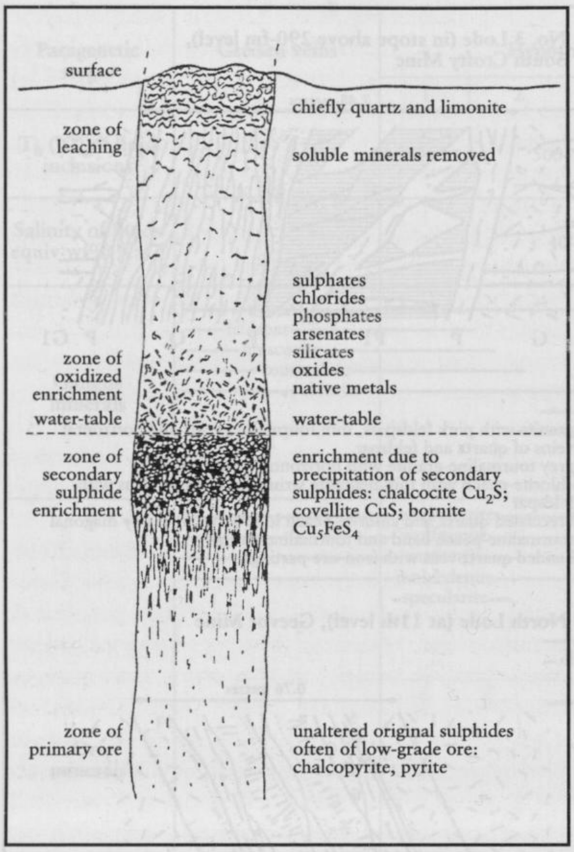


Figure 7.5 Secondary alteration, particularly of the base-metal sulphides above the water-table. After Embrey and Symes (1987).

caused the great variety of fine crystallized mineral specimens obtained from these secondary enrichment zones. Many of these specimens are species types and internationally recognized as classics (see Embrey and Symes, 1987). The finest pyromorphites from South-west England are from the **Wheal Alfred** GCR site, while the **Penberthy Croft Mine** GCR site is renowned for the extreme variety of minerals, especially of supergene origin.

A small number of sites do not fall within the overall network established for South-west England, in view of their uniqueness. The **Hope's Nose** GCR site is unique in the British Isles for its gold-palladium and selenide mineralization, hosted by limestones of Devonian age. The site is also important as the type locality for the very rare mineral chrisstanleyite. The **High Down Quarry** GCR site is the type locality for wavellite, while the **Hingston Down Quarry and Hingston Down Consols** GCR site is the type locality for arthurite, as well as showing fine exposures of both granite and granite-hosted mineralization. The **Penlee Quarry** GCR site also shows a range of mineralogical interests, including early pegmatitic mineralization, pyrometasomatic mineralization in greenstones, tin-copper main-stage mineralization, and late-stage cross-course mineralization. In contrast, the **Gravel Hill Mine** GCR site represents a single mineralogical interest, namely the Perran Iron Lode, which is the only example of such mineralization in South-west England. Finally, the **Dean Quarry** GCR site provides a classic occurrence of zeolite mineralization, in this case in gabbros of the Lizard Complex.

Finally, caution must be exercised in relation to the recording of mineral provenance, particularly in relation to material collected by, or described by, the late Arthur Kingsbury. It has come to light that Kingsbury falsified the provenance of a significant number of his specimens, following the detailed investigations of the late George Ryback and curatorial staff at the Natural History Museum (Ryback *et al.*, 1998, 2001). Tindle (2008) has recently provided the most detailed information relating to the scale of the fraud. Caution is therefore required whenever site accounts describe mineral occurrences which are based on published reports by Kingsbury. Some six GCR mineral sites in South-west England are in some way implicated to a greater or lesser degree, namely **South Terras Mine**, **Meldon Aplite Quarries**, **Hingston Down Quarry and Hingston Down Consols**, **Cligga Head**, **Red-a-Ven Mine**, and **High Down Quarry**.

MELDON APLITE QUARRIES, DEVON (SX 567 920)

Introduction

The Meldon Aplite intrudes Lower Carboniferous rocks on the north-west flank of Dartmoor. It contains a diverse range of accessory minerals including petalite, topaz, fluorite, bavenite, pollucite, spodumene and a variety of beryllium minerals.

The Meldon Aplite Quarries GCR site (originally known as the 'Graunulite Quarry') comprises two adjoining quarries, one each side of the Red-a-Ven Brook (host to the **Red-a-Ven Mine** GCR site) (see Figure 7.6), which worked

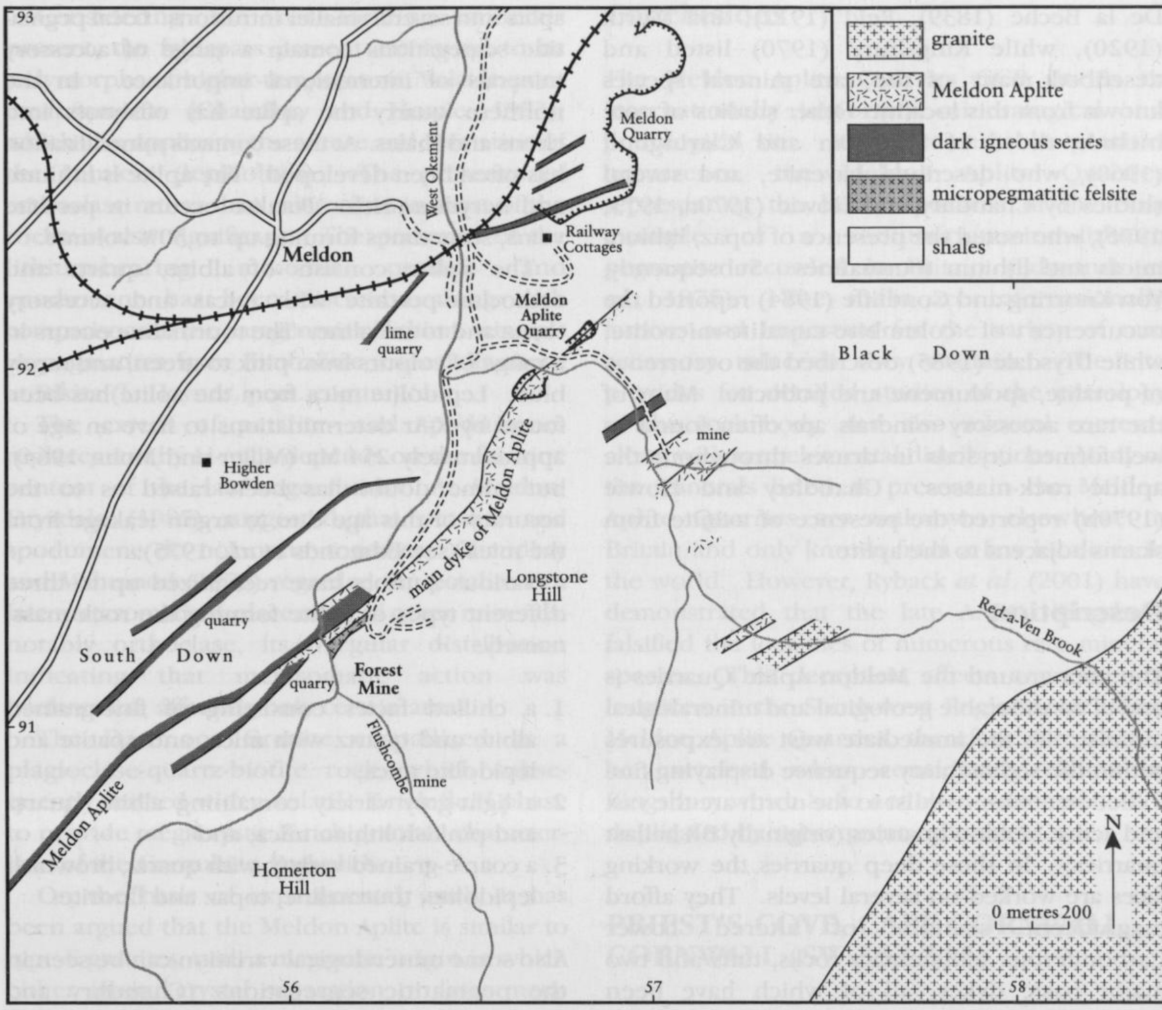


Figure 7.6 Map showing the location of the Meldon Aplite Quarries GCR site (shown on old maps as the 'Granulite Quarry'), and the Meldon Aplite.

the so-called 'Meldon Aplite'. The 'aplite' is essentially a dyke, some 3.5 km in length and up to 20 m wide, of mineralogically banded, medium- to fine-grained granite with some localized pegmatitic segregations. This dyke appears to be unique to South-west England, and is an unusual lepidolite-soda microgranite which has been intruded into tuffs and sedimentary rocks of Lower Carboniferous age. These comprise the Meldon Chert Formation (principally shales and impure limestones), as well as rocks of the older Meldon Shales and Quartzite Formation, which includes volcanic agglomerates and tuffs. These rocks have been much folded, faulted and overturned before intrusion of the granite, which has also metamorphosed them. The sequence now dips steeply to the north-west. As the Meldon Aplite intrudes metamorphosed country rocks, its relationship to the adjacent Dartmoor Granite is problematical, especially as it is richer in plagioclase feldspar and contains Li-micas, typical of E-type granites of Exley *et al*. (1983), which are otherwise unknown in the Dartmoor Granite. Of great mineralogical importance is the diverse array of accessory minerals and abundant topaz and fluorite associated with the aplite. The aplite shows an appreciable enrichment in Rb, Cs, F, B, Be and Nb, interestingly with almost no trace of Sn, W or sulphide mineralization. This directly contrasts with the St Austell Granite where this pattern of element enrichment is clearly related to mineralizing events.

The geological literature on the Meldon Aplite Quarries GCR site chiefly considers mineralogical aspects of the site. The aplite was mentioned by

De la Beche (1839), Reid (1912), and Worth (1920), while Kingsbury (1970) listed and described many of the rare mineral species known from this locality. Other studies of note include those of Dearman and Claringbull (1960), who described bavenite, and several studies by Chaudhry and Howie (1970a, 1973, 1976), who noted the presence of topaz, lithium micas and lithium tourmalines. Subsequently, Von Knorring and Condliffe (1984) reported the occurrence of columbite-tantalite-microlite, while Drysdale (1985) described the occurrence of petalite, spodumene and pollucite. Many of the rare accessory minerals are often found as well-formed crystals in druses throughout the aplitic rock-masses. Chaudhry and Howie (1970b) reported the presence of axinite from skarns adjacent to the aplite.

Description

The area around the Meldon Aplite Quarries is one of considerable geological and mineralogical interest. To the immediate west are exposures within the sedimentary sequence displaying fine folded structures, whilst to the north are the vast and active Meldon quarries (originally BR ballast quarries). In these deep quarries the working faces are worked on several levels. They afford magnificent sections of altered Lower Carboniferous sedimentary rocks, tuffs and two major basic dykes, all of which have been thermally and metasomatically altered by the Dartmoor Granite. The Meldon (British Rail) quarries are important mineralogically for the range of calcium and skarn manganese silicate minerals present. To the east of the Meldon Aplite Quarries, and closer to the Dartmoor Granite, are the mineral workings of the Red-a-Ven Mine (described in the **Red-a-Ven Mine** GCR site report, this chapter). It is believed that the aplite can be traced as a body for some 3.5 km from Sourton Tors to the main Meldon Quarries.

The aplite is a white to pale-grey, fine-grained, holocrystalline rock, but patches and lenses of pegmatite (some coarse-grained) occur within the body. In many places it is altered by the introduction of late-stage minerals. It also contains xenoliths of country rock, but these are also altered.

In the southern quarry, the aplite, which is in contact with hornfelsed shales and tuffs, is about 20 m thick. In the upper levels of the quarry it splits into several smaller intrusions. Local pegmatitic segregations contain a range of accessory minerals of international importance. In the northern quarry the aplite has offshoots into cherts and shales. At these contacts mineralization has often been developed. The aplite is lithium- and beryllium-rich. Petalite occurs in perthite veins, sometimes forming up to 30% volume.

The aplite consists of albite, quartz and orthoclase-perthite with micas and accessory topaz and tourmaline. The tourmaline occurs in a range of colours from pink to green, and rarely blue. Lepidolite mica from the aplite has been found by K-Ar determinations to have an age of approximately 254 Ma (Miller and Mohr, 1964), but some doubt has been raised as to the accuracy of this age due to argon leakage from the mica (see Edmonds *et al.*, 1975).

Various authors have recognized up to three different types of aplite forming the rock mass, namely:

1. a chilled facies consisting of fine-grained albite and quartz with mica, and apatite and lepidolite mica;
2. a light-grey variety containing albite, quartz and pinkish lithian mica; and
3. a coarse-grained variety, with quartz, brownish lepidolite, tourmaline, topaz and fluorite.

Also some mineralogical variation can be seen in the pegmatitic segregations (Chaudhry and Howie, 1973).

Where the aplite veins pass into the country rocks, the borosilicate minerals axinite and datolite are sometimes abundant. Many of the joints in the aplite are lined by a coating of blue fluorite. From some of the pegmatitic areas native arsenic and löllingite have been recorded.

Interpretation

The Meldon Aplite appears to be unique in Britain. A large number of factors need to be taken into account to provide a model for its genesis. In interpreting its formation it is necessary to account for the overall fine grain-size and its unusual composition when compared with granite differentiates elsewhere in Britain, and also in comparison to other Variscan granites in South-west England. Other aplites and pegmatites do occur in the area, but discussion has mostly centred on comparisons with the crystallization of the quartz porphyry ('elvan') dykes.

Considering the rock-forming minerals present, the feldspars present are found to be polymorphs of higher-temperature, volatile-poor environments (Chaudhry and Howie, 1973), which also applies to the nature and formation of the Li-micas (lepidolites). The presence of orthoclase rather than microcline in most of the rocks is also significant. The presence of the lithium-bearing minerals petalite and spodumene has been discussed along with comparisons to the paragenesis of lithium minerals in pegmatites from Zimbabwe, especially those at Bikita (L. Haynes, pers. comm.).

The extent of petalite- and spodumene-replacement by Li-mica depends on the fluorine content of the late-stage fluids. At Meldon, Drysdale (1985) suggested that petalite and spodumene do not occur together. Chaudhry and Mahmood (1979) regarded the petalite as a late metasomatic replacement of other minerals, notably orthoclase, its irregular distribution indicating that metasomatic action was preferential, affecting only certain areas.

The Dartmoor Granite crystallized as a plagioclase-quartz-biotite rock, which subsequently reacted with a volatile K-rich fluid phase to provide megacrystic K-rich granites characteristic of the Cornubian Batholith.

On the basis of experimental work, it has been argued that the Meldon Aplite is similar to type-E granites, with a magmatic origin in which either in-situ crystal separation or later metasomatism resulted in compositional inhomogeneities. It is considered that in peraluminous magmas, high fluorine contents could initiate early topaz crystallization. L. Haynes (pers. comm.) has made the following points considering the genesis of the aplite, namely:

1. the structure of the Meldon Aplite is similar to that of South-west England elvans, which crystallized in an opening fissure environment. Metasomatic replacement of an initial magma by a later fluid-rich magma could be the cause of some of the alteration features seen in Meldon;
2. chemical zonation and mineralogy is similar to that of Bikita-type pegmatites;
3. the crystallization history of the feldspars is similar to that of type-B Cornubian Batholith granites. The early crystallization of topaz and Li-mica may have been important; and
4. the later magma (forming the pegmatitic pods) may have been a late-stage type-E granite.

Conclusions

The Meldon Aplite Quarries GCR site is an internationally important mineralogical and petrological site. It is a remarkable 'granitic' occurrence, the Meldon Aplite Quarries representing the best exposures of the only example of a sodium-potassium-lithium pegmatite recorded in Britain (Edmonds *et al.*, 1975). The rocks are internationally famous and important for the variety of rare accessory minerals they contain. The site provides for detailed studies of the petrology of the rock body, and also mineral contents along with rare elemental distributions. Many of the minerals listed as present in the Meldon Aplite Quarries are unknown elsewhere in Britain and only known from a few localities in the world. However, Ryback *et al.* (2001) have demonstrated that the late A.W.G. Kingsbury falsified the localities of numerous rare mineral species. This deception affects a number of locations in the South-west England, including Meldon Aplite Quarries, therefore care should be exercised when considering claims by Kingsbury which have not been substantiated or duplicated by subsequent collectors.

PRIEST'S COVE, CAPE CORNWALL, CORNWALL (SW 352 315)

Introduction

The Land's End Granite is renowned for the geology of its contact relationships, for the adjacent variety of contact metamorphic hornfelses, and associated mineralization, especially in the coastal strip from Cape Cornwall to Pendeen. At Priest's Cove, biotite granite is intimately veined by a later variety with associated pegmatite pods and tubes. There is evidence of a major faulted contact with andalusite-biotite hornfels. Comparisons can be made between the tourmaline 'pods' of Priest's Cove and the massive tourmalinized features at Porth Ledden (SW 353 321).

Priest's Cove lies to the south of Cape Cornwall (see Figure 7.7). Above the cliffs of Priest's Cove were situated the St Just United mines which worked a series of lodes for tin. The chimney and mine buildings on the Cape Cornwall promontory (see Figure 7.8) are the remains of the St Just Amalgamated

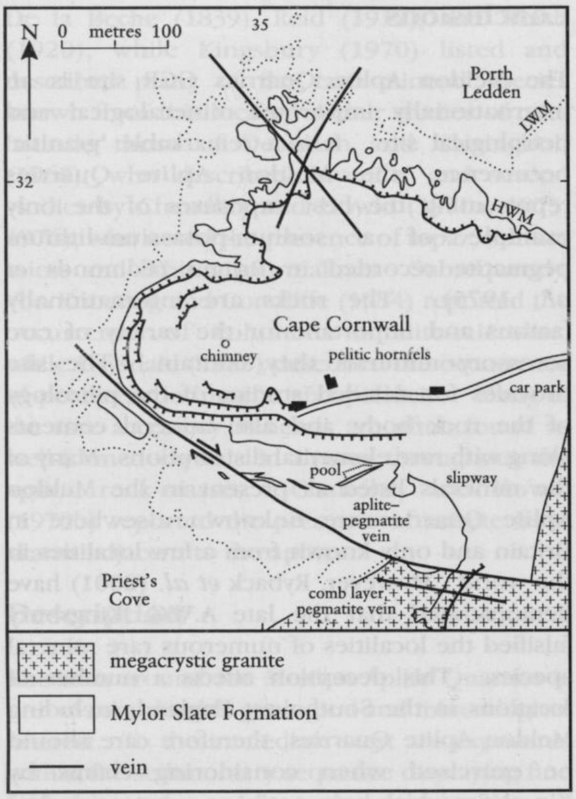


Figure 7.7 Map of Priest's Cove. After Halls, unpublished field guide.

mines which also worked tin-bearing lodes; eventually the two groups were merged sometime after 1878.

Important petrological and mineralogical features are remarkably well-exposed in the cliffs and rock platform of Priest's Cove, which include:

1. the development of pegmatitic features associated with the granite;
2. comparison of the tourmalinization present at the faulted Priest's Cove contact and the unfaulted Porth Ledden contact, to the north-east of Cape Cornwall; and
3. a study of the controls of mineralization.

Dines (1956) described the mining setts of the St Just Amalgamated and St Just United mines. The mines worked tin from a group of lodes trending south-eastwards from the southern side of the Cape Cornwall headland. The rocks hosting the mineralization are granites, overlain at Cape Cornwall by contact metamorphosed country rock ('killas') and some altered basic igneous rocks ('greenstones'). Records of output from St Just United between 1862 and 1904 were 1870 tons of 'black tin' (unrefined ore).

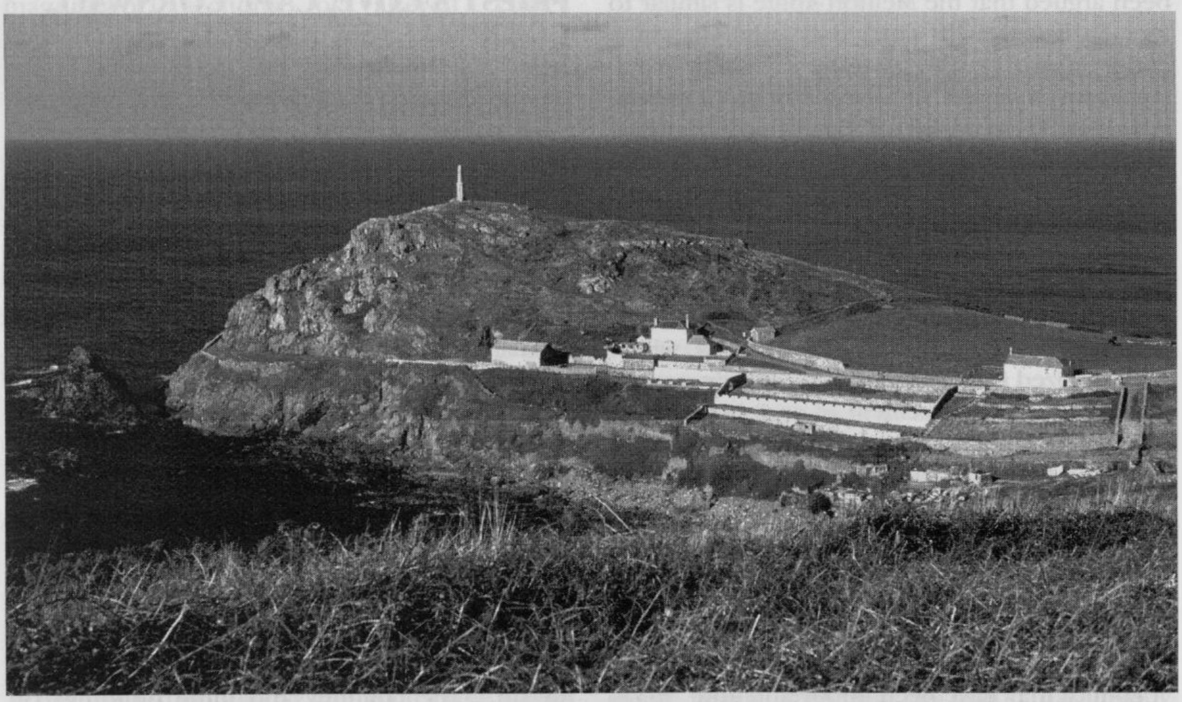


Figure 7.8 The headland of Cape Cornwall showing mine chimney, remnant mine buildings and processing floors. (Photo: S. Campbell.)

Details of the rocks in the Cape Cornwall area related to the contact phenomena of the Land's End Granite and adjacent killas, and late-stage granitic processes are given by Reid and Flett (1907), and Goode and Taylor (1988). The petrography of the Land's End Granite has been detailed by Booth and Exley (1987). Hall (1994) also described the geology of the area, while aspects of pegmatite development have been described by Hosking (1952), and hydrothermal activity by Jackson *et al.* (1982). The detailed petrology of the granitic rocks of the area between Priest's Cove and Porth Ledden has been described in the *Cape Cornwall* GCR site report presented by Floyd *et al.* (1993). Most recently Powell *et al.* (1999a,b) have described formation and emplacement styles of the Land's End Granite.

Description

Priest's Cove provides excellent exposures of folded spotted slates and hornfels of various types. In the cliff exposures close to the boat ramp can be seen some small-scale overturned folds. These are associated with considerable quartz veining filling tension gashes, and deformation of harder arenaceous bands in the mostly argillaceous slates. On the south side of the cove, a fault is marked by a small cave; this separates the hornfels from massive granite to the south. The Land's End Granite here is only slightly porphyritic, contrasting with the strongly megacrystic granite seen at Land's End and at the **Nanjizal Cove** GCR site. The granite is sheared and reddened close to the fault. The granite is also traversed by narrow bands of altered (greisened) granite and thin tourmaline veins. The Mylor Slate Formation meta-sedimentary rocks have been strongly mineralized and in places brecciated. Two joint-sets in the granite are occupied by early pegmatites and later quartz-tourmaline and greisen-bordered veins carrying mineralization. In places both the quartz and tourmaline form coarse aggregate masses.

The relationships between several periods and types of mineralization, along with pegmatite development associated with several texturally different types of granite, are exposed in the extensive wave-cut rock platform. At Priest's Cove the main granite seen to the south of the vertical faulted contact is medium- to fine-grained and sparsely megacrystic, somewhat different to much of the Land's End Granite elsewhere. However, Priest's Cove is well known for an area of coarse-grained granite exposed at low tide. This appears to intrude the main granite near the low-water mark and is important for the sporadic development of 'stockscheider' pegmatite along this contact. It is possible that the main fault displaced seawards a shallow-dipping roof contact, or alternatively the pegmatite might be due to a later intrusion. Some of the planar pegmatites have well-developed comb-textured feldspar megacrysts which are associated with areas of aplite.

Some areas to the north and south side of Cape Cornwall show remarkable development of tourmaline pods and masses, interpreted as being both of magmatic origin and also later hydrothermal growth accompanying cassiterite vein infill. Halls *et al.* (2001) provided field evidence for discrete episodes of intrusion during the emplacement of the Land's End Granite, based on results obtained from detailed mapping and observation of the Porth Ledden coastal section.

Pegmatitic 'spots' in the main granite are not related to faulting or vein structures, and consist of lenses of pink feldspar and quartz with euhedral black tourmalines. These sometimes abut against the contact, where a dark selvage of almost pure schorl (tourmaline) is often formed. However, the volume of the 'pods' of tourmalinite in Priest's Cove is small in comparison with that in Porth Ledden.

The main fault lode exposed at the base of, and in the cliff section at, Priest's Cove has been worked along a trial adit. This demonstrates very well features of the mineralized lodes in this area. The brecciated zone is up to 2 m wide, trending north-west–south-east with a dip of 70°–85° N. This is a similar trend to some of the lode structures of the Botallack–Geevor region to the north. Brecciation appears to be a normal associate of faulting and hydrothermal activity in Cornish lodes. The Priest's Cove lode-breccias may have formed during stoping contemporary with granite intrusion. The wall-rocks are formed from granite breccia and massive quartz vein material, while thin stringers of tourmaline become important towards the footwall.

Interpretation

One of the important features of the Priest's Cove to Porth Ledden section is the evidence provided for the relationship of magmatic to hydrothermal tourmalinization and the relationship of both to mineralization. Post-magmatic processes in South-west England and Brittany have been described by Charoy (1982). From the evidence at Priest's Cove it would seem that the tourmaline formation could be related to contrasting mechanisms. Magmatic tourmalinites, like the pegmatites, tend to be barren of ore minerals. It was the main-stage mineralization process which generated the tin-tourmaline association.

Authors such as Charoy (1982), and Manning (1985) have suggested that tourmaline-quartz rocks are evidence of the unmixing of a fluid phase from the granitic magma. Charoy (1982) established a sequence of unmixing events for the Cape Cornwall area (see Figure 7.9), with tourmalinites and tourmaline-bearing granites being of magmatic origin, while tourmaline with cassiterite appears to be of hydrothermal origin. The relative distribution of these varieties may be dependent on the nature and distribution of post-magmatic hydrothermal convection cells. It may be that the fracture system in the granite is better developed in the Priest's Cove area, leading to greater metallogenesis at that location.

From the work of various authors, including Charoy (1979), it is suggested that a staged evolution occurred, namely:

1. the normal sparsely porphyritic granite (granite porphyry of Charoy) crystallized;
2. a related fluid phase was responsible for the pegmatite of Priest's Cove and the tourmaline granite at Porth Ledden; and
3. tourmaline granite differentiated into a megacrystic contact facies and the tourmalinite of Porth Ledden.

Unlike the extensive petrological, mineralogical and geochemical studies that have been undertaken for the Megilligar Rocks at the **Tremearne Par** GCR site, studies on the Priest's Cove to Porth Ledden section are limited. Therefore the understanding of the late-stage granite processes at Priest's Cove awaits further studies. Only limited geochemical work has so far been described for the chemistry of individual mineral phases. Differences could relate to magmatic variation in the Land's End Granite or evidence of magmatic differentiation.

Conclusions

The Priest's Cove to Porth Ledden coast section provides excellent exposures in an area of classic granite-related coastline. At Priest's Cove a faulted contact between the Land's End Granite and Mylor Slate Formation metasedimentary rocks has been mineralized and hydrothermally brecciated.

A variety of pegmatitic, quartz-tourmaline and greisen veins can be viewed in the rock platform and cliffs of Priest's Cove, which are important to studies on the relationship between granites and mineralization, allowing study of the relationship

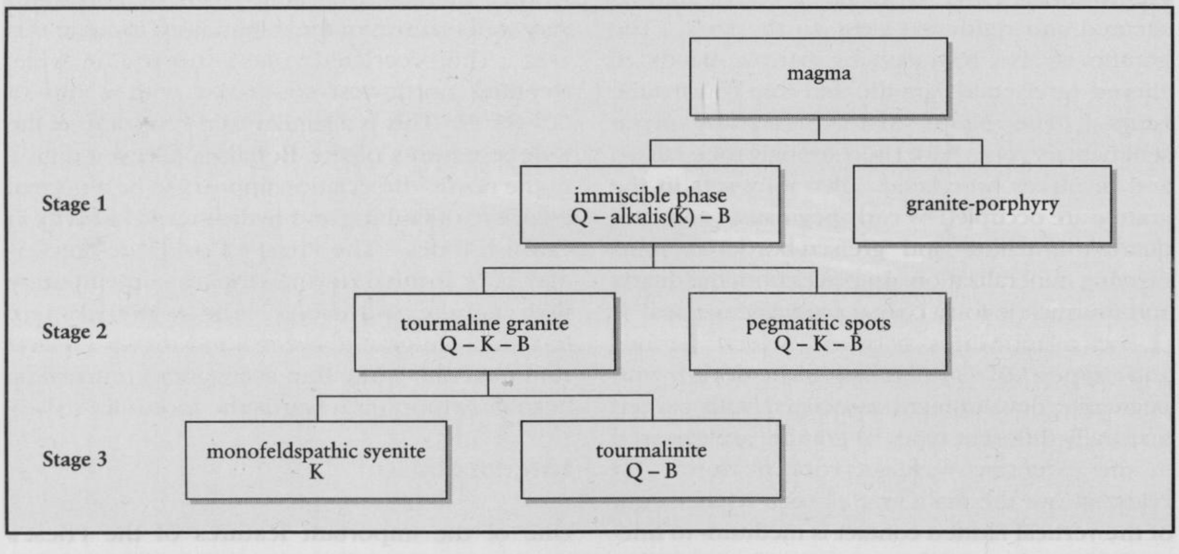


Figure 7.9 Diagram showing successive unmixing episodes from the crystallizaing magma at Porth Ledden and Priest's Cove. After Charoy (1979).

between magmatic and hydrothermal tourmalinization. The readily available wall-rocks of the St Just lodes provide material for study of the nature of the hydrothermal mineralizing fluids in this area of the Land's End Granite. Finally, comparisons can be made between this locality, the **Nanjizal Cove** GCR site, and other Cornubian Batholith exposures, such as those at the **Tremearne Par** GCR site.

TRELAVOUR DOWNS PEGMATITE, CORNWALL (SW 960 575)

Introduction

The Trevalour Downs Pegmatite GCR site exposes a coarsely crystalline pegmatite containing large sheaves of Li-rich biotite (up to 0.15 m in length), originally worked for its lithium content. Compositionally the pegmatite lies at the boundary of the D- and E-types (according to the classification of Exley *et al.*, 1983) of lithium-mica granite making up the St Austell Granite pluton. This pegmatite contains zinnwaldite, a lithium biotite (Selwood *et al.*, 1998). Elsewhere in the surrounding china-clay area similar exposures do occur but are rapidly disappearing. The preserved Trelavour Downs Pegmatite is therefore important to our understanding of the relationship between the volatile, metal-rich late granites and the megacrystic, metal-poor early granites of the Cornubian Batholith.

The Trevalour Downs Pegmatite is located in rough wasteland on the south side of the St Dennis to Whitemoor road, adjacent to extensive china-clay workings and tips, south-east of St Dennis. A shallow circular pit exposes the central quartz-feldspar portion of the pegmatitic body, which was worked for lithium in the early 1900s, as described by Davison (1926a,b). It is important as the selvages of the pegmatite are of 'biotite-rock', with some individual crystals reaching up to 0.15 m in length.

There is little literature specific to the site; Hosking (1952) briefly mentioned the locality, as did Edmonds *et al.* (1975). It was again briefly described by Cundy *et al.* (1960), while Stone *et al.* (1988) presented a single analysis of a Li-rich mica from Trelavour Downs. The pegmatite is not mentioned by Dines (1956), which is probably due to the fact that the pegmatite was not that well-exposed. However, in the 1970s the site was trenched during a mineral exploration exercise, which provided fresh in-situ exposures. Alderton (1993) reported on the likely temperature of the fluids responsible for the Trevalour Downs Pegmatite (500°–600°C), which has a bearing on proposals for its petrogenesis.

Description

Zonation of the rocks, described by Davison (1926b) from the then available exposures, was noteable with a central portion consisting of coarse feldspar and quartz with large 'books' of biotite, surrounded by massive, coarse-grained biotite, in turn surrounded by an outer zone of zinnwaldite and feldspar. Today this zoning cannot be observed due to the current limited exposures.

The important mineralogical and petrological features of the Trevalour Downs site relate to the nature of the micas, and the formation of the pegmatite and its relationship to metallogenesis. Lithium contents of the worked mica were reported by Hosking (1952) as being 1.5 wt%, which is extremely low for zinnwaldite, the figure therefore presumably referring to the biotite, which forms the bulk of the mica content in the deposit. Examples of ferroan zinnwaldite, originally described as biotite, from similar bodies in Gunheath China Clay Pit (SX 005 571) have been documented by Stone (1984), and Stone *et al.* (1988). It therefore seems that micas intermediate in composition between zinnwaldite and biotite may be widespread. Alternatively the 1.5 wt% Li_2O may refer to the overall grading of all mica in the pegmatite, for it is unlikely that the two types would have been readily distinguished at the time of extraction.

The analysis by Cundy *et al.* (1960) of zinnwaldite from Nanpean (SW 961 559) contains 4.10 wt% Li_2O, 5.7 wt% FeO and 6.80 wt% F. Zinnwaldite from type-E granite in Rostowrack Quarry (SW 953 566) contains 4 wt% Li_2O, 9.9 wt% FeO and 6.3 wt% F, but that from type-D granite in Gunheath China Clay Pit contains 2.9 wt% Li_2O, 10.5 wt% FeO and 5.75 wt% F (Stone *et al.*, 1988). The mica from the Trelavour Downs Pegmatite analysed by Stone *et al.* (1988) contained 1.6 wt% Li_2O, and 19.8 wt% FeO. Stone *et al.* (1988) stated that 'specimen E259 is the so-called zinnwaldite from the Trelavour Downs Pegmatite, but despite its high

Li and F contents it is actually a lithian "siderophyllite" body.' In this discussion it should be remembered that the pegmatite has been described as zoned, the bulk of the mica being biotite. The Trelavour Downs mica analysed by Stone *et al.* (1988) is, in most respects, intermediate between biotite and zinnwaldite. It contains much less-mafic and resitite mineral components than biotite, namely Cr, V, Ti, Zr, Ce and Th, but much higher contents of Rb, K, Li, and F.

Interpretation

L. Haynes (pers. comm.) comprehensively reviewed work on the pegmatites of this area, and this report takes account of those studies.

A 'plan' of the geology of the St Austell Granite is shown in Figure 7.10. The megacrystic lithium-mica granite (type-D) is now regarded as a metasomatic alteration of biotite granite by a type-E, volatile, lithium-mica granite magma (Manning and Exley, 1984). However, Stone (1984) has argued that textural evidence shows that metasomatism has not simply replaced one mica with another, because the zinnwaldite replaces both the feldspars as well as biotite. Furthermore, residual andalusite in the biotite granites was replaced by topaz at the same time. The conversion therefore represents a total impregnation and re-texturing of biotite granite by largely volatile components.

It has been recorded that in Gunheath China Clay Pit (in the St Austell Granite) a pegmatitic roof-zone is developed in the type-E granite, and its contact with a type-D granite is marked by curved-crystal pegmatites ('stockscheider pegmatite' of Baumann (1970), and Halls (1987)). These pegmatites are also exposed at what has been interpreted by Halls (1987) as the same contact in Goonbarrow Pit, and therefore it is argued that the type-E granite forms an intrusive cupola into the type-D granite, with a pegmatitic margin.

The significance of rhythmic pegmatite crystallization in relation to pulses of mineralization has been discussed at length by Halls (1987) (see Figure 7.11). The argument is that the layers of pegmatite represent periods of volatile build-up under the crystallizing cupola, and that the release of the volatiles into simple dilation fractures results in the sheeted-vein complexes of greisen-bordered veins so typical of many Cornish tin deposits. The best examples are found above granite cupolas, as seen at the **St Michael's Mount** and **Cligga Head** GCR sites; such a complex is also seen in the Old Beam Mine at Goonbarrow. Further discussion of the pegmatites in the St Austell area is given by Manning and Exley (1984).

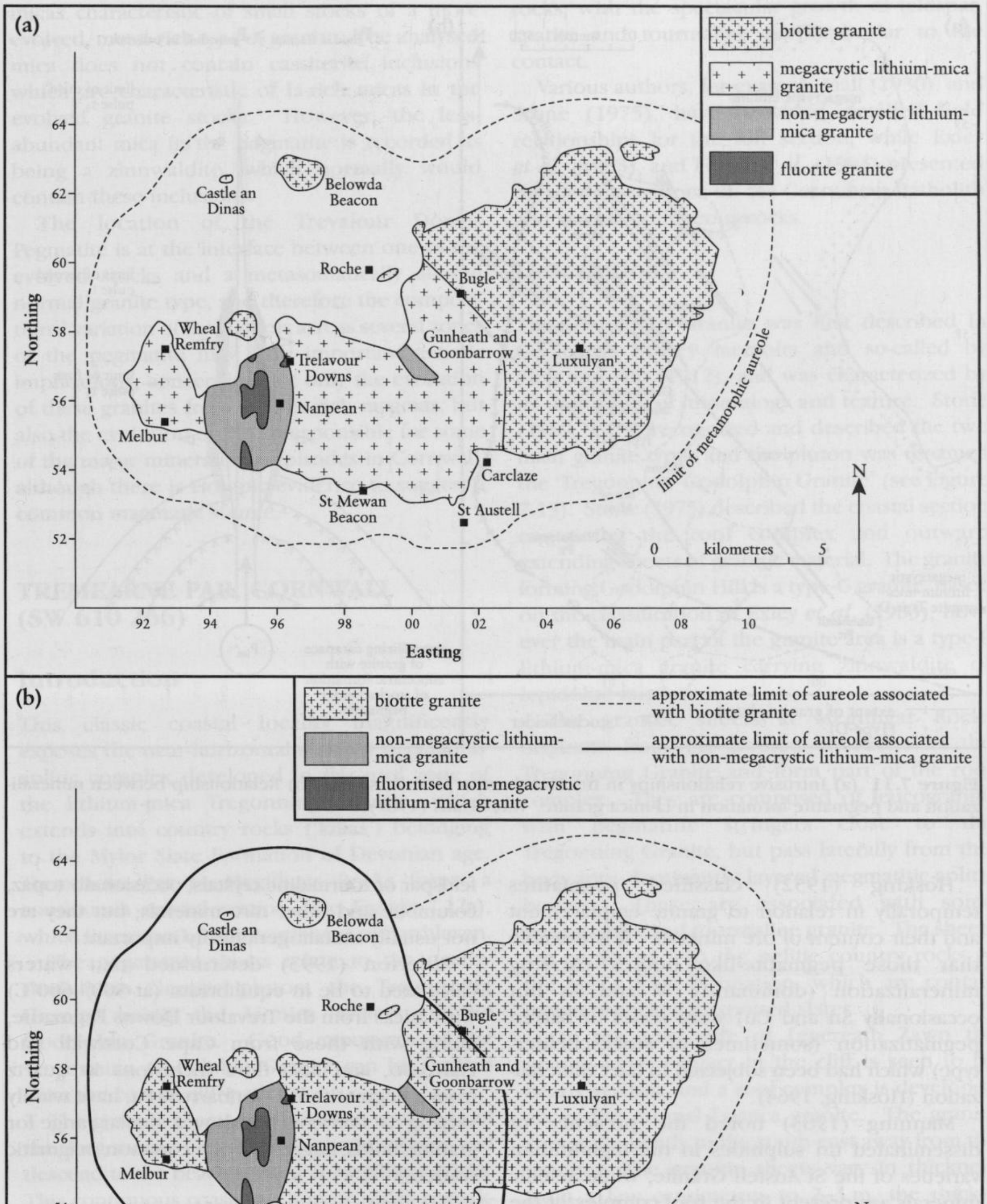
Hill and Manning (1987) determined a more complex picture by recognizing several new varieties of granite in this area, beside the normal B-, D- and E-types. How many of these varieties can be argued to represent separate intrusions, as distinct from compositional variations, is not clear, but if the principle that each pulse of magma is roofed by a stockscheider pegmatite is valid then there may be many different granites, albeit resulting from a single period of fractional crystallization.

Not all pegmatites are of a stockscheider-type. In the pegmatite veins in Gunheath China Clay Pit, microcline, quartz and zinnwaldite are the major constituents, but accessory apatite, topaz, opal and columbite are also present. The columbite is particularly rich in tungsten and scandium, and it is best developed in a vertical lens of unusual composition, consisting entirely of quartz, 'gilbertite' (secondary white mica) and apatite, with rare accessory torbernite.

The above observations made from other sites of pegmatite formation raise questions concerning the nature of the Trelavour Downs Pegmatite. It does not have the shape or attitude of a stockscheider pegmatite, for its alignment is not parallel to the supposed contact of the type-E granite. However, as it was targeted for mineral exploration in the 1970s, it was probably thought to be related to late-magmatic phenomena and tin mineralization (see Badham *et al.*, 1976). Perhaps the full lateral extent of the pegmatite has not been recognized, or perhaps it is part of a general pegmatite zone along the contact.

The Trelavour Downs Pegmatite was originally described as a zoned body with an outer selvage containing zinnwaldite. This might suggest that an original biotite pegmatite has been metasomatized by intrusion of adjacent type-E granite, and that an outer zinnwaldite-feldspar selvage was formed at this time, in addition to modification of the original biotite composition.

Figure 7.10▸ (a) Distribution of the granite varieties in the St Austell area (after Exley and Stone, 1982). (b) Simplified map of the primary granite varieties of the St Austell area and their metamorphic aureoles (new interpretation after Manning and Exley, 1984).



(a)
biotite granite
megacrystic lithium-mica granite
non-megacrystic lithium-mica granite
fluorite granite
Castle an Dinas
Belowda Beacon
Roche
Bugle
Wheal Remfry
Gunheath and Goonbarrow
Trevalour Downs
Luxulyan
Nanpean
Melbur
Carclaze
St Mewan Beacon
St Austell
limit of metamorphic aureole
N
0 kilometres 5
Northing
64
62
60
58
56
54
52
92 94 96 98 00 02 04 06 08 10
Easting
(b)
biotite granite
non-megacrystic lithium-mica granite
fluoritised non-megacrystic lithium-mica granite
approximate limit of aureole associated with biotite granite
approximate limit of aureole associated with non-megacrystic lithium-mica granite
Castle an Dinas
Belowda Beacon
Roche
Bugle
Wheal Remfry
Gunheath and Goonbarrow
Trevalour Downs
Luxulyan
Nanpean
Melbur
St Mewan Beacon
St Austell
N
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Northing
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62
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Easting

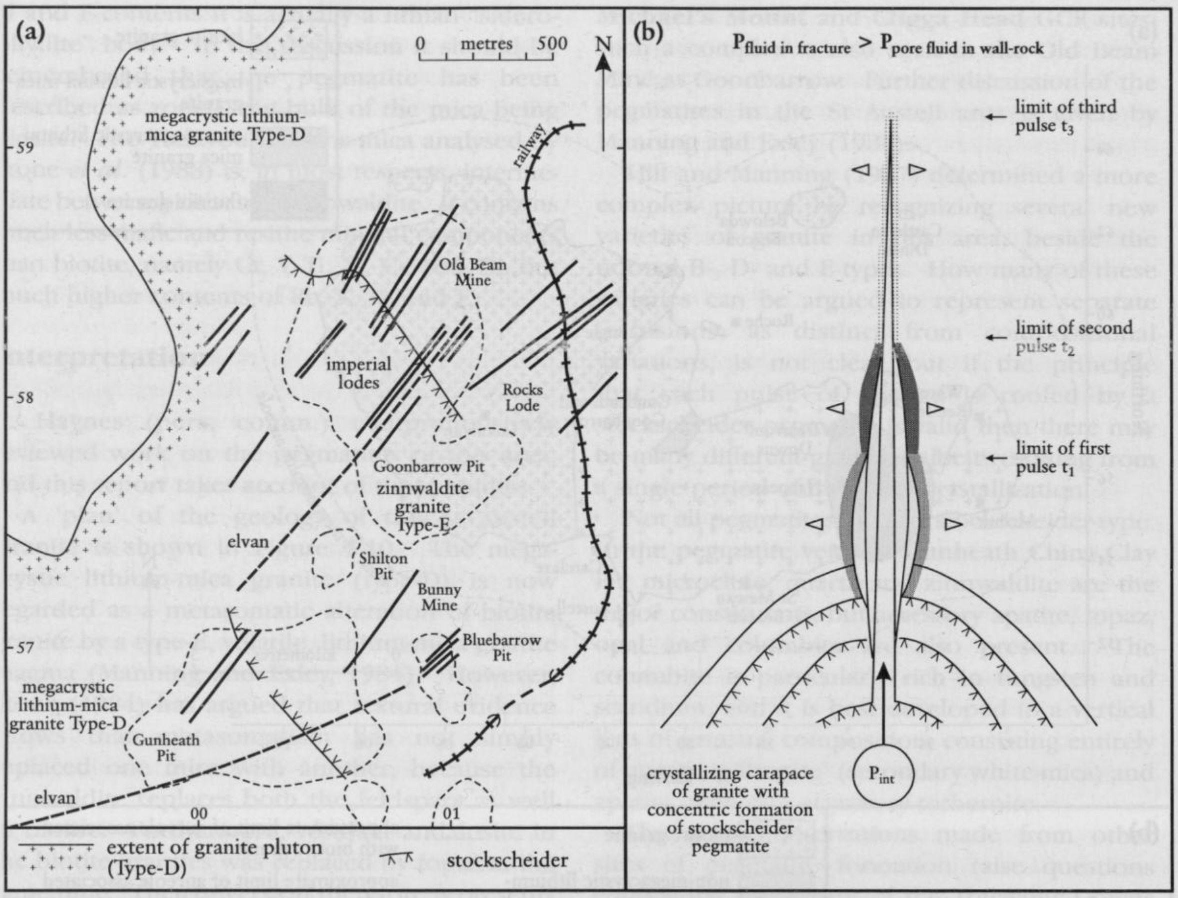

Figure 7.11 (a) Intrusive relationships in the Hensbarrow Granite stock. (b) Relationship between mineralization and pegmatite formation in Li-mica granite. After Halls (1987).

Hosking (1952) classified pegmatites temporally in relation to granite emplacement and their content of ore minerals. It is possible that those pegmatite-like bodies carrying mineralization (dominantly W and As but occasionally Sn and Cu) were zones of barren pegmatization (sometimes of stockscheider-type) which had been subjected to later mineralization (Hosking, 1964).

Manning (1983) noted the presence of disseminated tin sulphides in the high-lithium varieties of the St Austell Granite, while arsenic minerals are present in the roof complex of the other lithium-mica granite at Tregonning–Godolphin. Stone (1984) argued that minute cassiterite grains are probably ubiquitous inclusions in lithium micas, although there is no evidence that they are more abundant in pegmatite micas than in the micas of normal type-E granite. Most pegmatites may be mineralogically interesting, in containing large feldspar or tourmaline crystals, occasionally topaz, columbite and other rare minerals; but they are not usually metallogenetically important.

Alderton (1993) determined that waters calculated to be in equilibrium (at 500°–600°C) with micas from the Trevalour Downs Pegmatite, along with those from Cape Cornwall and Halvosso, and also fluid inclusions in quartz from a pegmatite at Goonbarrow Pit, have widely varying 'D' contents but show a similar range for granitic fluids, suggestive of a common magmatic source.

Conclusions

The Trelavour Downs Pegmatite contains two types of Li-bearing mica, although it is possible that only the most abundant of these has been analysed. This mica would appear to lie compositionally midway between the normal biotite of most Cornish granites and the Li-rich micas characteristic of small stocks of a more evolved, metal-rich type of granite. The analysed mica does not contain cassiterite inclusions which are characteristic of Li-rich micas in the evolved granite stocks. However, the less-abundant mica in the pegmatite is recorded as being a zinnwaldite, which normally would contain these inclusions.

The location of the Trevalour Downs Pegmatite is at the interface between one of the evolved stocks and a metasomatically altered normal granite type, and therefore the compositional variation of these micas across several zones of the pegmatite may have important genetic implications, concerning not only the evolution of these granites from volatile-rich magmas, but also the evolution of fluids responsible for some of the major mineralizing episodes in Cornwall, although there is isotopic evidence to suggest a common magmatic source.

TREMEARNE PAR, CORNWALL (SW 610 266)

Introduction

This classic coastal locality magnificently exposes the near-horizontal sheeted pegmatitic-aplitic complex developed in the roof zone of the lithium-mica Tregonning Granite, which extends into country rocks ('killas') belonging to the Mylor Slate Formation of Devonian age. Tremearne Par to Megilligar Rocks forms a continuous coastal section (see Figure 7.12a), which lies some 1.5 km north-west of Porthleven.

The pegmatitic sheets relate to the nearby Godolphin Granite pluton, the Tregonning Granite being the Li-mica variety of the Godolphin Granite. Good exposures of the Tregonning–Godolphin Granite can be studied from the coastal cliff-path.

The granitic sheets rise from the roof zone of the Tregonning Granite at Legereath Zawn and descend to the beach section at Megilligar Rocks. This continuous coastal section provides remarkable exposures for chemical and mineralogical studies of a granite pluton roof-zone complex. Megilligar Rocks are mainly pegmatitic- and aplitic-facies rocks associated with subordinate granite.

The contact between the granite and the country rocks at Megilligar Rocks is remarkably clearly exposed (see Figure 7.12b). Complete sections occur of the aplitic- and pegmatitic-facies rocks, with the spectacular growth of feldspar, apatite and tourmaline perpendicular to the contact.

Various authors, for example Hall (1930), and Stone (1975), have provided detailed field relationships for the full section, while Exley *et al.* (1983), and Floyd *et al.* (1993) presented detailed discussions on the Cornubian Batholith and associated igneous rocks.

Description

The Godolphin Granite was first described in Geological Survey memoirs and so-called by Flett and Hill (1912), and was characterized by its uniformity of mineralogy and texture. Stone (1969, 1975) recognized and described the two main granite types and the pluton was renamed the 'Tregonning–Godolphin Granite' (see Figure 7.13). Stone (1975) described the coastal section containing the roof complex and outward extending sheets of granitic material. The granite forming Godolphin Hill is a type-C granite, based on the classification of Exley *et al.* (1983); however the main part of the granite area is a type-E lithium-mica granite carrying zinnwaldite or lepidolite mica.

The granitic sheets at Megilligar Rocks originate from the layered roof-zone of the Tregonning Granite and form part of the roof complex. They are composed of leucogranite with pegmatitic stringers close to the Tregonning Granite, but pass laterally from this body into dominantly layered pegmatitic-aplitic bodies. These are associated with some leucogranite and tourmaline granite. The sheets are emplaced into the pelitic country rocks of the Mylor Slate Formation, which are contact metamorphosed to spotted slates.

On the west side of Legereath Zawn the granite–killas contact in the cliff is seen to be nearly vertical, and a roof complex is developed above the normal Li-mica granite. The granite sheets dip gently to the south-east away from the granite. The granitic sheets vary in thickness from a few centimetres to 2–3 m, the thicker units being a complex mixture of pegmatite and aplite, at times showing merging of two or more sheets, then diverging. Some of the thinner bodies are concordant to the foliation. Stone (1969, 1975) described textures of the sheets in detail, the most spectacular textural structure being the perpendicular growth of the large K-feldspar, tourmaline and apatite crystals.

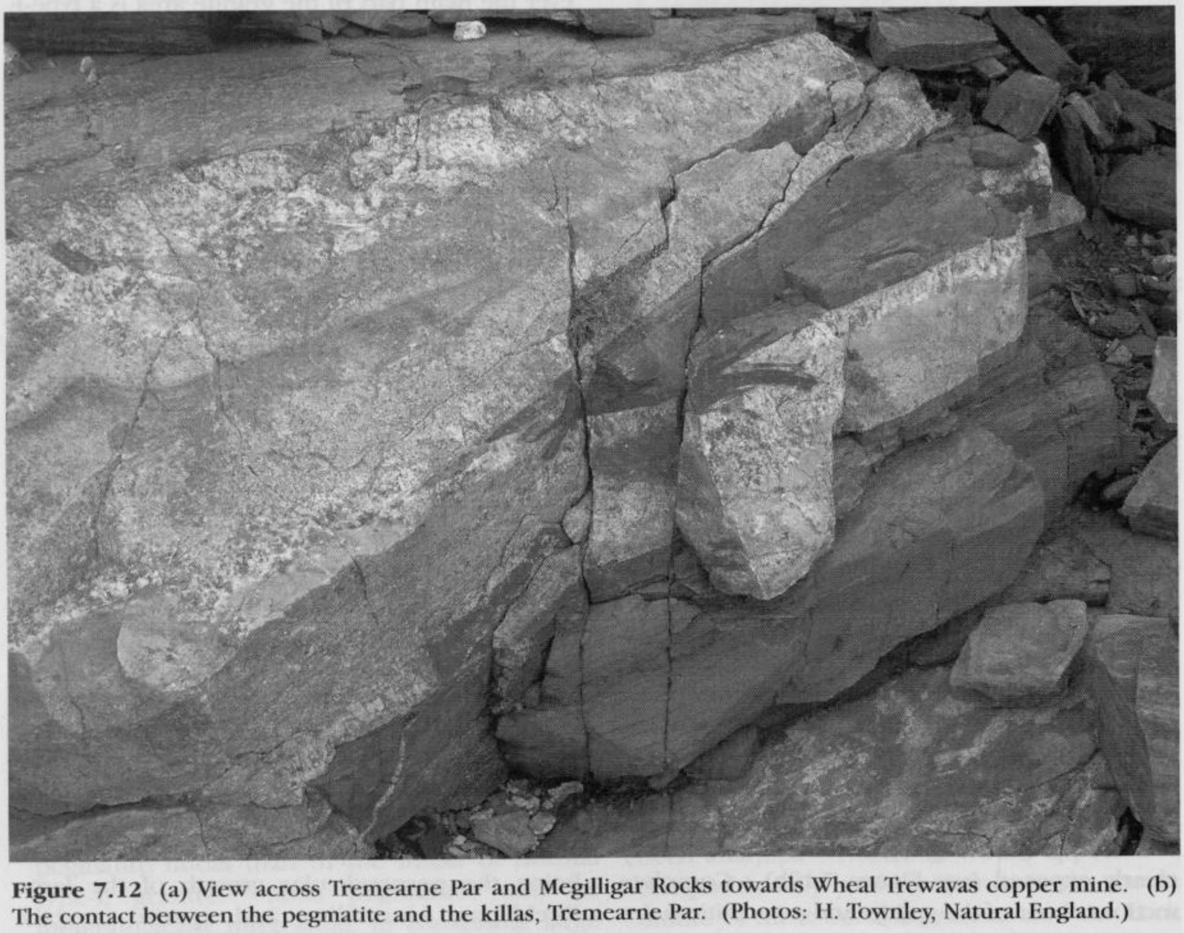

Figure 7.12 (a) View across Tremearne Par and Megilligar Rocks towards Wheal Trewavas copper mine. (b) The contact between the pegmatite and the killas, Tremearne Par. (Photos: H. Townley, Natural England.)

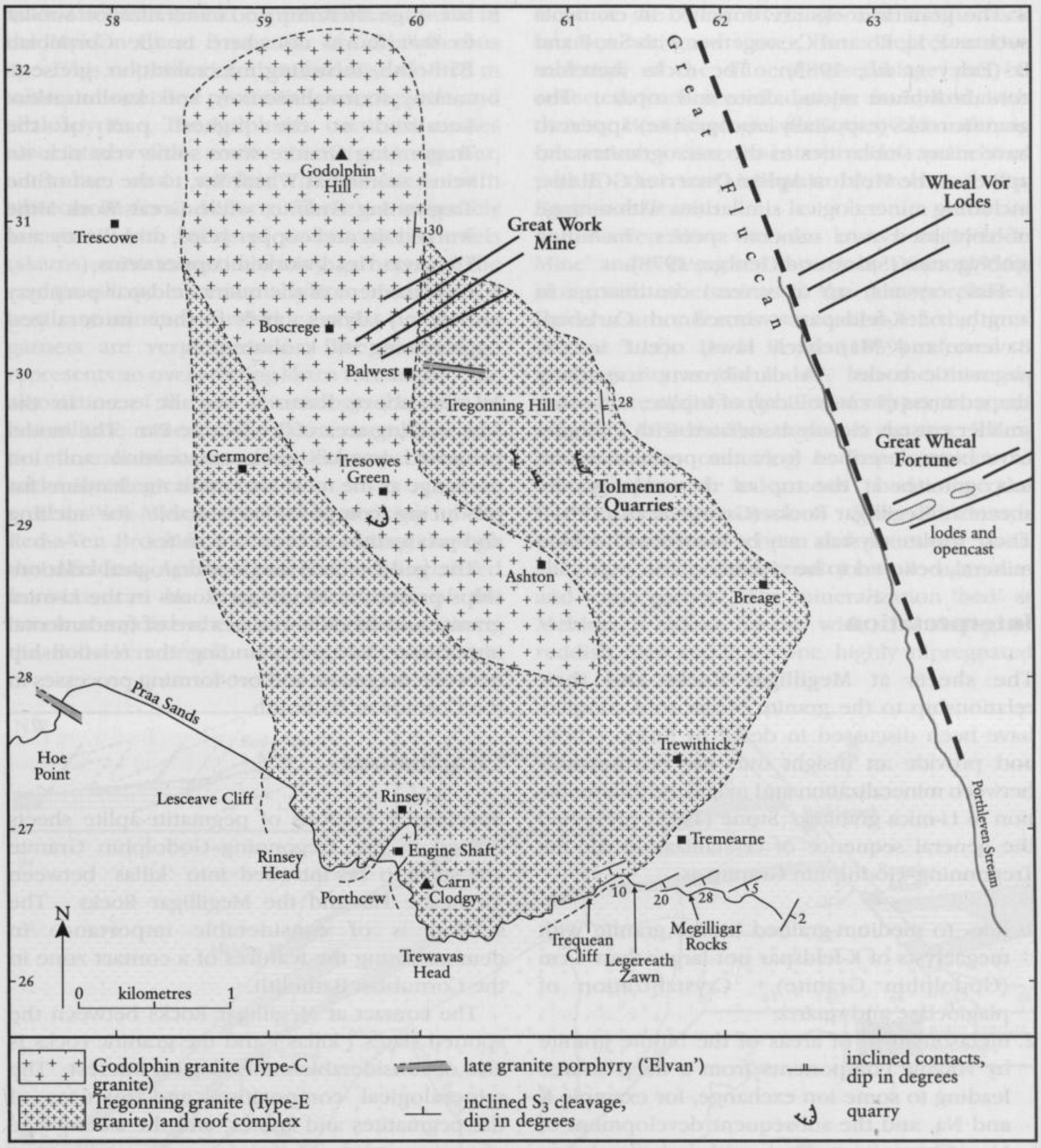

Figure 7.13 Geological sketch map of the Tregonning–Godolphin Granite. The area without ornament is composed of the Mylor Slate Formation. Solid lines mark exposed boundaries; dashed lines mark inferred boundaries. After Stone (1969). Granite boundaries modified by Taylor and Wilson (1975).

Disorientated xenoliths occur within the sheets and in the roof pegmatites. Some of the xenoliths are commonly enriched in tourmaline. In the pegmatitic areas brown-black-blue tourmaline prisms reach several centimetres in length, while light-green apatites also grow up to several centimetres. The Li-mica occurs as a pale-brown lepidolite, zinnwaldite and/or muscovite ('gilbertite'). Fluorite, löllingite, triplite and amblygonite are also present, while topaz is an early mineral in the paragenetic sequence. The phosphate minerals and ore minerals appear to have formed late in the magmatic or immediate post-magmatic crystallization sequence.

The granitic rocks are enriched in elements such as F, Li, Rb and Cs, together with Sn, P and B (Exley *et al.*, 1983). The rocks therefore contain lithium micas, albite and topaz. The granitic rocks (especially leucogranite) appear to have many similarities to the microgranites and aplites at the **Meldon Aplite Quarries** GCR site, including mineralogical similarities with a range of contained rare mineral species, including amblygonite (Stone and George, 1978).

Fine crystals, up to several centimetres in length, of K-feldspar, twinned on Carlsbad, Baveno and Manebach laws, occur in the pegmatitic rocks. A dark-brown, irregularly shaped mass (5 cm × 2 cm) of triplite, and some smaller crystals closely associated with löllingite have been described from the pegmatites and leucogranites at the top of the main granite sheets at Megilligar Rocks (George *et al.*, 1981). These triplite crystals may be coated with a blue mineral, believed to be vivianite.

Interpretation

The sheets at Megilligar Rocks and their relationship to the granite of the roof complex have been discussed in detail by Stone (1969) and provide an insight into the relationships between mineralization and magmatic differentiation in Li-mica granites. Stone (1975) presented the general sequence of crystallization for the Tregonning–Godolphin Granite as:

1. fine- to medium-grained biotite granite with megacrysts of K-feldspar not larger than 4 cm (Godolphin Granite). Crystallization of plagioclase and quartz;
2. metasomatism of areas of the biotite granite by volatile components from a deep source leading to some ion exchange, for example K and Na, and the subsequent development of Li-mica granite magma, with volatiles being located in Li-mica, topaz and tourmaline;
3. as the Li-mica granite crystallized, volatiles accumulated under the roof, producing the layered leucogranite, aplite and pegmatitic complex of the roof zone, probably with several phases of re-melting, fluid metasomatism and crystallization;
4. build-up of pressure causing lifting of the roof and horizontal fractures in the country rocks at or near roof level, magma movement from roof zone into fractures and differentiation into the Megilligar Rock sheets;
5. late-stage alteration and mineralization similar to that found elsewhere in the Cornubian Batholith, including mineralization, greisenization, tourmalinization and kaolinization. Localized at the highest part of the Tregonning Granite were some very rich tin veins, worked at Wheal Vor, to the east of the Tregonning Granite, while Great Work Mine worked tin and copper veins, and Rinsey and Trewavas Head worked copper veins;
6. emplacement of the quartz-feldspar porphyry ('elvan') dykes, and further mineralized greisening and kaolinization.

All the above features may be seen in the surrounding area of Tremearne Par. The model proposed invokes metasomatization and ion exchange as the most important mechanisms for producing compositions suitable for melting and production of Li-mica granites.

The geochemical and mineralogical relationships present at Megilligar Rocks in the Li-mica granite and its differentiates are of fundamental importance to understanding the relationship between magmatic and ore-forming processes in the Cornubian Batholith.

Conclusions

Spectacular sections of pegmatite-aplite sheets related to the Tregonning–Godolphin Granite are seen to be intruded into 'killas' between Tremeane Par and the Megilligar Rocks. The section is of considerable importance in demonstrating the features of a contact zone in the Cornubian Batholith.

The contact at Megilligar Rocks between the spotted slates ('killas') and the granitic rocks is also of considerable mineralogical interest. The mineralogical composition and textures of the pegmatites and aplites, and the assemblage of minor minerals, for example triplite, are important to fuller understanding of the section.

RED-A-VEN MINE, MELDON, DEVON (SX 570 917)

Introduction

The Red-a-Ven Mine GCR site exposes tin-bearing skarns in the stream section of the Red-a-Ven Brook. The site is important for the availability of specimens from the dumps associated with an old copper trial and mine in the Meldon Chert Formation of Carboniferous age. This sulphide-rich chert bed is some 0.75 m wide and contains pyrrhotite, arsenopyrite and chalcopyrite. The sulphides occur in masses associated with rocks containing garnet, actinolite and axinite, interbedded with siliceous shales and cherts. These are intimately associated with bands of wollastonite hornfels (skarns) containing tin-bearing garnets and the rare tin silicate mineral malayaite. Malayaite is a very rare mineral worldwide, whilst tin-bearing garnets are very unusual. The assemblage represents an overprinting skarn formation. The association of the ore mineralogy, the suite of borosilicate minerals, the skarn assemblage and tin mineralization are of significant petrological and mineralogical interest.

Red-a-Ven Mine is reached by walking up the Red-a-Ven Brook from the path cutting through the **Meldon Aplite Quarries**. Mineralized horizons can be seen in the banks of the brook at a point where a minor tributary meets the Red-a-Ven Brook, where a shaft was sunk. Most of the mine workings and in-situ rock sections are grown over, but a representative selection of the mineral assemblage can be collected from several dumps associated with the site. Host lithologies are Lower Carboniferous calcareous metasedimentary rocks and cherts within the metamorphic aureole of the Dartmoor Granite.

Red-a-Ven Mine was also known as 'Meldon Mine' and is described as such by Dines (1956), along with other mines in the metamorphosed Lower Carboniferous succession of the area (Figure 7.14). De la Beche (1839) referred to the deposits as 'tin lodes', but the minerals present are mainly sulphides of copper, iron and arsenic. At Red-a-Ven there are no true lodes, mineralization occurring as impregnations in metamorphosed calcareous beds in the Carboniferous succession. The old dumps consist mainly of chert and limestone with alteration along cracks and joints to actinolite and some garnet. The mineralization 'bed' at Meldon is about 76 cm wide, consisting of reddish chert and limestone, highly impregnated

Figure 7.14 Geological map of part of the northern margin of Dartmoor, showing the location of the Red-a-Ven Mine GCR site. After El Sharkawi and Dearman (1966).

with pyrite and arsenopyrite, while axinite is also present.

The mineralization at Red-a-Ven Mine is further described by Durrance and Laming (1997). Dines (1956) also described other mines in the same geological context and provided outputs for the nearby Belstone Consols (SX 632 945) and Ramsley (SX 651 930) mines. No outputs are given for Red-a-Ven Mine, and it is possible that the deposits were too irregular and sporadic to be of economic value. A series of papers important to the understanding of the geology and mineralization of the Meldon and Red-a-Ven area are those of Dearman (1959, 1966), Dearman and Butcher (1959), Dearman and El Sharkawi (1965), and El Sharkawi and Dearman (1966).

Description

In the contact zone of the north-west part of the Dartmoor Granite occur mineral deposits which were formerly worked for a variety of metals, including copper and arsenic. As can be seen from Figure 7.14, a series of mines were established on these deposits.

Wheal Fanny Mine (see Dines, 1956), where chalcopyrite and arsenopyrite were reported from shales and cherts, occurs in the western part of the mineralized belt. Forest Mine (see Dines, 1956) was quoted by De la Beche (1839) as a tin working, although the dumps have revealed only arsenopyrite and sphalerite. It is possible that the tin mineral present here was malayaite. Forest Mine now lies beneath the waters of Meldon Resevoir. Ramsley Mine and Belstone Consols Mine occur at the eastern extremity of the belt (see Figure 7.14), and occur on either side of the Sticklepath–Lustleigh Fault, the ore horizons at Ramsley being displaced some 2 km south-east relative to Belstone. These two mines were the largest producers of the belt. At Belstone a garnet-rich rock contains actinolite, axinite and sulphides; chalcopyrite, arsenopyrite, löllingite and pyrrhotite are the main sulphide ore minerals. At Ramsley Mine, specimens of the assemblage are still available on the extensive dumps. Within the axinite-actinolite-bearing rocks chalcopyrite and pyrrhotite are the main sulphide minerals, while löllingite and Co-Ni arsenides have also been recorded. The mine is famous for abundant scheelite specimens, which often occur as quartz pseudomorphs after bipyramidal scheelite crystals (see Embrey and Symes, 1987).

The mineralized horizons are confined to the Lower Carboniferous outcrop and lie within or just below the Meldon Chert Formation. Host rocks are shales and cherts with some volcanic horizons. All carry disseminated pyrite, pyrrhotite and arsenopyrite, but mineralization also occurs as garnet-rich calc-silicate skarns. The Lower Carboniferous rocks are disposed in a tight, southerly-overturned anticline, with the Red-a-Ven and Forest mines occurring in the steeper-dipping overturned limb. The structure of the area has been discussed by Dearman and Butcher (1959), Edmonds *et al.* (1975), and Issac *et al.* (1982).

Geochemical prospecting, based on a programme of soil analysis, revealed a strong arsenic-copper-tin anomaly, lenticular in shape and elongated along the strike of the calcareous beds, on both sides of the valley of the Red-a-Ven Brook (Dearman, 1966). Cassiterite has not been found at the mine but instead a tin-bearing analogue of titanite, the mineral malayaite ($CaSnSiO_5$), is present in the wollastonite hornfels. Investigations of tin contents in other associated minerals present in the calc-silicate rocks show that both grossular and andradite also carry significant tin values (El Sharkawi and Dearman, 1966).

The rare mineral malayaite was first collected from the Red-a-Ven Mine in 1948 by G.F. Claringbull, on a visit to the Meldon area by the International Geological Congress. The mineral was shown by Claringbull (pers. comm.) to be isostructural but not identical to titanite.

Further studies by Claringbull (unpublished) showed it to be malayaite with about 0.2 wt% TiO_2 and 0.7 wt% FeO. Malayaite is generally cream or yellowish-brown in hand specimen, and although it is often hard to identify a useful determinative property for identification is its white fluorescence in ultra-violet light.

Interpretation

An area of important mineralogical interest occurs in the Meldon area, on the north-west margin of the Dartmoor Granite, where a strip of folded Lower Carboniferous chert, shale and subordinate limestone country rocks border the granite contact. Contact metamorphism and metasomatism have produced a calc-silicate mineral assemblage with garnet, vesuvianite, wollastonite and diopside. Some of the Mn-rich horizons contain a complex assemblage of Mn silicates including bustamite, spessartine, rhodonite and tephroite (Howie, 1965). A further phase of metasomatism led to the formation of Fe- and B-rich skarns, with an assemblage of hedenbergite, Fe-wollastonite, andradite, axinite and datolite, these phases tending to replace earlier-formed minerals. Finally, ore minerals were introduced after the silicates, leading to crystallization of sphalerite, pyrite, chalcopyrite, arsenopyrite, molybdenite and löllingite. Scheelite has been recorded from the area, especially at Ramsley Mine, as well as a little fluorite. Tin anomalies have been recorded (up to 3000 ppm) during soil surveys over some of the Red-a-Ven area. The tin appears to be localized in silicate minerals, such as malayaite, andradite and grossular.

The bedded mineral deposits at Meldon are at the same stratigraphical horizon as the magnetite deposits in the **Haytor Iron Mine** GCR site, near Ilsington on the south-east margin of the Dartmoor Granite. It is generally thought that this latter deposit was linked to emanations from the granite, although it could be that the deposit was formed from remobilization of bedded iron ores within the Lower Carboniferous country rocks. However the close parallel between hydrothermal activity resulting in recrystallization of cassiterite, hematite and tourmaline deposits in the granite and the metasomatic activity involving tin, iron, and boron in the calcareous sediments appears to show that some epigenetic agencies have been involved. Alderton (1993) showed that stable isotope analyses for the fluids responsible for the massive skarns of South-west England are indicative of an origin from magmatic waters.

In the mining region of South-west England, tin generally occurs as cassiterite in a gangue of tourmaline, chlorite and quartz in granite or 'killas' (normally slaty country rocks). On Dartmoor the paragenesis is cassiterite, tourmaline, specular hematite, quartz and a little pyrite. This ore assemblage is well typified by the mineralization at the Birch Tor and Vitifer Mine (SX 687 808) on Dartmoor.

Following the early phase of calcium metasomatism in the calc-flintas it is clear that tin was introduced, locally, with the calcium, aluminum and iron that caused the formation of grossular in the external reaction zones. The same applies to the andradite skarns and to the presence of malayaite in the wollastonite hornfels. Tin is concentrated in garnet or in malayaite. The presence of stanniferous garnet in the non-reactive datolite veins cutting through the deposit of the Red-a Ven Mine shows that tin was still available during the final phase of metasomatism.

The unusual tin occurrence at Red-a-Ven Mine may be indicative of an emanative centre and therefore suggests that part of the mineralization is granite-derived. This could be seen to be true for higher-temperature tin and perhaps tungsten phases; however there is a question over the origin of the sulphide mineralization. It is possible that some of the pyrrhotite was formed by the remobilization of original sedimentary pyrite (Beer and Fenning, 1976). The proximity of volcanic rocks in a condensed Lower Carboniferous shale sequence suggests perhaps that some of the copper, zinc and arsenic contents may have been derived from sedimentary rocks by thermal reworking during emplacement of the granite. Granitic volatiles seem to have been important, however, and led to formation of axinite, datolite, bustamite and fluorite in the skarns. Other components of the ore assemblage may have been introduced directly from the granite along with volatiles. Cross-cutting veinlets of chalcopyrite indicate post-metasomatic deposition, which could indicate a hydrothermal phase which may be co-eval with normal main-stage lode development.

L. Haynes (pers. comm.) has suggested that the Red-a-Ven Mine mineralogy actually represents two skarn assemblages, which have been superimposed, namely:

1. copper-rich exoskarns which resulted from the metamorphism of a volcanogenic sulphide mineralization in ferruginous cherts, (i.e. with little input from granites). Economic deposits where calcareous lithologies have been converted to skarns are exemplified by the Ramsley Mine deposit; and
2. a later Sn-W exoskarn has been superimposed on the copper skarn in the Meldon (Red-a-Ven) area. This skarn may be related to late Li-mica granite intrusions associated with the main megacrystic biotite Dartmoor Granite.

El Sharkawi and Dearman (1966) showed that although the lithologies at the nearby **Meldon Aplite Quarries** GCR site are similar to those at Red-a-Ven Mine, the garnets contain much less tin. In the Meldon Quarries andradite garnets are reported to carry 0.51 wt% SnO_2, while at Red-a Ven andradite garnet contains up to 1.15 wt% SnO_2. In addition, malayaite-bearing rocks at Red-a-Ven may contain up to 6.82 wt% SnO_2 (El Sharkawi and Dearman, 1966), the mineral not being present elsewhere. The richest tin-bearing lithologies all contain wollastonite, indicating that they are metamorphosed limestones rather than cherts. Tin therefore seems to be focused at Red-a-Ven, and although tungsten also occurs within the Red-a-Ven assemblage its occurrence is more widespread. Such observations led El Sharkawi and Dearman (1966) to propose the existence of an emanative centre at Red-a-Ven, possibly associated with a zonal scheme of mineralization. They also discussed the relationship of iron metasomatism to such a centre.

Conclusions

Lower Carboniferous cherts and limestones lie within the contact metamorphic aureole on the north-west margin of the Dartmoor Granite. Tin is concentrated in these rocks up to 6.82 wt% SnO_2, centred on the Red-a-Ven Mine in the altered cherts, andraditic skarns and the rare tin silicate mineral malayaite.

At Red-a-Ven Mine a sulphide-rich chert bed contains abundant pyrrhotite, arsenopyrite and chalcopyrite. It is associated with narrow bands of wollastonite skarns. These contain tin-bearing garnets and malayaite. Other minerals of interest present are scheelite, axinite, datolite, danburite, löllingite, molybdenite, diopside, hedenbergite and vesuvianite. However, Ryback *et al.* (2001) have demonstrated that the late A.W.G. Kingsbury falsified the localities of numerous rare mineral species. This deception affects a number of locations in the South-west England, including Red-a-Ven Mine, therefore care should be exercised when considering claims by Kingsbury which have not been substantiated or duplicated by subsequent collectors.

Fluids responsible for the formation of tin-bearing skarns and other tin-rich calcareous hornfelses in the rocks bordering the north-west part of the Dartmoor Granite are considered to be related to the granite itself. As such the site is of considerable petrological and mineralogical interest. Red-a-Ven Mine, with its high tin values, may be the focal point within a broad zone of iron-metasomatism. However, this appears to have been superimposed on an earlier sulphide skarn assemblage. The ore assemblage, borosilicate assemblage and tin-bearing silicates make this site of considerable international mineralogical importance.

HAYTOR IRON MINE, DEVON (SX 772 770)

Introduction

The Haytor Iron Mine GCR site, at Haytor Vale, lies 4.5 km west of Bovey Tracey. Haytor Iron Mine provides underground exposures of stratiform iron ores sited within the metamorphic aureole at the eastern margin of the Dartmoor Granite (see Figure 7.15). The deposit is the largest and best developed of a group of iron mines in the eastern Dartmoor region which are notable for the presence of magnetite and various calc-silicate minerals.

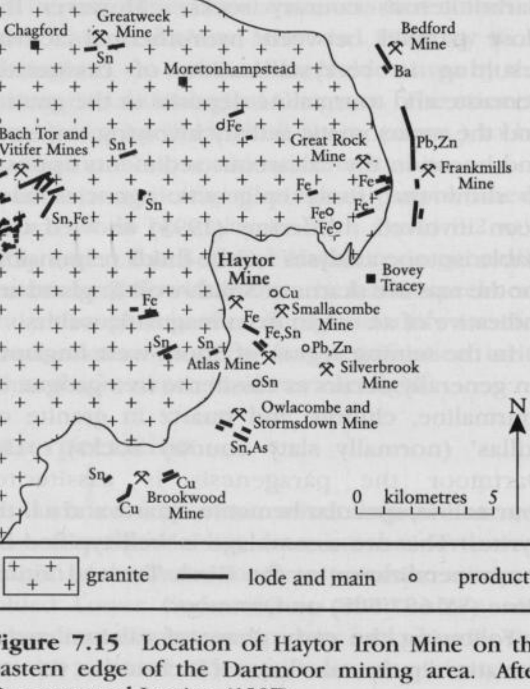

Figure 7.15 Location of Haytor Iron Mine on the eastern edge of the Dartmoor mining area. After Durrance and Laming (1997).

The iron mines of the district to the west of the village of Ilsington include Haytor Mine, Smallacombe Mine (SX 777 766), and Atlas Mine (SX 778 762), and have a long history of working. Dines (1956) stated that 'lode stones' were known from Haytor Mine in the 16th century or earlier, and recorded the production of various types of iron ore, including magnetite, 'brown hematite' and mineral pigments, in the 19th century. There was some prospecting in the 20th century in the period leading up to and including the First World War, after which the mines remained closed. Hamilton Jenkin (1981) reported that Haytor Mine was developed opencast (SX 7715 7703) and by an incline shaft prior to 1828, and that Smallacombe Mine was worked initially by adits, but was subsequently developed as an open quarry, known as 'Smallacombe Cutting'. At Haytor Mine, in the period after 1828, the mine was worked by an adit level driven from a portal (SX 7728 7713) in the valley bottom some 200 m east of the Rock Inn at Haytor Vale. This level intersected the ore some 36 m beneath the opencast workings and is the principal means of access at the present day. Haytor Mine has received considerable attention from geologists and mineralogists, including Foster (1875), MacAlister (1909), Collins (1912), and Scrivener *et al.* (1987).

Description

Haytor Mine is situated some 500 m to the east of the contact of the Dartmoor Granite, and lies within its metamorphic aureole. At the adit level, the portal is driven towards the south-west in a barren sequence of metapelites with thin quartzite interbeds that are mapped as part of the Late Carboniferous (Namurian) Crackington Formation. Some 150 m along the adit level there is a high-angle fault, apparently trending north-east–south-west, which brings the barren metamorphosed shale and sandstone strata into contact with siliceous metapelite, which forms the host rock to the ore deposit. At adit level, the deposit comprises three conformable beds which dip to the north-east at 30°–35°. The uppermost bed is 3.05 m thick, with some 0.61 m of included hornfels waste, the middle bed is 4.27 m thick with some 0.30 m of waste, and the lowest is 1.83 m thick with about 0.3 m of waste. The total thickness of ore-beds and intervening barren hornfels is 11.50 m. Immediately above the lowest ore-bed is a sill-like body of tourmaline-bearing aplite, with irregular margins, up to 0.30 m thick.

The ore-beds are exposed in two stopes, which are partly backfilled with waste, and in short exploratory drives. The higher-level stope, which corresponds to the upper ore-bed, shows faces in low-grade, massive magnetite ore with common partings of hornfels and siliceous or cherty rock. The lower stope, which worked the middle and lowest ore-beds, shows banded magnetite ore with local seams and patches of garnet and minor aggregates of sulphide minerals.

Much of the ore consists of an intimate intergrowth of magnetite and hornblende, which may be massive or show bedding-parallel banding marked by the predominance of one or other mineral phase. Some joints show coarsely crystalline magnetite, and there are fibro-radiate aggregates of hornblende in places. However, in spite of some early references, for example Dines (1956), no actinolite has been found in the ore-beds. A minor component of the ore-beds is garnet, which occurs as discontinuous layers and irregular pockets of coarse crystals. Scrivener *et al.* (1987) demonstrated that the garnet crystals typically comprise a core zone, with an irregular corroded margin, and an outer zone, which is paler in colour. In terms of composition, XRD and SEM-EDA investigations have shown that the core is pure andradite, while the outer zone is andradite$_{90}$–grossularite$_{10}$. Other minor minerals in the ore-beds include axinite, siderite, calcite and apatite, and there are also traces of sulphides such as arsenopyrite, pyrite, chalcopyrite and sphalerite. Of historical and mineralogical interest is the rare occurrence of pseudomorphs in chalcedony after datolite; these were originally considered to be a distinct mineral species termed 'haytorite' (Lévy, 1827; Phillips, 1827; Tripe, 1827), figured in Embrey and Symes (1987) (see Figure 7.16).

Interpretation

The Haytor iron deposit is considered to be an example of a magnetite skarn, originating from the contact metamorphism and early hydrothermal alteration of a ferruginous host. In consideration of this are two genetic factors, namely, the original nature of the host, and the

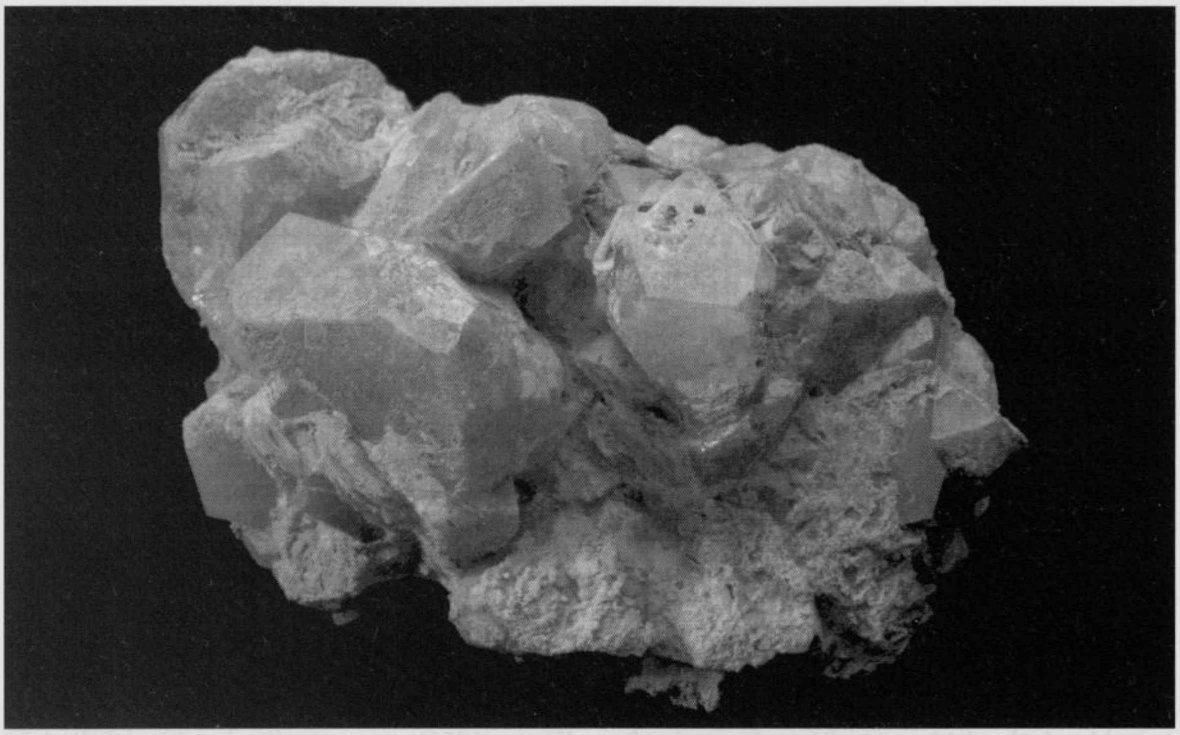

Figure 7.16 'Haytorite' from Haytor Iron Mine, Devon. (Photo: © The Natural History Museum, London.)

source of the metamorphic heat and hydrothermal fluids. As far as the latter is concerned, the proximity of the Dartmoor Granite, and the presence within the deposit of an aplite sill, strongly suggest that the granite and its associated hydrothermal fluids were the main agencies in the skarn formation. Radiogenic isotope work (Chesley *et al.*, 1993) provided a ^{40}Ar-^{39}Ar age of 280.3 ± 1.0 Ma for hornblende from the Haytor deposit, which is in very close agreement with a U-Pb age of 280.4 ± 1.2 Ma for the granite from the nearby Haytor Quarry (Scrivener, pers. comm.). Scrivener *et al.* (1987) drew attention between the similarity of fluid-inclusion characteristics in quartz from the magnetite-hornblende skarn and those in tourmalinite veins and wall-rocks from the Dartmoor Granite, suggestive of a genetic relationship. Other notable magnetite-bearing skarns in South-west England are the cassiterite-magnetite-tourmaline 'floors' of Grylls Bunny, near St Just-in-Penwith (Jackson, 1974), and the cassiterite-magnetite orebodies at Magdalen Mine, Ponsanooth (Dines, 1956), which contrast with the more calc-silicate-dominated skarns exposed at the **Red-a-Ven Mine** GCR site, at Meldon, on the north-west margin of the Dartmoor Granite.

There has been considerable speculation on the nature of the iron-rich host from which the skarn was formed. Foster (1875) favoured the alteration of sedimentary iron ores within the 'Culm Measures', while Dines (1956) suggested an origin from greenstones (altered basic igneous rocks) in the Upper Devonian or Lower Carboniferous strata. Scrivener *et al.* (1987) suggested that the ores represent the alteration of ferruginous beds in the Ashton Shale, which is the lowest part of the Late Carboniferous Crackington Formation. The matter remains problematic as no such protore rocks have been demonstrated in the most recent geological survey. It is considered more likely that the ores have been developed in a faulted block of Lower Carboniferous chert (the Teign or Mount Ararat cherts), which have extensive outcrops to the east of Ilsington, and which comprise bedded cherts with interbeds of calcareous shale and local basic lava and tuff. The presence of the calc-silicate minerals at Haytor Mine certainly supports an origin from a calcareous host.

Conclusions

Haytor Mine is an excellent example of a magnetite skarn, a type of deposit unusual in South-west England, contrasting with the more calc-silicate-dominated domains present on the north-west margin of the Dartmoor Granite, seen for example at the **Red-a-Ven Mine** GCR site. The underground workings preserve exposures of the ore in good condition, associated with examples of minor mineral occurrences such as garnet and axinite.

BOTALLACK MINE AND WHEAL OWLES, CORNWALL (SW 358 328–SW 363 342)

Introduction

The remarkable stretch of coastline from Cape Cornwall to Pendeen Watch is an area of outstanding importance in relation to the history of Cornish metalliferous mining (see Figure 7.17). Here, in cliff section and at cliff top are exposed the geological features of this area (see Figure 7.18), and the multiple dumps still provide opportunities for study of the mineral assemblages of numerous lodes of the area. The lodes were rich in both copper and tin, and exploited by a series of mines such as Wheal Edward, Wheal Owles, Botallack, Levant, and in more-recent times Geevor (see Figure 7.17). All activity has now ceased. The GCR site constitutes the coastal strip which runs from Wheal Edward Zawn northwards to Carn Vellan. An excellent interpretation centre and museum has recently opened at the Geevor Mine site.

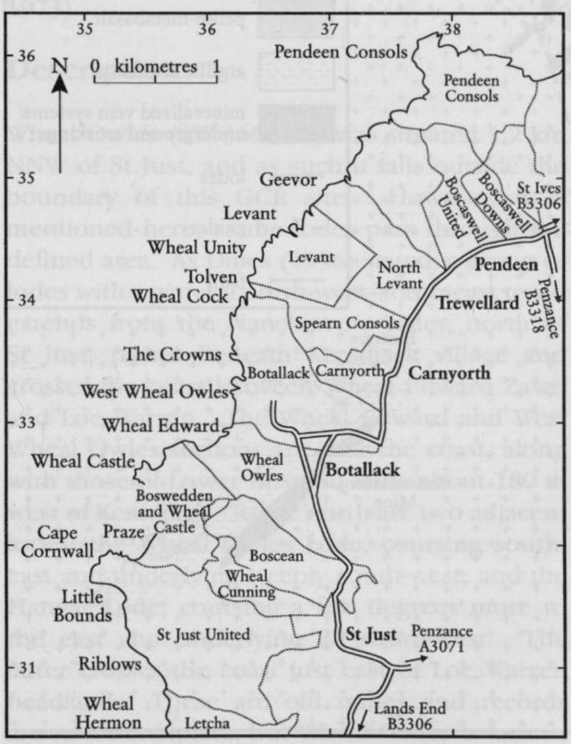

Figure 7.17 Mines of the St Just district. After St Just Mines Research Group (2000).

The Land's End Granite was emplaced into middle- to late-Devonian-age country rock ('killas') consisting of argillaceous rocks containing altered basic intrusions ('greenstones'). Metamorphism and metasomatism of this sequence has caused the formation of a variety of hornfelses and skarns (e.g. below the Botallack engine-houses). The hornfelses can best be studied in a series of minor folds in the cliff section. South of Botallack, the cliff-top exposures are formed of several types of basic hornfelses, some with large cordierite crystals. A series of fine-grained granite intrusions and leucogranite-aplite-pegmatite veins and sheets are common at the contact zone, and are reported as running through the various levels of the mines. The emplacement and consolidation of the granite (in late Carboniferous to Permian times) led to fracturing of the rocks of the metamorphic aureole and the already consolidated granite, so that hydrothermal mineralizing fluids were driven through the rock pile and led to mineralized infill to the available fractures. A great range of mineralized structures were therefore formed rich in a variety of metals. That several phases of mineralizing fluids or fluid movement were involved can be seen by the generally intense sequence of alteration associated with the fissure veins so that both hangingwall and footwall may be feldspathized, hematized or chloritized. Extensive tourmalinization also occurred directly consequential upon the infill.

Full listings of the minerals present for the Wheal Edward–Wheal Cock–Wheal Owles area can be found in the Field Notes, Russell Society AGM Meeting, Cornwall 1998, and are given in Table 7.1

The minerals and mineralization are described in Embrey and Symes (1987), while Dines (1956) gave full details of the mines with

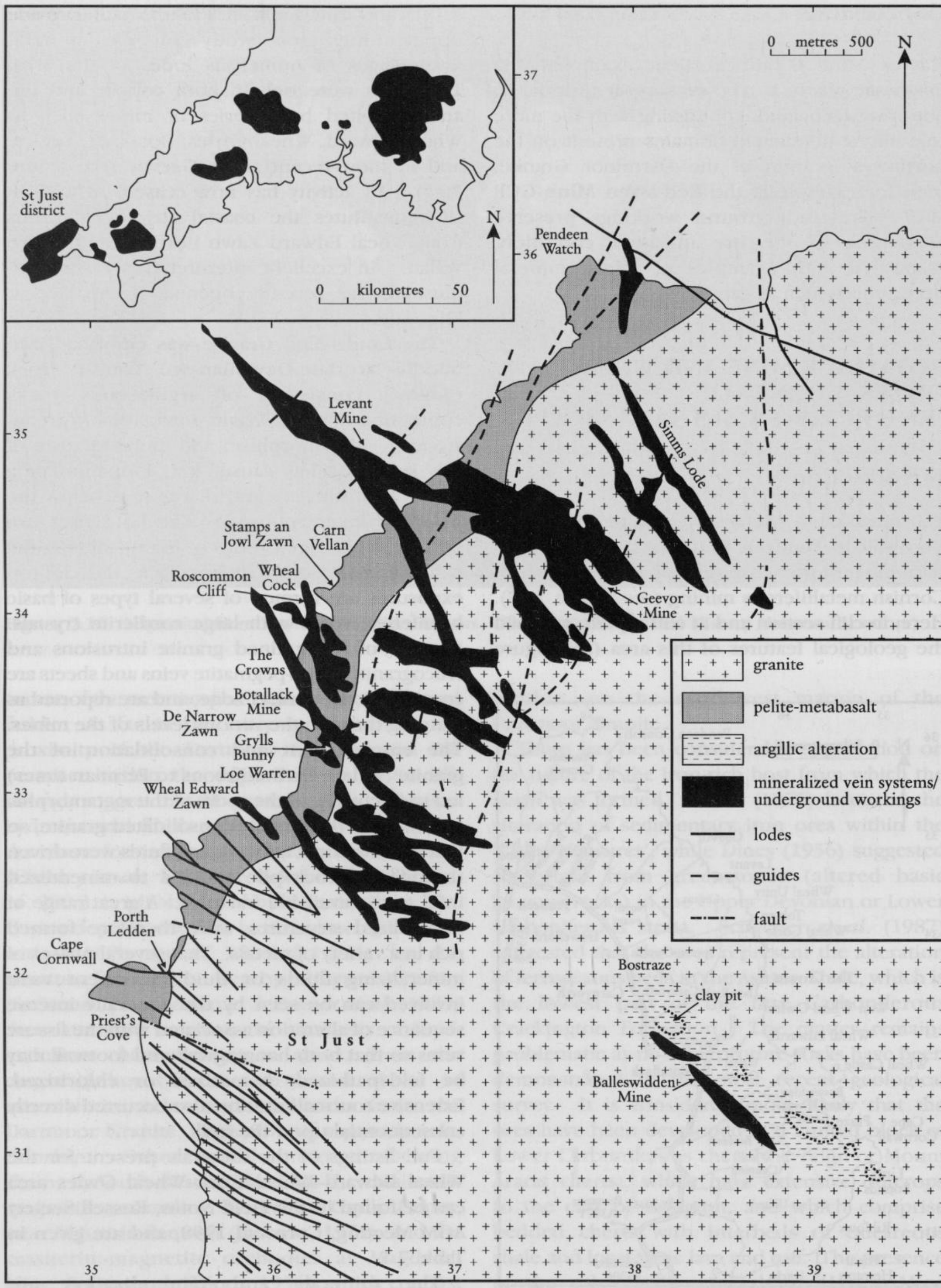

Figure 7.18 Geology and mineralization of the St Just mining district, between Cape Cornwall and Pendeen Watch. After Jackson *et al.* (1982).

Table 7.1 List of minerals recorded in the Wheal Edward–Wheal Cock–Wheal Owles area. From Elton and Hooper (1998).

Actinolite	Chalcopyrite	Kaolinite	Sphalerite
Agardite-(Ce)	Chrysocolla	Kasolite	Torbernite
Amorphous copper sili-	Clinoclase	Langite	Tourmaline
cate	Connellite	Lavendulan	Triploidite
Anthophyllite	Copper	Limonite	Trogerite
Aragonite	Cordierite	Malachite	Tyuyamunite
Arsenopyrite	Compreignacite	Metanovacekite	Unidentified rare-earth
Atacamite	Cumengeite	Metavoltine	calcium uranyl carbon-
Autunite	Cummingtonite	Metazeunerite	ate hydrate
Barite	Cuprite	Mixite	Unknown basic lead
Biotite	Cuprosklodowskite	Neotocite	uranyl carbonate
Bismuthinite	Dewindtite	Novacekite	Uraninite
Boltwoodite	Djurleite	Orthoclase	Uranophane
Bornite	Erythrite	Pharmocosiderite	Uranopilite
Botallackite	Fluorapatite	Phenakite	Vandendriesscheite
Brochantite	Fluorite	Phosphuranylite	Vivianite
Calcite	Galena	Pyrite	Widenmannite
Cassiterite	Goethite	Rutherfordine	Wolsendorfite
Cerrusite	Hematite	Saleeite	Zeunerite
Chalcedony	Ilmenite	Schoepite	Zippeite
Chalcocite	Johannite	Siderite	

recorded outputs. In addition, there is a very extensive literature on the history of mining and industrial archaeology of the area (see Noall, 1973).

Description

Wheal Owles (SW 366 325) was situated 1.2 km NNW of St Just, and as such it falls outside the boundary of this GCR site. However, it is mentioned here, as the lodes pass through the defined area. As Dines (1956) stated, a group of lodes with a general north-west–south-east trend extends from the Nancherrow valley, north of St Just, passes beneath Kenidjack village and crosses the coast between Wheal Edward Zawn and Loe Warren. The Wheal Edward and West Wheal Owles sections are near the coast, along with those of Lower Boscean Mine about 180 m west of Kenidjack. To the north are two adjacent lodes; the Wheal Owles Lode, coursing south-east and underlying steeply south-west; and the Hangar Lode, coursing a few degrees more to the east and underlying 20° south-west. The latter crosses the coast just east of Loe Warren headland. These are old mines and records are never complete, but Wheal Owles is known to have restarted in 1810. In 1863 Wheal Edward was re-opened (although first returns show a date of 1821). In 1880 all of the development faces in Wheal Owles were declared unproductive, although some production continued in the Cargodna section. The mine closed in 1893, due to flooding. In 1978, when the Botallack Mine was reconstructed, the whole of the Wheal Owles group was included. However, no further exploration was undertaken beyond some limited prospecting for uranium (pitchblende) in the Wheal Edward section. Between 1957 and 1959, 19 tons of uraniferous ore were extracted from the Wheal Edward cliff lode by the Atomic Energy Authority (C. Sparrow, pers. comm.).

Economic mineralization within the Owles sett occurs within fissure veins, generally trending north-west–south-east, which inland were locally rich in tin (cassiterite), while coastal sections were enriched in copper (chalcopyrite-chalcocite). Also important in the Wheal Owles sett was the formation of late N–S-trending cross-course veins (Pearce, 1878). These carried argentiferous galena, bismuth and uranium ores. In Wheal Edward pitchblende is said to have occurred on the 40-fathom level, and uraninites (Dines, 1956) on the 20-fathom level. Interestingly a specimen of uraninite from the Wheal Edward cliff lode has been dated at 58 ± 3 Ma (Pockley, 1964). The main-stage mineralization took place considerably earlier, around 270 Ma consequent upon the emplacement of the granite (Jackson *et al.*, 1982). The Tertiary date of the Wheal Edward specimen may be due to remobilization of uranium by later mineralogical processes.

For the period 1821 to 1856 Wheal Edward output is recorded as 2 tons of 'black tin' and 955 tons 9% copper ore. The tips around the Wheal Edward Incline and elsewhere have recently yielded specimens of cassiterite, chalcocite and copper secondaries and the rare mineral compreignacite (Elton *et al.*, 1994).

The West Wheal Owles site includes the exposures in Loe Warren Zawn (Elton and Hooper, 1995) and some mine tips. It is possible to study underground exposures on the Cargodna vein section, and recently a variety of rare supergene minerals have been recorded.

A group of important tin-copper lodes trending north-west–south-east cross the granite–killas contact and the coast at Botallack. Here the coastal strip of metamorphosed killas is underlain by granite at relatively shallow depth. The Botallack Mine, north of St Just, is probably the best known of all Cornish mines. The images of the Crowns section (see Figure 7.19) of the famous Botallack Mine are known worldwide, and the area has World Heritage status for the former mining history landscape heritage. Both the winding and pumping engine-houses are now mostly restored and preserved. The mine is justly renowned for the richness and variety of its mineral deposits. The section of the workings on the Crowns Lode of Botallack Mine (Figure 7.20) shows the relationship of the orebodies to the Land's End Granite.

The mine is noted for the variety of minerals that have been recorded, these being chiefly secondary copper minerals but also include minerals containing cobalt, bismuth, lead, zinc, arsenic, uranium and silver.

The lodes worked together under the name Botallack have been described by many authors, for example Borlase (1758), Pryce (1778), Hawkins (1818), and Dines (1956). The lodes fall into two groups, namely those with a more-or-less north–south trend, and those with an east–west trend. Of the former, perhaps the best known was the Wheal Cock Lode, and of the latter Bunny Lode. The Wheal Cock and North lodes were opened up from Crowns Engine Shaft on the cliffs just south of Wheal Cock Zawn. The famous Crowns Lode (see Figure 7.21) courses S30°E and underlies about 12°E and was worked from the Boscawen Diagonal Shaft. The cavernous stope on the Hazard Lode contains atacamite, rare aurichalcite, botallackite, connellite and native copper. Heulandite has been reported from the adit portal. Skarns are seen in two localities within the Botallack sett. At Crowns Rock (and at depth in the mine) mineralogical zoning in the skarn can be studied, with garnet-magnetite and some axinite being found. At Grylls Bunny the exposures have been formed by mining near-horizontal tin-bearing skarns. In both cases the host rocks are metabasalts and metapelites belonging to the Middle Devonian Mylor Slate Formation.

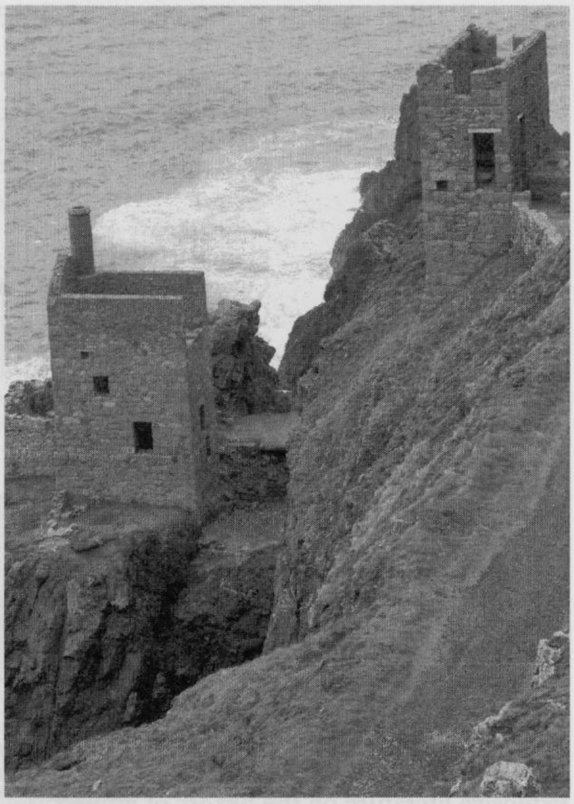

Figure 7.19 Crowns Engine House. (Photo: Kevin Zim.)

The occurrence of 'tin floors' has attracted much attention. These occur throughout the St Just area, but are best seen at Grylls Bunny (Carne, 1822) within the Botallack sett. They consist of nearly horizontal orebodies 1–4 m thick, irregular in outline and 3–12 m across. They occur in killas, greenstone, or granite

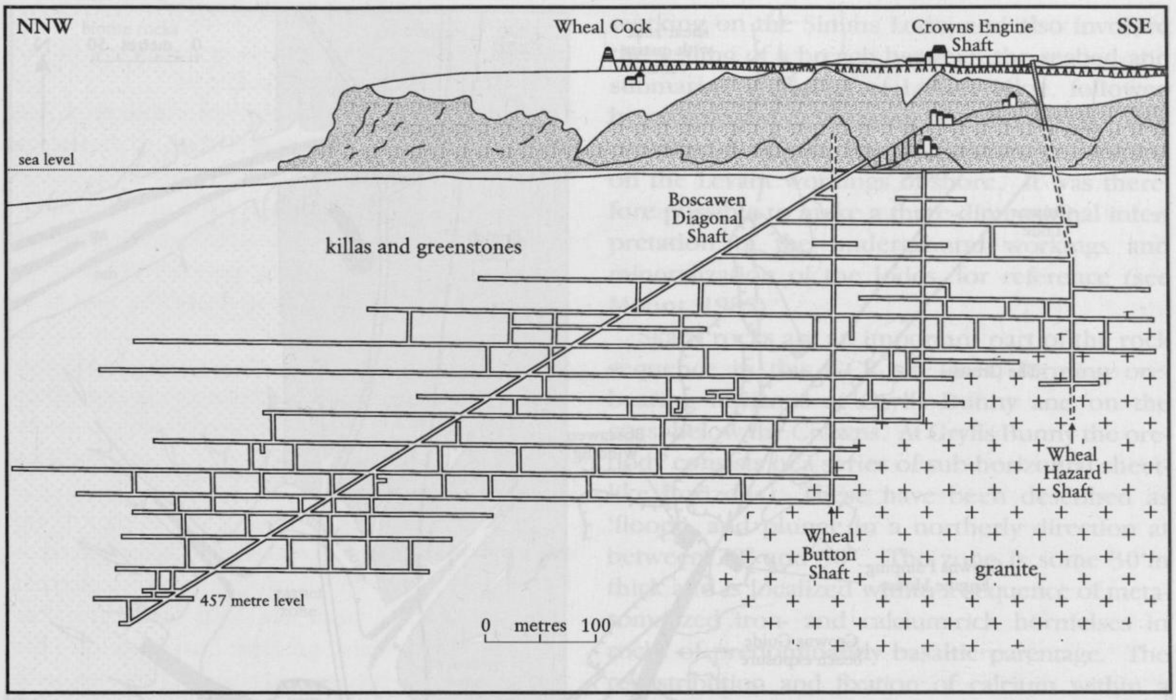

Figure 7.20 Section through the working on Crowns Lode. After Embrey and Symes (1987).

rocks. At Grylls Bunny, several 'floors', separated by a few metres of country rock, occur one above another. The cassiterite in the 'floors' is associated with tourmaline, the latter often occurring as layers with high tin values (Jackson, 1974).

In the Botallack lodes copper was obtained principally from the coastal area in metamorphic rocks, while tin was obtained principally from the inland sections in granite.

The early history of the Botallack mines is not known, although some of the mines were active in the early part of the 18th century. Wheal Cock was re-opened in 1778, and was united with Botallack after 1841. In 1906 all became part of Botallack Mines Ltd. Operations ceased at the end of 1914. Various workings extended 760 m beyond the cliffs; indeed Pryce (1778) quoted that 'The mine of Wheal Cock in the parish of St Just is wrought eighty fathoms in length under the sea'. Collins (1912) quoted a prospectus stating the value of ores between 1836 and 1895 was in excess of £1 million.

Botallackite (a copper chloride) is named for the locality, from where it was found by Talling in 1865, almost certainly from the upper levels of Wheal Cock (see Embrey and Symes, 1987).

On the Wheal Cock section the tips of greatest interest are those around Wheal Hen and around Skip and Crowns Engine Shaft. Specimens of chalcomenite, a rare copper selenide, have recently been recorded. The cliff exposures of Roscommon, Wheal Cock Zawn and Stamps an Jowl Zawn (SW 362 340) are of considerable mineralogical interest. The rare Sn silicate mineral stokesite has been described from the cliffs on the south side of Wheal Cock Zawn, which is the type locality (Couper and Barstow, 1977).

The Levant Mine sett (SW 368 345) and the Geevor Mine sett (SW 372 349), just to the north of this GCR site area, are not discussed here, although they constitute an essential part of the Aire Point to Carrick Du SSSI.

Spectacular developments of cordierite-anthophyllite and cordierite-cummingtonite hornfels in greenstones are best seen at Kenidjack Cliff Zawn. Massive cordierite-rich hornfels, with large cordierite porphyroblasts (1 cm in size) form the rocks on which the Crowns winding engine is built. Below this exposure, the rocks upon which the Crowns pumping engine is built contain a massive, zoned skarn in which an outer amphibole-rich zone and an inner garnet-rich zone can be recognized (Figure 7.22).

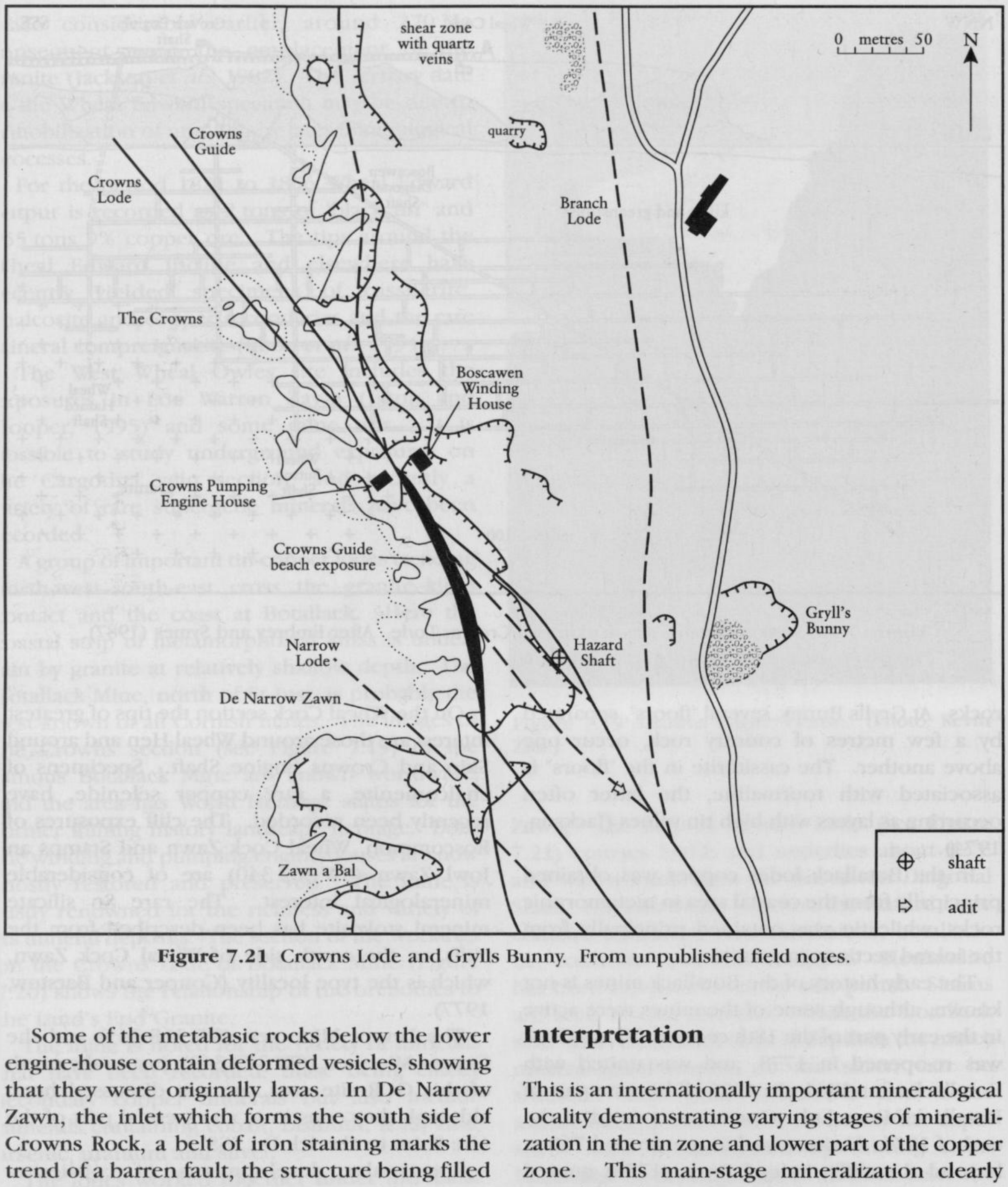

Figure 7.21 Crowns Lode and Grylls Bunny. From unpublished field notes.

Some of the metabasic rocks below the lower engine-house contain deformed vesicles, showing that they were originally lavas. In De Narrow Zawn, the inlet which forms the south side of Crowns Rock, a belt of iron staining marks the trend of a barren fault, the structure being filled only with quartz and hematite.

There appear to be two mineral assemblages in this area, namely a low SnO_2 vesuvianite ± magnetite assemblage with accessory axinite, chlorite, biotite, tourmaline and amphibole, and an Sn-bearing skarn consisting of chlorite, amphibole, cassiterite and titanite, with silicates containing high SnO_2 values.

Tourmaline is invariably present, being late stage and almost certainly associated with mineralization.

Interpretation

This is an internationally important mineralogical locality demonstrating varying stages of mineralization in the tin zone and lower part of the copper zone. This main-stage mineralization clearly post-dates the granite and the metamorphism of the killas rocks. The development of primary skarn assemblages in greenstones and meta-sedimentary rocks, and later tin mineralization has superimposed a secondary assemblage on the primary skarns. This area also provides a study area for petrology, petrogenesis and geochemistry of granite, contact and aureole rocks.

Records from the mines show a story of complex lode mineralization, wall-rock alteration

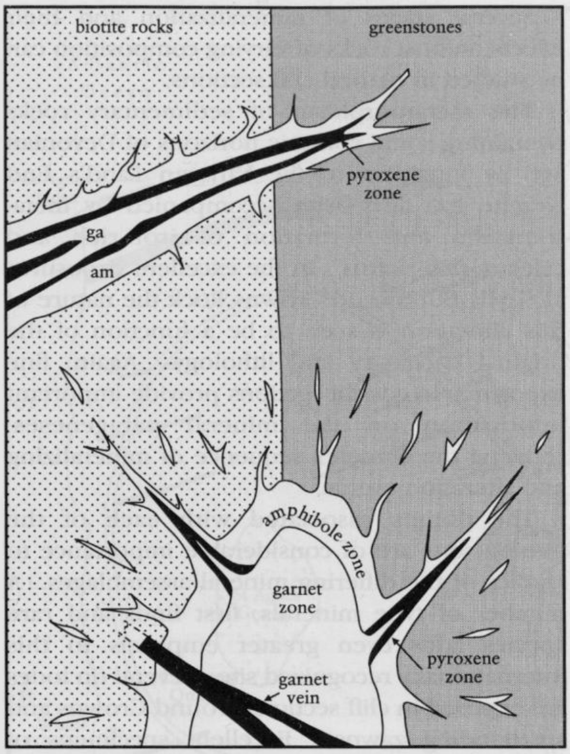

Figure 7.22 Schematic structure of skarn zoning showing the relation between vein and massive skarns ('am' denotes the amphibole zone, the pyroxene zone is shown in black, and 'ga' denotes the garnet zone). After van Marke de Lummen and Verkaeren (1985).

and skarn formation, with many stages of differing metamorphic–metasomatic action and alteration of previously formed assemblages.

The fact that underground access is now so limited, means that three-dimensional interpretation has to be based mostly on former mine records and scientific papers. Important papers are those by Jackson (1974), Alderton and Jackson (1978), and Van Marke de Lummen and Verkaeren (1985).

The Geevor Mine lies slightly to the north of the designated GCR site. However, as it only closed in the 1990s a modern interpretation has been possible. The geological and mineralogical features are relatively similar to all mines of the area (see Figure 7.18), and perhaps the most important evidence for interpretation comes from the studies of the mine geologists at Geevor Mine during the last development period at Geevor Mine. This episode involved dewatering of the Boscaswell Downs Mine, which gave access to the north-east, allowing working on the Simms Lode, and also involved the sealing of a breach between the seabed and submarine workings of Levant Mine, followed by progressive dewatering of lower levels. This provided access to the vein swarm converging on the Levant workings offshore. It was therefore possible to make a three-dimensional interpretation of the underground workings and mineralization of the lodes, for reference (see Mount, 1985).

Skarn rocks are an important part of the rock sequence in this GCR site area, forming ore-bearing horizons at Grylls Bunny and on the coast below the Crowns. At Grylls Bunny the ore-body consists of a series of sub-horizontal sheet-like horizons. These have been described as 'floors', and plunge in a northerly direction at between 20° and 30°. The zone is some 30 m thick and is localized within a sequence of metasomatized iron- and calcium-rich hornfelses in rocks of predominantly basaltic parentage. The re-distribution and fixation of calcium within a metabasite sequence has produced a rock type with a skarn mineral assemblage. Contact metasomatism has locally (and at depth in Geevor Mine) formed rock rich in garnet and magnetite, while the following K-metasomatism caused the development of biotite-rich horizons. The whole is encompassed in relatively undeformed banded hornblendic hornfels.

Mineralization occurred soon after granite emplacement, with some selective boron metasomatism of Al-rich horizons, followed by precipitation of cassiterite and quartz. Mineralizing fluids were controlled by the structure, lithology and chemistry of the zonal rocks. The mineralization associated with the skarn formation appears to be a separate event to the main-stage lode mineralization, and to precede the main tin-copper lodes.

The north-west flank of the Land's End Granite, at Geevor, consists mainly of medium- to coarse-grained megacrystic granite with minor exposures of fine-grained granites at deeper levels, evidence for which is found at various sites at Geevor. Mount (1985) considered that the fine-grained granite is one of the subsequent but important controls of mineralization. The fine-grained granite intrudes the coarse-grained granite as a late differentiate. Where these granite types have penetrated the hornfelses important replacement mineralization has taken place. Several dykes can be traced towards the fine-grained granite masses. The hornfels roof is penetrated by numerous granite dykes of variable dip and strike. Acting as local structural controls some dykes have provided sites for ore deposition. The 'carbona' of Levant Mine is considered to have been formed in this way.

From Geevor and also from records of the lodes within the GCR site, it can be seen that in this area all of the various types of Cornubian Batholith lodes have been fully exploited, which are:

1. mineralized faults ('normal lodes'), which are repeatedly opened mineralized fault structures, the mineralizing fluids here of Sn-Cu hypothermal origin;
2. replacement veins of adjacent wall-rocks, or veins remote from fissures usually due to lithological control;
3. carbonas – rich local replacement of wall-rock by migrating solutions along small fractures, which are most commonly found in the granite assemblages; and
4. stockworks – vein swarms usually associated with granitic cusps.

The hypothermal Sn-Cu lodes were extensively mined from the area. These lodes exhibit a classical zoning, with tin occurring close to the granite contact and copper farther away (Dines, 1956). Crowns Lode is in the copper zone at surface but passes into tin at depth. In Crowns Engine Shaft the granite contact is located at 220 m and slopes at 40° NNW.

Production from the mine also included replacement mineralization in wall-rocks adjacent to the fissure veins, mainly in the metabasites and calc-silicates. Again this development depends both on structural and lithological controls. In places elongate or podiform stockwork systems have formed where sub-horizontal lithological variation in the hornfelses are cut by sub-vertical fractures in the roof zone of the fissure-vein system.

Conclusions

This composite and complex site is of great importance to the understanding of the geological and mineralogical processes in this coastal area of the Land's End Granite contact. Some underground access is still possible in places from the side of the zawns; however dump material still provides the best evidence of the nature and formation of the mineralogical assemblages.

Several stages of mineralization and their effects on host rocks of varying composition can be studied in natural cliff sections.

The metamorphism of sedimentary rocks containing some volcanic horizons of Devonian age by intrusion of the Variscan Land's End Granite has also been accompanied by metasomatism and formation of iron-rich and calcium-rich skarns. In the excellent exposures at Grylls Bunny and Crowns Rock the nature of this alteration is seen to be a function of the original chemistry and lithology. Again, fine exposures in coastal sections provide important information on the mineral parageneses, showing the complex sequence of mineralizing and alteration events.

The dumps associated with each of the mining setts are of considerable importance to studies of the differing mineral assemblages. A number of type minerals, first finds and rare species adds even greater emphasis to this internationally recognized site. Several tin lodes are exposed in cliff sections around Crowns and surrounding zawns. Excellent specimens of the primary tin assemblage are found on the Wheal Cock dumps. This area is the type locality for botallackite and paratacamite, while Roscommon Cliff is the type locality for stokesite. The Wheal Owles dumps have yielded many interesting minerals, particularly around the western section of the mine at Wheal Edward where a range of uranium minerals are recorded. The opencast tin workings at Grylls Bunny and the adjacent area expose the only example of a tin 'floor' deposit on view in South-west England. Here mineralization has selectively migrated along suitable (horizontal) lithologies and structures.

The site constitutes an internationally important locality of the study of mineralogical and mineralization processes.

WHEAL COATES, CORNWALL (SW 698 499)

Introduction

Wheal Coates is situated in the southern part of the Perranporth–St Agnes–Porthtowan coastal strip (see Figure 7.23). It is in an area of considerable importance in understanding mineralization processes in Cornwall, and should be considered in conjunction with the

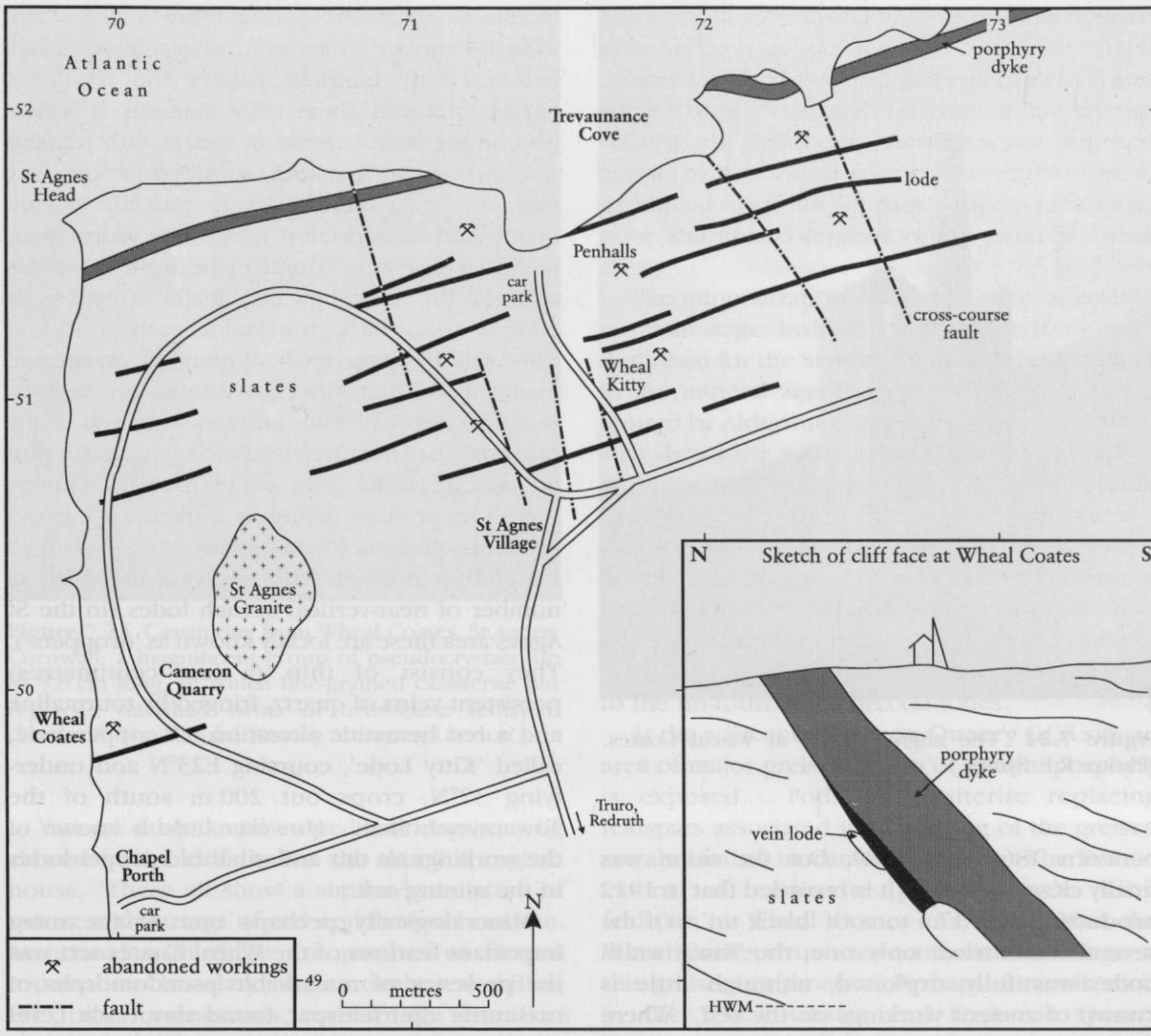

Figure 7.23 Position of major veins and the St Agnes Granite, around Wheal Coates and **Trevaunance Cove**. The inset map shows a sketch of the Wheal Coates cliff lode. Based on unpublished field notes.

descriptions of the neighbouring **Cameron Quarry**, **Trevaunance Cove** and **Cligga Head** GCR sites.

Wheal Coates Mine is situated 0.5 km south-west of **Cameron Quarry**, and lies directly south of St Agnes Head. Various outcropping lodes of the Wheal Coates sett, especially the Towanwrath Lode, are excellently exposed in the cliffs north of Chapel Porth. At the top of the cliff are the preserved remains of the engine house (see Figure 7.24) and associated mine buildings above Towanwrath Shaft. However, the excellent cliff exposures in the lower part of the cliff are only accessible from the beach, reached from the north side of Chapel Porth at low tide. All other worked features are in steep cliff sections. The cliffs are formed of dark-grey hornfels with some strong psammitic bands. The most important lode, the Towanwrath Lode, is situated directly below the engine house, 600 m north of Chapel Porth. Other minor lodes are marked by small trial adits. The mine produced tin (cassiterite) and some copper. Foster (1878) described the mine, and a detailed account is contained in Dines (1956). Although described as rich in minerals, the old mine has been active only intermittently and was worked until 1889. In 1911 the mine was dewatered and batch sampled, and output was recorded as 10–14 lbs of 'black tin' per ton. Dines (1956) recorded an output of 335 tons of 9% copper ore and 700 tons of 'black tin' in 1836 and

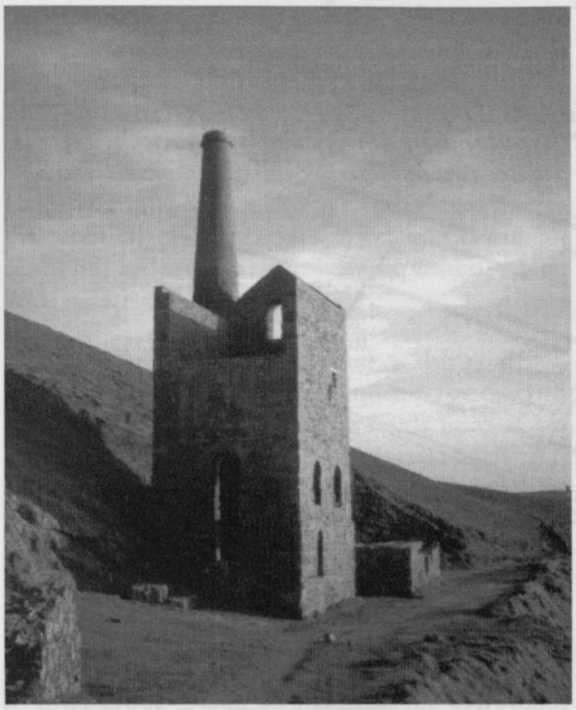

Figure 7.24 The engine house at Wheal Coates. (Photo: R.F. Symes.)

between 1861 and 1889, but the mine was finally closed in 1913. It is recorded that in 1912 production was 17.5 tons of 'black tin'. Of the several lodes tried, only one, the Towanwrath Lode, was fully exploited, although little is known of ancient workings on the sett. Where the lode crops out in the cliff it has been eroded to form a large sea cave.

Description

The lodes of the Wheal Coates sett are in metamorphosed 'killas', traversed by a quartz-feldspar porphyry ('elvan') dyke, and overlie the St Agnes Granite. It is reported that the granite margin along the Towanwrath Lode lies some 500 m offshore (Dines, 1956).

The Towanwrath Lode courses E22°N and underlies 10°–18° south-east, cropping out in the cliff 550 m north of Chapel Porth. In this section the lode follows the footwall of an elvan dyke which is 2.5 m wide and dips 70° south-east and strikes ENE–WSW. In the cliff section the lode is 1.5 m wide, although in the mine it is reported to have been between 0.5 m and 3.5 m wide and to depart from the elvan, so that both the hangingwall and footwall were in killas. The lode is mostly formed of brecciated killas cemented by banded quartz; the whole is covered by red (hematitic) staining. Underground the lode consists of quartz with veins of red and brown hematite, some pyrite and clay minerals. Cassiterite occurs patchily in the quartz and is associated with some tourmaline. Richest areas were found to be from the killas area of the hangingwall, which in places is altered to a dark tourmaline schist and is traversed by interlaced veinlets of cassiterite, mainly associated with clay. Veinlets on the footwall were less extensive and less numerous. It is reported that fractures in the hangingwall elvan do contain some lode mineralization veinlets, the elvan perhaps acting as a barrier to movement of solutions (Dines, 1956).

On the footwall (cliff section) there are a number of near-vertical branch lodes (in the St Agnes area these are locally known as 'droppers'). They consist of thin (a few centimetres) persistent veins of quartz, fringed by tourmaline and a red hematitic alteration. A copper lode, called 'Kitty Lode', coursing E23°N and underlying 32°N, crops out 200 m south of the Towanwrath Shaft. However little is known of the workings on this and other old copper lodes in the mining sett.

Mineralogically perhaps one of the most important features of the Wheal Coates sett was the presence of remarkable pseudomorphs of cassiterite after feldspar, found about Adit Level (Davey, 1832). The original feldspars were Carlsbad-twinned orthoclase (see Figure 7.25). These classic mineral pseudomorphs were found where tongues of coarse-grained granitic rock about the Adit Level were cut by the lode. These pseudomorphs were found mostly in light-red (hematitic) sand (compare with the **Cameron Quarry** GCR site).

Small opencast workings are seen higher in the cliff, and on the cliff top are the remains of the engine house on the Towanwrath Shaft. Small dumps in the area are mostly formed from red hematite-stained killas, but some blocks still contain arsenopyrite, chalcopyrite, cuprite and native copper. Some of this material may be derived from the copper Kitty Lode. Although the granite margin lies some 500 m from the coast along Towanwrath Lode, several tongues of granite are reported to intersect the mine workings.

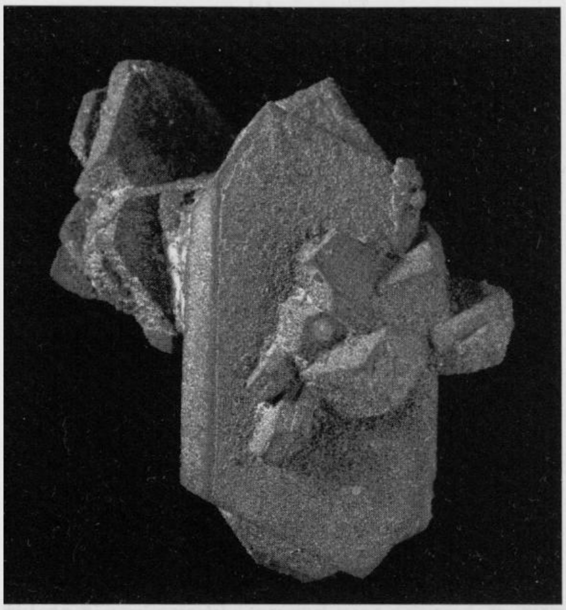

Figure 7.25 Cassiterite, from Wheal Coates, St Agnes, Cornwall: a magnificent group of pseudocrystals, up to 5.6 cm long, in which fine-grained cassiterite has replaced Carlsbad twins of orthoclase feldspar. (Photo: © The Natural History Museum, London.)

Various other small stoped workings can be viewed in the cliffs below the derelict engine-house. These all show a similar association of quartz with strings of red and brown hematite. Associated with these are patches of fibrous tourmaline in slaty metamorphosed killas, the latter sometimes containing abundant andalusite. In the cliff section of the Towanwrath Lode, on the footwall side, there are several vertical smaller branching structures ('droppers'), consisting of the same mineralogical association. They are regarded as being formed by hydraulic fracturing caused by fluid pressure.

Interpretation

Studies of the St Agnes mineralized area suggest that the dip of the Towanwrath Lode is clearly an exception to the regional pattern and should be compared to the observation of Dines (1956) that a copper lode striking ENE–WSW and dipping 32° north outcrops 200 m south of the Towanwrath Shaft.

Wheal Coates is considered to be a tin mine but there also seems to be an anomaly (reversal) of the St Agnes ore mineral paragenesis. Although farther south the Porthtowan copper-producing area is encountered, in the Wheal Coates sett both N- and S-dipping lodes carry some copper. It may be that Wheal Coates reflects the boundary between the tin and copper zones. Both copper and tin have been produced, but tin occurs only in relatively poor amounts compared to the main St Agnes area.

The mineralization at Wheal Coates is related to main-stage hydrothermal mineralization as described for the St Agnes area, and is illustrated in the mineral zonation scheme described and figured by Alderton (1993, fig. 6.30). This figure also shows the modelled migration of the focus of fluid convection away from the granite during cooling and erosion of the overlying sediments, after Sams and Thomas-Betts (1988).

Structures, as seen in the cliff section, which controlled both the major mineralized lode and the elvan, appear to be a series of earlier S-dipping faults. These seem to have formed prior to the tin-tourmaline breccia lodes.

At the adjacent **Cameron Quarry** GCR site an area of major greisenization of granite porphyry is exposed. Pods of cassiterite replacing feldspars associated with jointing of the greisen are also found in Cameron Quarry. The limited extent of cassiterite pseudomorphs after feldspar in Wheal Coates may show that the Wheal Coates structures controlled the fringe of this greisening process. Perhaps mineralization in the Wheal Coates and Cameron Quarry developed during two distinct episodes.

Conclusions

Wheal Coates is best known for its dramatic position overlooking the sea and its restored industrial mining remains. At Wheal Coates, a S-dipping tin lode is developed in the footwall of an elvan dyke in country rocks close to the St Agnes Granite. It is possible that the elvan controlled the emplacement of the lode, and this accounts for the anomalous dip, as compared to the main St Agnes area. However, to the south, within the copper zone, lodes dip both to the south and north. The elvan appears to have been a barrier to movement of mineralizing fluids rather than as a fluid channel-way, as at the **Great Wheal Fortune** GCR site. The site is crucial in understanding the mineralization history of the St Agnes orefield.

LIDCOTT MINE, CORNWALL (SX 240 851)

Introduction

Lidcott Mine is an old manganese mine which worked stratabound pyrolusite and rhodonite ores within a chert horizon, part of a Lower Carboniferous sequence of shales and cherts. The mine was worked both opencast and partly underground in a large excavation. The lower levels are not accessible but the ore workings can be studied in the main cavern. Both the cavern and associated dumps are readily accessible. A partially blocked adit-level occurs at a lower level draining into the river.

Manganese ores are widespread in east Cornwall and west Devon, and are part of a band extending from the Launceston area to Milton Abbot, in west Devon. However, deposits are always small and patchy, and ore grade is generally low. Initially the ores were used in the production of glass, or as a reagent in the manufacture of bleach. Later, manganese was used in the manufacture of steels, but these deposits were not able to compete with imported ores.

There appears to be relatively little literature on the Lidcott Mine, although the mine and minerals present were described by Boase (1832), and Dines (1956). Similar manganese ores to those at Lidcott Mine occur in west Devon, which have been well-documented by Durrance and Laming (1997). An important mineralogical reference to the manganese minerals of Lidcott and other mines in this area was presented by Russell (1946).

Description

Lidcott Mine occurs in an area where the country rocks consist of Lower Carboniferous strata, being essentially shales, with chert beds and bedded lavas. These are also associated with altered intrusive masses ('greenstone'). The ore occurs within a chert bed enclosed by black shales and purple-coloured grits.

At Lidcott Mine the ore was followed underground from an open working and confined to a 2–3 m-thick chert bed which dips at 35°–40° NNW and is recorded to extend for about 75 m along strike. The chert is traversed by several 5–7 cm-wide strips of comby quartz, and is often altered to rhodonite plus a little rhodochrosite. Small crystals of pyrite and galena occur in the altered rock. Pyrolusite impregnates walls and cracks in the rock sequence along with some rhodochrosite (Russell, 1946). On both sides of the cavern, the walls are formed from the bedded sequence, and the nature of the patchy orebody can be inferred from the worked pockets along the strike. Minor quartz-rich veins and some calcite veins cut through the rock succession parallel to the strike. The deposit was worked mostly from irregular pockets where the black ore (pyrolusite) and rhodonite occurred. The main cavern area measures about 15 m by 10 m and is some 3 m high. At depth there are several side passages, some of which contain patches of manganese ore. All the old shafts and trenches to the north-east have been filled in and levelled. In the past, dump material adjacent to the workings was used to block the cavern, but the area has now been cleared and is readily accessible.

The mine was active about 1820 and is referenced by Boase (1832), who described the mine as in profitable working and some 20 fathoms deep. Earliest workings were opencast, forming the cavern structure, but later the ore horizons were worked from shafts connecting with an adit-level towards the bottom of the valley. The mine was last worked between 1875 and 1881, when recorded output was 310 tons of manganese ore. The deposit is said to be exhausted.

Blocks on the dumps are mostly of shales, while grey chert blocks present contain rhodonite associated with some rhodochrosite. Both the rhodonite and rhodochrosite are rose-pink and fine-grained with some richer, coarser patches. Although rhodochrosite is intimately intergrown it has a distinctive cleavage; some quartz and pyrite are also present. Large blocks of the main manganese oxide minerals, namely pyrolusite and psilomelane are also plentiful on the dumps.

Rhodonite often occurs as kernels to the manganese oxide ores. The pyrolusite is sometimes botryoidal or occurs as a powdery wad. Blocks of red jasper are also common on the dumps.

The manganese deposits in the Launceston and west Devon area are therefore characterized by the following features:

1. almost invariably occurring in chert beds;
2. having a close association in these beds with intrusive masses of greenstones;

3. an irregular form to the orebodies, which suggests alteration or impregnation of the more siliceous beds in the host rocks. The irregular orebodies are usually linked by cracks, joints and minor faults, and these and the mine walls are stained or impregnated by black oxides of manganese.

Interpretation

The Lidcott Mine GCR site provides a well-exposed and typical example of a suite of small pyrometasomatic replacement orebodies in cherts of east Cornwall and west Devon, of pre-granite age (Alderton, 1993). The ore is predominantly manganese, but disseminated pyrite in the chert has been recrystallized to form cubic crystals, and the chert has often been altered to red jasper. It is possible that the cherts were related to minor volcanic activity of late Devonian to early Carboniferous age, and that manganese mineralization was introduced later, from black siliceous mudstones, probably during Variscan metamorphism. As Lidcott is some distance north of the contact with the Bodmin Moor Granite, the granite does not appear to have directly contributed in any way to the mineralization.

At Lidcott Mine, pockets of ore are found as patchily developed replacements of the chert beds, usually linked by mineralized cracks. It appears that the chert was originally replaced by rhodonite, or an intermediary mineral of which there is no preserved evidence, which was later altered to the black manganese oxide assemblage. The origin of the ores is still a matter of speculation but the lithological control on mineralization and the usual association of mafic igneous rocks suggest that they may have formed from contemporaneous metal-rich solutions associated with volcanism. They appear to be earlier than the main Cornubian Batholith intrusion episode, and therefore do not appear to have a direct genetic association with granite. However later granite intrusions possibly influenced some alteration and remobilization of the orebody. Some lithologies are more favourable to pyrometasomation than others, the replacement ores being invariably found in cherty beds. However, the host rocks may be impure limestones, as at the Treburland Mine, at Altarnun, Cornwall (Russell, 1946).

Scrivener *et al*. (2001) described various manganese assemblages from a number of west Devon mines. Important in these deposits is the early formation of the calcium-manganese mineral kutnohorite. Later silicification and oxidation led to formation of rhodonite and various manganese oxides.

As can be seen elsewhere, for example in the Meldon area of Devon (Dearman and Butcher, 1959), sequences of black pyritous shales, cherts, impure limestones and volcanic rocks commonly contain accumulations of sulphides which when metamorphosed produce pyrometasomatic mineral deposits in the form of skarns and calc-flintas. Strong concentrations of manganese are often associated with such sequences, and manganese minerals are normally well-developed close to greenstone intrusions and within bedded cherts.

In general there appear to be three types of mineralization developed within the Lower Carboniferous succession in South-west England. These are:

1. bedded sulphides, as at the **Red-a-Ven Mine** GCR site, Meldon;
2. bedded iron ores as at the **Haytor Iron Mine** GCR site; and
3. bedded manganese ores as at the Lidcott Mine GCR site.

All three ore-types have been associated with fumaroles linked to contemporaneous volcanism. All three ore-types have been further modified by metamorphism associated with the Variscan Orogeny and granite emplacement.

Further studies are needed to resolve the sequence of mineralization, especially whether the oxide or silicate phases represent the primary mineralization. Comparisons with the **Red-a-Ven Mine** GCR site suggest an origin by selected pyrometasomatic replacement of chert by rhodonite. The rhodonite produced during the low-grade metamorphism–metasomatism then broke down to pyrolusite and wad by late hydrothermal action, leading also to the introduction of quartz and some sulphides.

Conclusions

The Lidcott Mine GCR site demonstrates a stratabound relationship between manganese mineralization and replacement of chert beds. At Lidcott Mine manganese ores have developed along with stringers of comby quartz in a massive chert bed enclosed in black shales. The site also still provides an opportunity to study this type of mineralization in detail and to make comparisons with material from other similar sites, for example Lee Wood (SX 437 836) and Week Mine, Milton Abbot (SX 457 807).

WHEAL EMILY, DEVON (SX 540 498)

Introduction

The small, isolated Wheal Emily Mine (SX 542 498) is situated on the western bank of the River Yealm, close to Wembury and north of Newton Ferrers, in Devon (see Figure 7.26). It reputedly produced lead and antimony, and was reported by Dines (1956) to carry small amounts of silver. This metallic association is suggestive of an epithermal (hydrothermal) deposit, falling into zone 5b-6 of Hosking (1964).

A shallow adit to the mine lies on the northern side of a small stream, situated in a steep-sided wooded valley. Recent work has cleared the adit portal (see Figure 7.27).

There are no records of mine output. However, a specimen of dump veinstone showed a content of 6 oz of silver per ton (Dines, 1956). Probably due to its isolated and well-concealed position there appears to be only limited geological literature on this mine.

Description

Lying on the west bank of the River Yealm, just south of its junction with Cofflette Creek, Wheal Emily was notable for the presence of antimony in association with silver-lead mineralization. Dines (1956) described an antimony lode, coursing E 30°S and underlying south-west

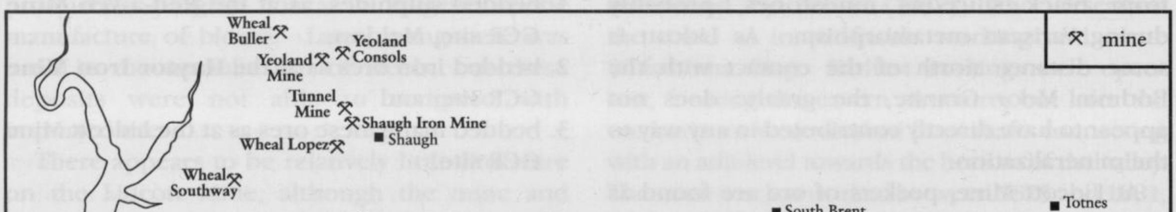

Figure 7.26 Map of Plymouth and the south Devon coast showing the position of the mines in the area, in particular the Wheal Emily GCR site. After Hamilton Jenkin (1974).

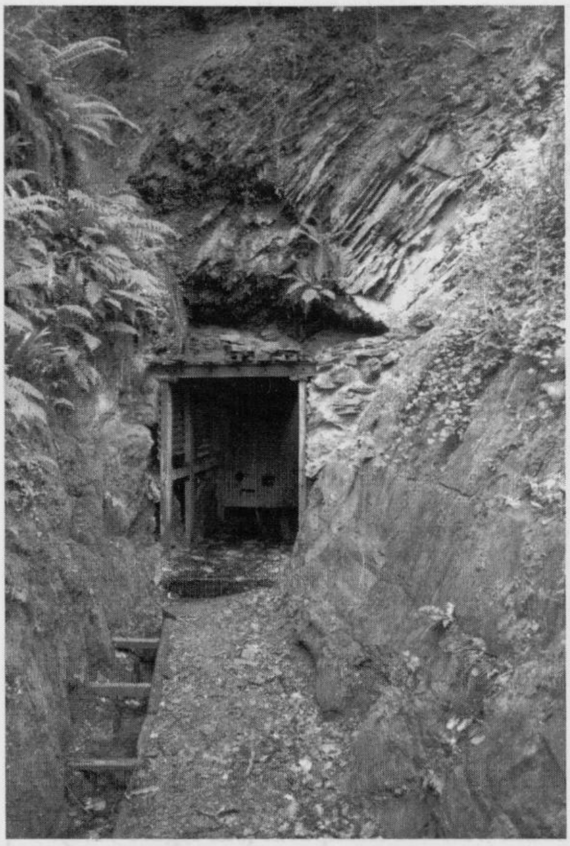

Figure 7.27 The re-opened and gated mine adit at Wheal Emily. The adit cuts through Devonian (Meadfoot Group) beds. (Photo: Natural England.)

which was opened up by a vertical shaft and by two adit-levels. Following earlier working, the mine was re-opened in 1849 when the development consisted of sinking a vertical shaft and driving two adits. In 1849, assays of the ore in the 12-fathom level gave figures of 45 oz, 80 oz and 110 oz of silver per ton. A winze sunk below this level showed a branch of solid lead ore 1 foot wide which was opened up for a length of 24 fathoms. In this the assay value of the silver was said to have been as high as 375 oz per ton. Five assays were made in the following year by a Mr W. Knott, of Wheal Langford, which gave values ranging from 14 oz to 53 oz per ton. A single stone of antimony selected from the dressing-floors yielded 19 oz of silver to the ton. Further rich silver ores were discovered in 1850 and the Deep Adit was cleared. However, it appears that all working ceased before 1852. There is only a limited literature on the mine, the best descriptions being given by Dines (1956), Hamilton Jenkin (1974), and Durrance and Laming (1997).

The shaft is situated in a piece of rough ground bordering the south side of Wembury Wood, about 60 m above river level. Shallow Adit lies in the steep wooded slopes below (90 m ENE of the shaft), and was driven 35 fathoms south-west to where it meets the lode, which it then follows 5 fathoms to the south-east and 20 fathoms to the north-west, passing the shaft on the north-east side. Deep Adit Level is about 30 fathoms below the shaft collar and passes on the south-west side of the shaft, and was driven 25 fathoms north-west and 225 fathoms south-east to its portal on the west bank of the River Yealm.

Dines (1956) reported that a fault trending N30°W passes through the sett but it is not mineralized. The Ivybridge 1:50 000 sheet (Institute of Geological Sciences, 1974) confirms a faulted junction between Lower Devonian Meadfoot Group beds and Middle Devonian slates. The fault is described as barren of mineralization, concurring with the report in Dines (1956).

The country rocks ('killas') consist of light-coloured slates of Devonian age. These dip at 60° to the east and can be seen in exposures above the adit portal. It has been reported that the clearance of the cross-cut adit now allows access as far as the vein (L. Haynes, pers. comm.) and some ore is said to have been worked. Some dumps (mostly killas) line the side of the hill below the adit, and small piles of the characteristic ore-assemblage are now scattered around the site.

A small worked cutting to the side of the mine buildings exposes killas with a little mineralization. Inspection of loose veinstone specimens shows siderite and calcite with blebs of grey, massive lead-bearing antimony sulphides. It has been reported that the ore was a complex intergrowth of jamesonite, with bournonite, boulangerite, semseyite and galena. Small heaps of ore near the mouth of the shallow adit were examined by the late Sir Arthur Russell in 1949 and yielded jamesonite with pyrite and quartz, together with a small quantity of bournonite and galena.

Interpretation

The mine lies in the area bordering the south-eastern margins of the Dartmoor Granite, but is well to the south of the area of granitic mineralizing influence and would appear to be an isolated occurrence. The metallic association is suggestive of lower-temperature hydrothermal deposition, although it is suggested that the mineralized veins at Wheal Emily were not formed as late as the normal north–south cross-course lead lodes.

L. Haynes (pers. comm.) has likened the structural and stratigraphical setting of the mineralization at Wheal Emily as similar to that at Loddiswell Mine (SX 721 515), some 5 km east of Modbury in the South Hams area (see Stanley *et al.*, 1990b). Mineralized faults at Loddiswell are described as having a similar trend to those at Wheal Emily. These faults are described by Stanley *et al.* (1990b) as dextral wrench faults occupying major, linear, NW–SE-trending fracture zones of Variscan age, some of which were re-activated during the Tertiary as dextral wrench faults and hence guided late- and post-Variscan hydrothermal circulation. Although Dines (1956) described the fault at Wheal Emily as being barren, some evidence of faulting of similar trend has been reported in the area, and maybe a fault of pre-Tertiary age parallels the fault at Wheal Emily.

Recent work at Loddiswell has suggested a strong relationship between Au-As-Sb-Pb mineralization along NW–SE-trending faults and stratiform pyrite deposits closely associated with volcaniclastic material in the Devonian sequence. Certainly parts of the stratigraphical sequence in south Devon contain evidence for some volcanic activity; the Yealm Formation contains pyroclastic beds and conglomerates with volcanic debris, and the Meadfoot Group beds are recorded as containing some agglomerate and tuffaceous horizons. Also, there are certainly described examples of exhalative pyrite mineralization in highly altered tuffaceous rocks, as at Ugborough, near Ivybridge (Leake *et al.*, 1985). The deposit at Wheal Emily could have formed due to remobilization of some of these types of deposits. Alderton (1993) recorded the sporadic occurrence of antimony in many cross-courses in South-west England, occurring as thin stringers and brecciated veins in sedimentary and volcanic rocks, suggesting a volcanic-epithermal link, as seen at the **Bwlch Mine** GCR site, in North Wales (see GCR site report, Chapter 5). At Loddiswell the mineralization is considered to be the result of fluid extraction during shear movements on north-west–south-east structures, with structural pathways guiding post-Variscan hydrothermal circulation.

Conclusions

Wheal Emily demonstrates a rare occurrence of lead-antimony ore in South-west England. At present the cross-course mineralization at Wheal Emily is readily accessible in a small, isolated mine-working. Parts of the underground workings allow for the killas and mineralization to be studied. Further research investigations will add to the debate on the influence of volcanic horizons in the stratigraphical record of south Devon and the relationship of the deposit to Variscan and post-Variscan faulting.

CLIGGA HEAD, CORNWALL (SW 738 536)

Introduction

The Cligga Head GCR site comprises two major sections, both illustrating extremely fine examples of endogranitic greisen vein swarms resulting from the fracturing of a granite cusp. Cligga Head is situated on the coast 1.5 km south-west of Perranporth (see Figure 7.28).

Around the derelict remains of the Cligga Mine buildings, near to the position of Contact Shaft, the dumps of waste material contain fine representative samples of the veinstone and the country rocks. The granite is a coarse, white, porphyritic variety grading into, or veined by, dark-grey, finer-grained greisen (quartz-mica rock). The vein material consists mainly of quartz with chlorite and tourmaline, together with the ore minerals cassiterite, wolframite, chalcopyrite and arsenopyrite. To the north-west of the mine, a small quarry at the top of the cliff faces north-eastwards towards Perran Beach. In this quarry can be seen the numerous parallel greisen-bordered veins which have made this locality an internationally important mineralogical site (see Figure 7.29).

From the northern end of this quarry a path leads around the headland, to views of a near-vertical 90 m-high sea-cliff and the beach of a small cove. Looking along the strike of the veins from above the cove, numerous holes mark the entrances (adits) to many old mineral workings. Mining here of tin and tungsten probably goes back to Prehistoric times, and continued on and off until 1945. As a mining proposition, the deposit resembles a stockwork but it was not

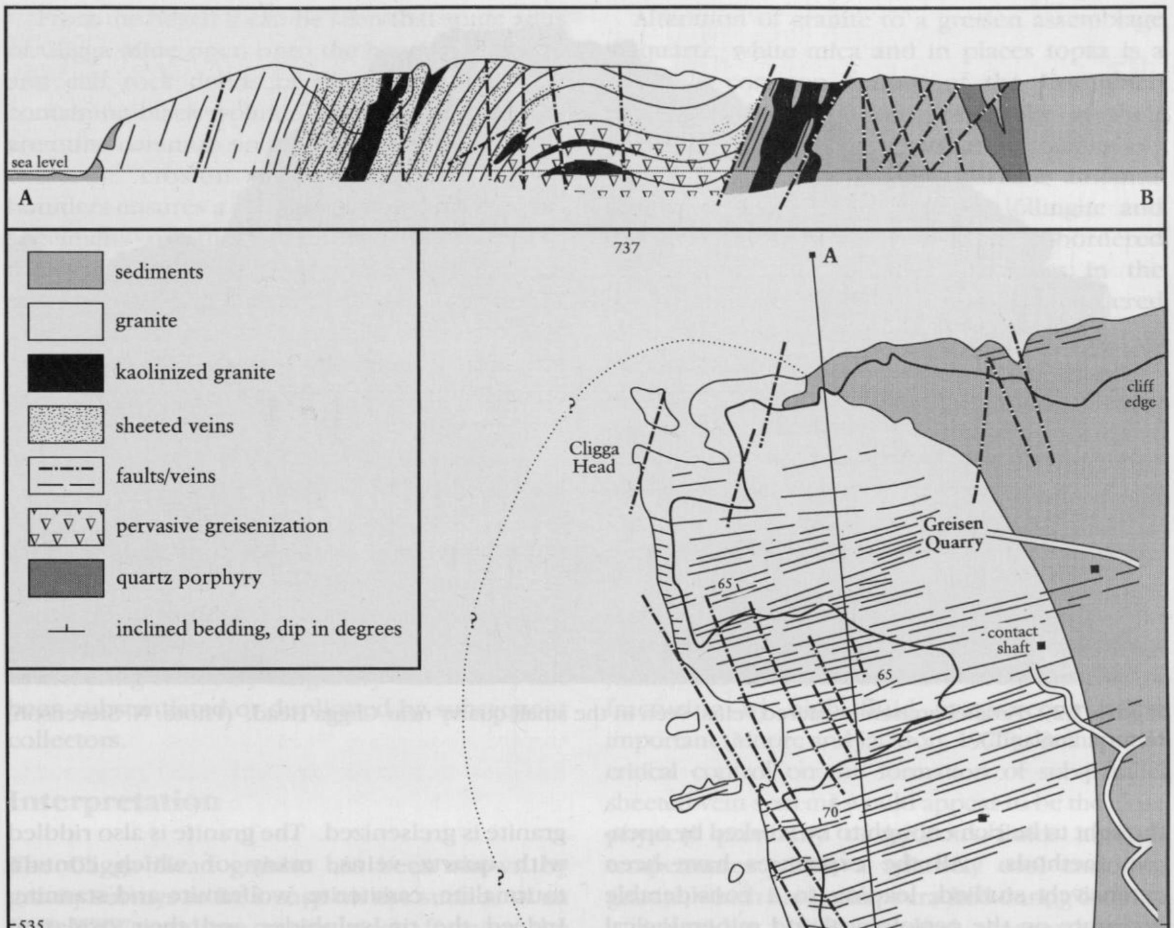

Figure 7.28 Structural, lithological and mineralogical interpretation of Cligga Head. After Moore and Jackson (1977).

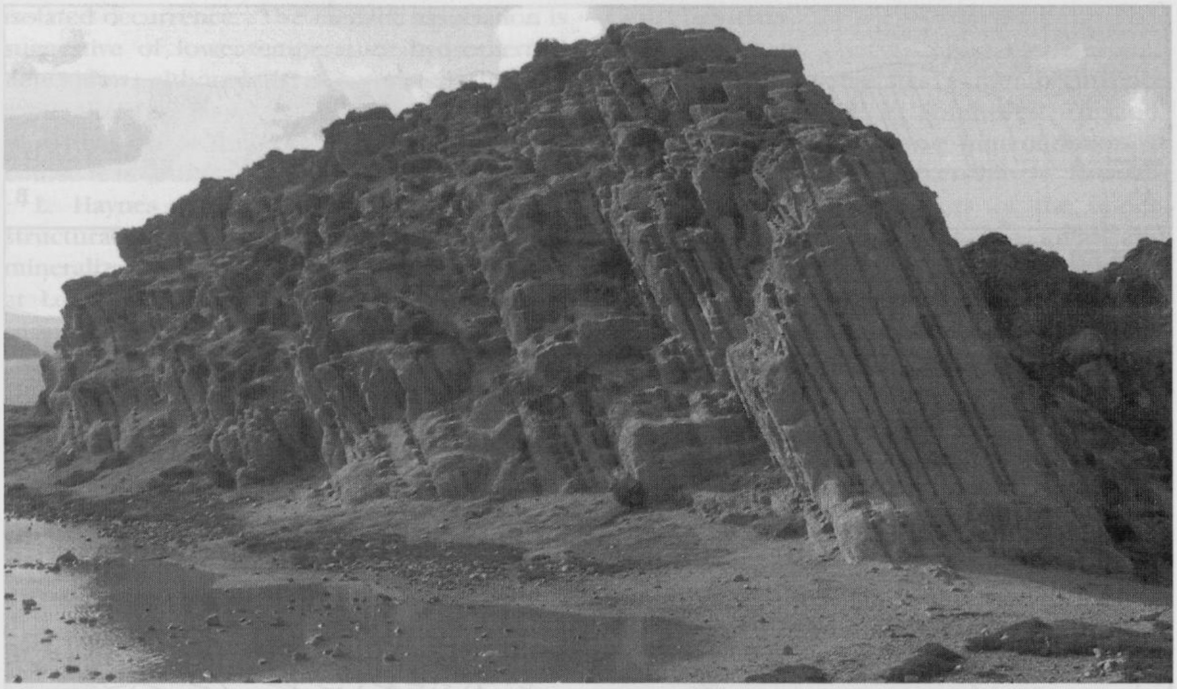

Figure 7.29 Parallel greisen-bordered veins, seen in the small quarry near Cligga Head. (Photo: N. Stevenson, Natural England.)

thought to be rich enough to be worked by open-cast methods. All the exposures have been extensively studied, leading to a considerable literature on the petrological and mineralogical features, including papers in Hosking and Shrimpton (1966) which discussed the mineralization at Cligga Head, Hall (1971) who studied the chemical and mineralogical changes associated with greisenization, and Moore and Jackson (1977) who described the mineralization in terms of the local structural patterns. Dines (1956) presented a detailed account of the mineralization and mining, while a general description is given in Selwood *et al.* (1998).

Description

The sea-cliff and quarried section expose the remnant of the eastern side of a granite boss belonging to the Cornubian Batholith, of Amorican age intruded into Devonian slates ('killas') which have been contact metamorphosed. Contacts with the highly metamorphosed killas at the eastern and southern margins are steep but irregular. Innumerable joints, in the main trending ENE–WSW and underlying steeply northwards, traverse the whole mass. In the vicinity of the joints the granite is greisenized. The granite is also riddled with quartz veins, many of which contain tourmaline, cassiterite, wolframite and stannite. Indeed the tin sulphides and their oxidation products are the most characteristic minerals of the area. Varlamoffite, the secondary alteration product of stannite, was first recorded from this locality. Fine crystalline specimens of some secondary minerals have also been recorded from this locality, for example scorodite, olivenite and pharmacosiderite.

The numerous parallel veins at both the quarry section and sea-cliff range in thickness from a few centimetres up to more than 30 cm. Each vein is bordered by bands of greisen, whilst between the greisen bands the granite is often kaolinized and soft. The veins in the quarry section virtually all dip to the north at a high angle. However in the cliffs the veins appear to be curved into the shape of an anticline and syncline (Figure 7.28). They occupy planes in the granite that are roughly parallel to the contact and form a type of stockwork. Southwards the veins become less numerous and lose the parallelism seen in the quarry section. The rocks also become increasingly iron-stained, along with patches of green colouration, indicative of the presence of copper-bearing veins.

From the beach it can be seen that some adits of Cligga Mine open onto the beach. Boulders and cliff rock debris of the quartz veinstone containing black wolframite and other minerals are quite common on the beach.

Marine erosion of the veins and beach boulders ensures a continuing supply of mineral specimens on the beach, and a rough ore concentration is present due to tidal action.

A large number of mineral species are recorded from Cligga Head, including for instance cassiterite, isostannite stannite, chalcocite, molybdenite, arsenopyrite and wolframite. Cligga Head is also the type locality for the mineral ferrokësterite (Kissin and Owens, 1989). However, Ryback *et al.* (2001) have demonstrated that the late A.W.G. Kingsbury falsified the localities of numerous rare mineral species. This deception affects a number of locations in the South-west England, including Cligga Head. Therefore care should be exercised when considering claims by Kingsbury which have not been substantiated or duplicated by subsequent collectors.

Interpretation

The Cligga Head granite has been shown by gravity surveys to be a cusp on the surface of an ENE–WSW-trending granite ridge forming the largely concealed St Agnes–Cligga Head granite cupola (Bott *et al.*, 1958). The granite is essentially a type-B megacrystic variety, but the presence of zinnwaldite instead of biotite, along with abundant late muscovite ('gilbertite') and topaz, suggest metasomatism by a possible Li microgranite. The granite–killas junction is exposed at the southern end of the western cliff-face. Approximately 2 m from the contact the killas is highly tourmalinized, and beyond that is bleached and traversed by small quartz veins.

The endogranitic greisen veins are joint-orientated. The hard, brownish greisen bands contrast strongly with the white or buff colour of the granite. In the greisen the original feldspars are altered to quartz and muscovite with associated topaz, while occasionally nests of 'gilbertite' and occasional cassiterite crystals are found. The joints, alongside which the greisen occurs, range from thin partings to sometimes fissures up to 15–20 cm in width. In the southernmost 165 m of the section the veins are barren of ore mineralization, and here the greisen has been worked for roadstone.

Alteration of granite to a greisen assemblage of quartz, white mica and in places topaz is a relatively common feature of the Cornubian Batholith granite plutons, especially at their margins. The greisen alteration commonly encloses veins of quartz with variable amounts of cassiterite and/or wolframite, löllingite and other minor sulphides. These greisen-bordered veins often form sheeted complexes in the granite bodies. Usually the greisen-bordered sheet-vein systems show no brecciation and appear to be the result of hydraulic fracturing with controlled egress of hydrothermal fluids. Further, the development of sheeted greisen vein complexes is commonly accompanied by pervasive argillic or sericitic alteration.

In the past, discussions on the origin of greisenization have focused on the importance of fractures in relation to greisen-bordered sheeted-vein system. Hosking (1964) thought that the fractures at Cligga Head were thermal contraction joints, but later authors have seen the role of fracturing by high fluid pressure as being important (Moore and Jackson, 1977). Perhaps the critical control on the formation of sub-parallel sheeted-vein systems would appear to be the close physical proximity of hydrous fluids at high temperatures within a relatively cool enclosing granite, which has perhaps cracked during cooling.

Schneider (1993) studied thermochemical models for greisen alteration, and determined six zones that reflect distance from a fracture and also differences between the amount of fluid percolating into the rock and that simply moving along the fracture. Temperatures along the vein were taken to decrease from about 600°C to less than 400°C, with orthoclase feldspar being seen at the higher-temperature end, and the replacement of feldspar by muscovite at or below 400°C.

Hosking (1964) considered that the apparent folding of the greisen-bordered veins was the result of emplacement in a set of contraction joints, which had formed parallel to a former undulatory granite roof. However, Moore and Jackson (1977) thought that the contraction joint pattern follows the normal dome structure expected above the core of a crystallizing cupola but that faulting had caused modification of the dome on the south side of the core.

The sheeted-vein systems throughout South-west England contain very large tonnages of low-grade ores, but somewhat surprisingly represent only a small proportion of the overall production of tin and tungsten.

Conclusions

The Cligga Head area forms one of the finest exposures of endogranitic greisen-bordered mineral veins in Britain and most probably Europe. The site has attracted the attention of geologists since the early 1800s, when mining was active. The Sn- and W-bearing veins belong to the main-stage mineralization linked to the Cornubian Batholith of South-west England. Comparisons can be made with other areas with greisens in South-west England, for example at the **St Michael's Mount** and **Cameron Quarry** GCR sites.

CAMERON QUARRY, CORNWALL (SW 704 506)

Introduction

The small, disused Cameron Quarry, is situated to the west of St Agnes Beacon (see Figure 7.30). The quarry lies at the south-west end of the St Agnes–Cligga Head granite ridge and provides an exposure of the contact between country rock ('killas') and the St Agnes Granite. The quarry is situated within the St Agnes copper and tin orefield, and consists essentially of highly contorted, somewhat arenaceous hornfelses of Devonian age, intruded in Permo–Carboniferous times by a granite cupola. This high-level magmatic intrusion led to development of a local but clearly defined metamorphic aureole. The igneous mass exposed in Cameron Quarry is a porphyritic granite. A quartz-feldspar porphyry ('elvan') dyke lies to the north of the quarry, and its ENE–WSW trend corresponds approximately to that of the major tin and copper lodes of the district. The igneous mass has experienced extensive greisenization, and although much of the cassiterite- and sulphide-bearing greisen has been removed by mining and quarrying activity, excellent sections are still available for study.

Description

Within Cameron Quarry porphyritic granite is partly covered by biotite-tourmaline hornfels, originally sedimentary rocks of Devonian age. The hornfels has been further intruded by granitoid veins, an elvan dyke, and quartz-cassiterite-bearing veins. Almost all of the visible igneous rock has been converted to a pervasive grey-green 'gilbertite' (muscovite) greisen, but near the hornfels contact red-pink and white potash feldspar megacrysts occur, which have been greisened and later argillized to varying degrees. The site provides an excellent example of endogranitic greisenization associated with the Cornubian Batholith granite(see Alderton, 1993).

Although mineralization is not prolific it is of importance to the understanding of ore genesis in the area. At various places in the east wall of the quarry, within the silicified greisen, small voids are partially filled with cassiterite or tourmaline, whilst in the west wall similar voids contain sphalerite and chalcopyrite. This small quarry is elongated in a NNE–SSW direction. At the north-eastern end, the degree of greisenization, although strong, is at a minimum, the rock being argillized, which may be of supergene origin. Voids in the rock variably contain tourmaline, apatite, cassiterite, wolframite and some copper-bearing sulphides. In the hornfels of the northern part of the quarry there are some cassiterite-bearing veins, which have been followed below surface by a small prospecting shaft. At the southern end of the quarry there are a number of late, steeply dipping veins, each less than 1 cm in width.

Mineralization and mining in the general area has been described by Dines (1956). Although not specifically referenced, Cameron Quarry lies on the edge of the Wheal Coates ore sett. The interpretation below is based on the detailed study of Cameron Quarry by Hosking and Camm (1985) (see Figure 7.31).

Interpretation

Field evidence clearly demonstrates that the quarry is sited on part of a cusp of porphyritic granite, emplaced at high level and from which granite veins and dykes invade the overlying hornfels. Jointing and marked fracturing allowed for fluid access, causing reddening of feldspars, and also greisenization of the whole rock. A set of microfractures to the south of the quarry permitted further mineralizing solutions to invade the rocks, causing extensive silicification, and tourmalinization. This was followed by a period of deposition of cassiterite, a little wolframite and some sulphides and fluorite. At a much later stage quartz and quartz-fluorite veins were emplaced. Supergene activity probably caused the relict feldspar to

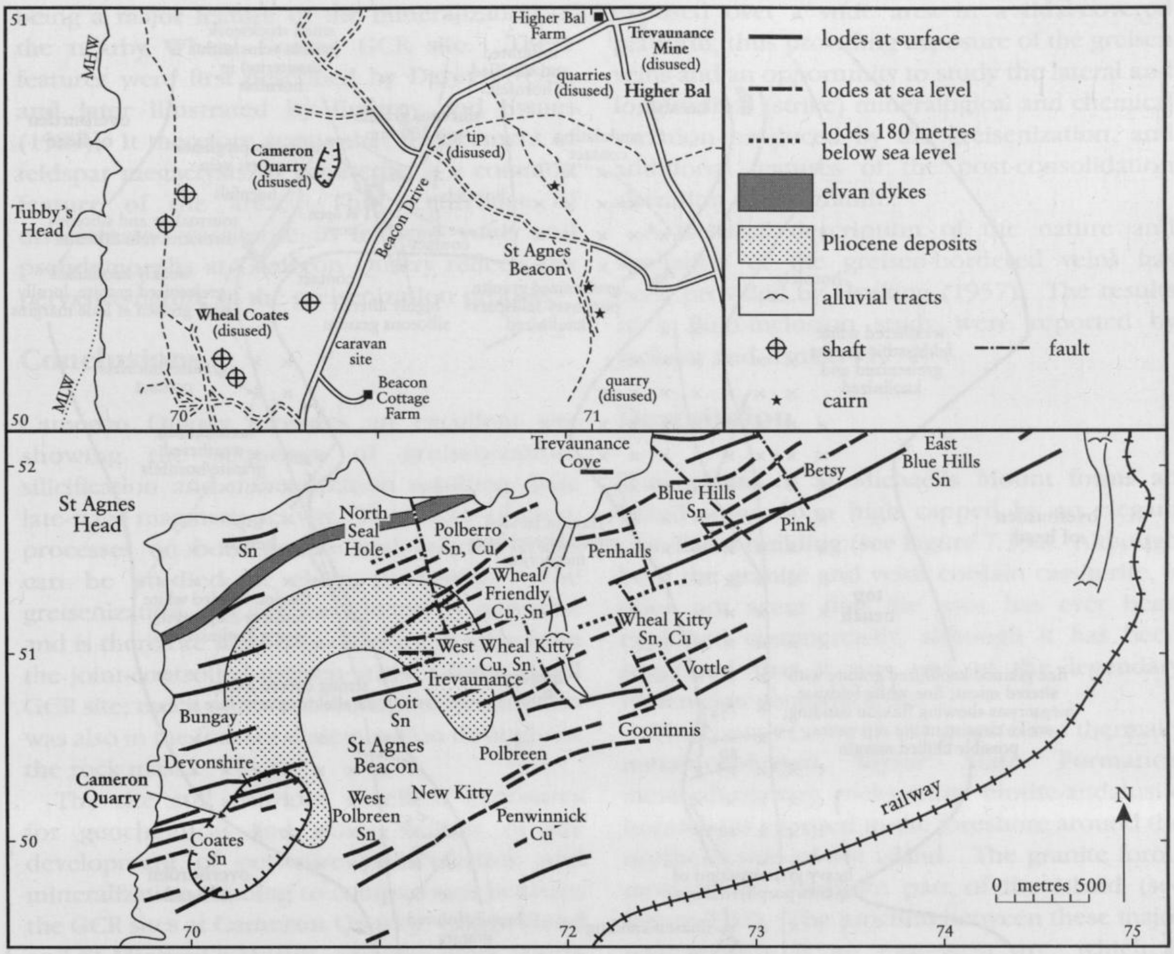

Figure 7.30 Location map of Cameron Quarry showing the distribution of lodes in the area. After Dines (1956).

be argillized. From the available evidence in Cameron Quarry it appears essentially to be a small stockwork within a greisened porphyritic granite.

The massive greisen may be due to ponding of greisening agents under the impermeable hornfels. The important difference to the **Cligga Head** GCR site greisen is that there is no major joint-system, which is so characteristic of the Cligga Head outcrop. At Cameron Quarry a system of open, but very narrow, irregular fractures may have been important.

Hosking (1964) first presented a paragenetic sequence for mineralization at Cameron Quarry. He considered it to be similar to large hypothermal, complex mineral lodes, but which at Cameron Quarry were 'telescoped' into a vertical distance of a few metres. Hosking and Camm (1985) provided evidence that greisenization was followed by silicification, metallic mineral deposition and finally quartz-fluorite veins. Tourmaline is present as a magmatic mineral (as a brown variety) and is sometimes overgrown by a hydrothermal blue variety.

Hosking and Camm (1985) proposed that the greisen spread by a series of randomly orientated microfractures in the granitic cupola, caused by cooling and the increasing vapour pressure of the residual magma. The main feature of the greisen is that it is almost completely pervasive. It seems that the first stage of alteration of the porphyry resulted in the conversion of white feldspar to reddish feldspars. The feldspars of the cusp were replaced wholly or in part mostly by quartz and 'gilbertite'.

One of the most interesting features of the quarry is the degree of greisenization or alteration of the feldspars. It was Coon (1933) who described the occurrence of pseudomorphs of cassiterite after feldspar, this

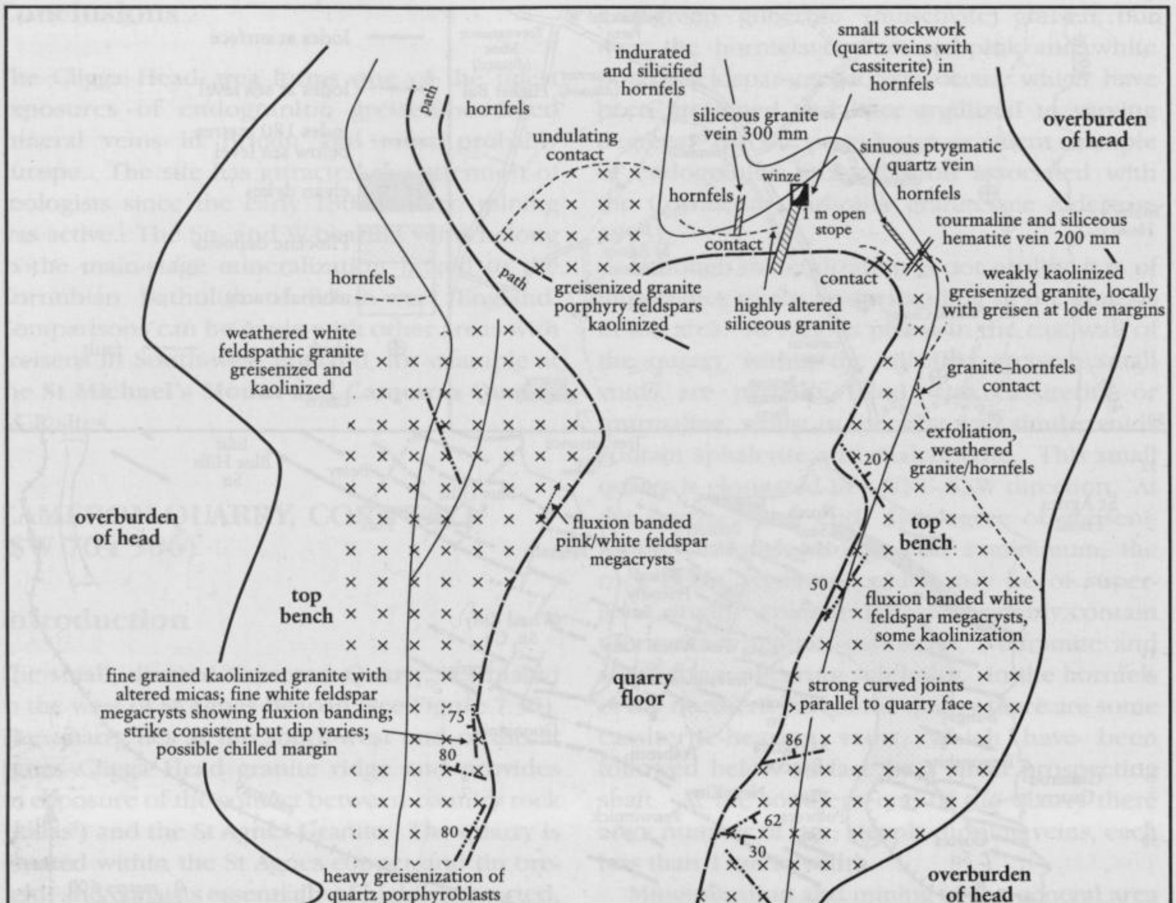

Figure 7.31 Structure and mineralization in Cameron Quarry. After Hosking and Camm (1985).

being a major feature of the mineralization of the nearby **Wheal Coates** GCR site. These features were first described by Davey (1832), and later illustrated by Embrey and Symes (1987). It therefore seems that replacement of feldspar megacrysts by cassiterite is a common feature of the area. The occurrence of disseminated cassiterite in feldspar voids and pseudomorphs at Cameron Quarry reflects the pervasive nature of the greisenization process.

Conclusions

Cameron Quarry provides an excellent site showing the sequence of greisenization, silicification and mineralization resulting from late-stage magmatic activity. The effects of these processes on both granite and country rocks can be studied in close proximity. The greisenization at Cameron Quarry is pervasive and is therefore markedly different in style from the joint-controlled greisen at the **Cligga Head** GCR site; much of the subsequent mineralization was also in the form of dissemination throughout the rock mass.

The site still provides excellent exposures for geochemical and other studies of the development of pervasive greisenization and mineralization, leading to comparisons between the GCR sites at **Cameron Quarry**, **Cligga Head** and **St Michael's Mount**, and also other South-west England greisens.

ST MICHAEL'S MOUNT, CORNWALL (SW 515 298)

Introduction

The megacrystic granite of St Michael's Mount is a fractured cusp of the Cornubian Batholith. Indeed Hosking (1949) suggested that the mount may be the highest part of an undulatory granite ridge extending from Land's End to the Tregonning–Godolphin Granite masses.

The granite contains disseminated tin mineralization and is of considerable interest and importance, as the granite contains an abundance of sub-parallel, endogranitic greisen-bordered mineral veins (see Figure 7.32), rather similar to those at the **Cligga Head** GCR site. At St Michael's Mount the veins are excellently exposed over a wide area in a tidal-covered platform, thus providing exposure of the greisen veins and an opportunity to study the lateral and longitudinal (strike) mineralogical and chemical variation produced by the greisenization, and additional features of the post-consolidation alteration of the granite.

A detailed description of the nature and formation of the greisen-bordered veins has been provided by Hosking (1957). The results of a fluid-inclusion study were reported by Jackson and Rankin (1976).

Description

The granite of St Michael's Mount forms an island some 60 m high capped by an elegant castellated building (see Figure 7.33a). Although both the granite and veins contain cassiterite, it does not seem that the area has ever been exploited commercially, although it has been suggested that it was one of the legendary Phoenician sources of tin.

The contact between the granite and thermally metamorphosed Mylor Slate Formation metasedimentary rocks (now biotite-andalusite hornfels) is exposed in the foreshore around the northern side of the island. The granite forms most of the southern part of the island (see Figure 7.32). The junction between these major components is an east–west arc, which is concave towards the south. As the effects of thermal metamorphism die out between the island and the mainland it is probable that the granite dips steeply to the north.

Large numbers of granite-related veins penetrate into the slate (hornfels) (see Figure 7.33b). Excellent exposures of these can be seen in a more-or-less continuous rock outcrop on the eastern side of the island in line with a small fortification, just above the foreshore. Although large numbers of veins can be seen to cut the quartz-rich hornfels at this rock outcrop, greisenization has not occurred. Several small aplitic and pegmatitic bodies are developed close to the granite contact. Within the western part of the rock platform, parallel pegmatitic veins are cut by some of the greisen veins; in these areas the feldspars have a rough comb-layered texture. Similar comb-layered feldspar-rich veins can be seen at low tide in the beach section of the **Priest's Cove** GCR site, at Cape Cornwall.

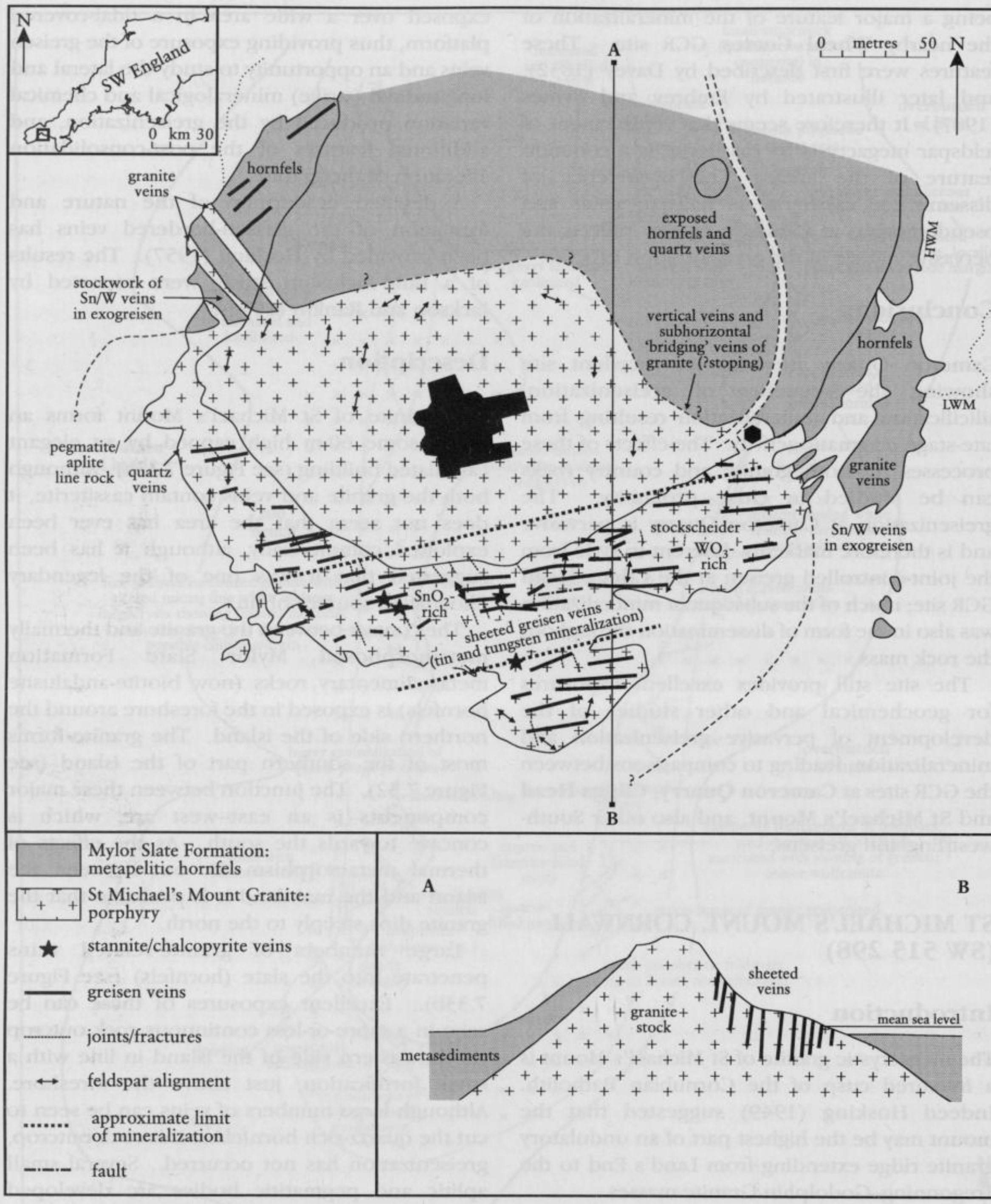

Figure 7.32 Geological map of the St Michael's Mount area. After Halls *et al.* (2000).

The pegmatitic veins are later than the joint system in the granite but earlier than greisenization and mineralization.

The granite is a megacrystic K-feldspar variety with muscovite as the main mica, although biotite increases to the south of the outcrop. Plagioclase is said by Moore (1977) to be about An_{12} (albite–oligoclase). There is very little evidence of post-magmatic alteration, although the granite carries abundant tourmaline and some accessory topaz, fluorite, zircon, apatite, and cassiterite. Cassiterite is most highly

Figure 7.33 (a) St Michael's Mount causeway from Marazion. (Photo: Natural England.) (b) Veins cutting through slate, St Michael's Mount. (Photo: M. Murphy, Natural England.)

concentrated in the west–central portion of the granite platform where veins are most numerous and greisenization most intense.

The swarm of roughly parallel, east–west (20° to the north of east) quartz veins cut the granite, which is altered to greisen on either side of the veins. Some of the greisen structures are up to 1 m in width and may contain several quartz veins. The veins sometimes diverge and then coalesce, sometimes forming large patches of massive greisen. The greisen areas usually consist of quartz, sericite, muscovite, topaz, tourmaline, apatite, Li-mica and cassiterite. The veins are mineralized, and black plates of wolframite, with some cassiterite, can often be seen in the central vuggy parts of the veins. In a few places green secondary copper minerals can be seen to be disseminated in the greisen as well as in the vuggy quartz veins (good examples of copper-carrying veins can be seen below the small gated entrance to the foreshore). In many areas the greisen and quartz veins stand out above the surface (sometimes up to a few centimetres), due to the greater resistance of the veins to erosion in comparison to the granite. The greisen veins can be seen to coalesce, and in places intersect and also open and taper. Hosking (1957) presented a detailed study of the morphology of the veins. Sometimes a vein, perhaps 25–50 mm, shrinks rapidly to only a few millimetres and then 1 m along strike opens up again to its original width. Hosking (1964) presented sketches of the vein types exposed in the wave-cut platform exposures.

Metalliferous minerals recorded in the veins include cassiterite, stannoidite, wolframite, chalcopyrite, arsenopyrite, löllingite and varlamoffite, the latter being an alteration product of Sn sulphides. Gangue minerals are mostly quartz along with tourmaline, topaz and apatite. However, detailed inspection of the veins shows considerable variation in the amounts of the various minerals present such that there may be phases of infill of the veins (or fissures) with changing compositions to the infilling fluids over time. Unlike most of the greisen at the **Cligga Head** GCR site, the mineral veins may not be centrally disposed with respect to greisenization and may not occupy the same fractures. A different timing is inferred for phases of vein infill.

Hosking (1957) considered that the distribution characteristics of the minerals in the veins are of considerable importance when attempting to provide a formation model. For instance the narrow portions of some of the veins may often be very rich in relatively coarse mica at the expense of quartz; such mica may be early and formed along narrow microfractures, which are eventually widened and greisenized. Topaz crystals, rarely more than a few millimetres in length, also occur in the narrow vein areas.

Feldspar tends to become more common as the vein systems are traced from east to west. Also in places throughout the development feldspathization and mica enrichment of the greisen have taken place. Virtually all the vein feldspar is orthoclase.

Interpretation

The St Michael's Mount Granite can be equated with a type-D granite (Exley *et al.*, 1983) similar to that at the **Cligga Head** GCR site, although it is somewhat less metasomatized. The greisen, when compared to that at Cligga Head, contains higher concentrations of Li, F, and P (Hall, 1971; Moore, 1977). The processes that have taken place are similar to other areas of greisen-bordered veins, but the nature of the fissure 'plumbing system' and evolution of the ascending greisenizing and mineralizing fluids warrants further study.

The formation of systems of parallel greisen lodes in the granites of South-west England was discussed by Halls *et al.* (1999), while the influence of fluid pressure in governing fracture geometry and mineral textures was presented by Halls *et al.* (2000).

A general interpretation is as follows:

1. on consolidation of the granite, open fissures were developed (linked perhaps to regional stress, contraction associated with cooling of the granite, or varying gas pressure);
2. solutions then ascended along these fissures, depositing quartz, cassiterite, wolframite and other phases. At about the same time as the minerals were being deposited within the fissures, the adjacent granite was being converted to greisen.

Detailed studies by Hosking and others have, however, suggested that such an interpretation is too simplistic and does not take into account many relevant features, including the greisen-vein relationships, the shapes and nature of the veins, and the varying distribution of the minerals composing the veins.

During the early phases of granite emplacement the adjacent country rocks were thermally metamorphosed and a few quartz-tourmaline veins were developed in them. At about the same time poorly developed pegmatitic and aplitic bands developed in structural traps, while a later magmatic differentiate formed a fine-grained granite, containing feldspar phenocrysts (Hosking, 1964). This stage was followed by the formation of simple, vein-like, feldspar-rich pegmatites, which are usually parallel to the later hydrothermal and/or pneumatolytic veins. Towards the end of the pegmatitic phase mineralizing agents migrated along a series of vertical fissures, and converted the granite to greisen for an equal distance on either side of the fissure passageways. Eventually the micro-fissures along which the greisen-forming fluids passed were further used by mineral-forming fluids. In time a succession of other fissures within the greisened areas and also in the greisen-free granite were opened up and filled. Mineralization may have formed veins by replacement or by the thrusting apart of walls of microfractures. Reactions may have converted the original greisen textures and mineralogy, such that veins became feldspar- and mica-rich areas along with some tourmaline development. A more-or-less final stage of fissure infill gave rise to a mineralogical assemblage of mica, apatite, topaz and quartz, and a large number of replacement veins consisting essentially of quartz. After this a succession of new fractures was initiated, largely in the greisen but also in the granite and hornfels, which are generally wider vein structures, containing much of the cassiterite, wolframite and copper-bearing sulphides.

Conclusions

The St Michael's Mount GCR site provides excellent exposures of endogranitic greisen-bordered mineralized veins in a wave-cut platform. These exposures exhibit the variation in chemistry and mineralogy of the greisenizing process along and across the veins. Comparisons can be made with other greisen-swarm areas of South-west England, for example at the **Cligga Head** and **Cameron Quarry** GCR sites.

MULBERRY DOWN OPENCAST, CORNWALL (SX 019 658)

Introduction

The Mulberry Down Opencast GCR site is situated 2.5 km north-west of Lanivet near Bodmin. At this site a low-grade tin stockwork in country rock ('killas') is exposed in a large open and deep working. The site is of considerable geological and mineralogical importance as the strike of the sheeted-vein structures is almost north–south, a trend almost perpendicular to that of the major Sn-W lodes of Cornwall, as seen for example at the **Hingston Down Quarry and Hingston Down Consols** GCR site. Also, the stockwork is in killas and not granite; indeed the nearest outcrop of granite (St Austell Granite) is some 3 km south-east. This site constitutes an 'exogranitic' stockwork according to the scheme of Alderton (1993). The mineral assemblage consists of cassiterite, wolframite, arsenopyrite and a little chalcopyrite.

Although often cited as an important example of stockwork mineralization, surprisingly little has been written on the geology of the area. Collins (1912) described the Mulberry opencast as one of the most ancient tin workings in Cornwall. The ore was generally low-grade, but the tin ore occasionally occurred in relatively coarse masses (crystals) in soft killas rocks. Old workings were marked on Thomas Martyn's 1748 map of Cornwall. Dines (1956), and Hosking (1964) recorded details of the site, with Hosking referring to the anomalous strike of the mineralization. Recorded output from 1859 to 1916 (its closure date) is 1350 tons of 'black tin' (unrefined tin ore), the average annual yield being about 30 tons and the maximum 77 tons. Some exploratory drilling and other studies were carried out in the 1980s but there has been no further interest since then.

Description

Ore occurs as a stockwork on the high ground of Mulberry Down, numerous mineralized veinlets traversing the host killas in a general NNE–SSW direction. Mulberry is a major deep opencast pit, with very steep near-vertical sides (see Figure 7.34). The pit follows the trend of the veins which are virtually north–south. It is 274 m long and up to 46 m wide, reaching up to 36 m deep, although there are benches at lesser depths. Veinlets occupy joint-fissures ranging from minute cracks up to 15 cm in width, underlying slightly west. The veinlets are often closely spaced, mostly a matter of centimetres but rarely up to 30 cm apart, and are mostly parallel although occasionally running one into another. The killas consists of pale and dark-grey siltstones dipping 45° north-west, which are friable towards the southern end of the quarry but tougher and more siliceous elsewhere. The killas immediately adjacent to the veinlets is of light colour and is usually greisenized and mineralized with tourmaline (especially in the more argillaceous bands) and quartz. The wider

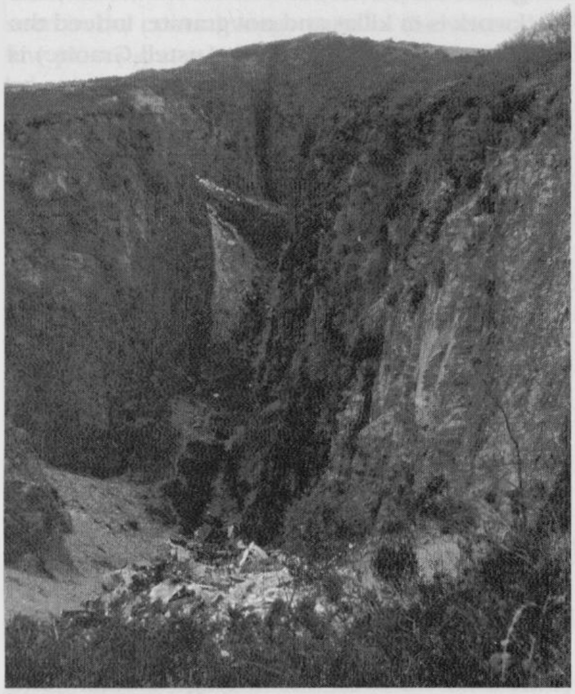

Figure 7.34 View of the open pit at Mulberry Down. (Photo: JNCC.)

veinlets are quartz-rich, and sometimes 'gilbertite' (a variety of muscovite) and topaz are abundant. All the mineralized veins carry relatively coarsely crystallized cassiterite and some wolframite. Arsenopyrite and copper ores (chalcopyrite) are also present. The average content of the rocks of the stockwork is stated to be between 2.75 kg and 3 kg of black tin per ton.

A minor copper lode is recorded as coursing a few degrees south of east and crossing the middle of the quarry, but there is no record that it has been worked for ore. It is also reported that a vein rich in wolframite (iron manganese tungstate) was cut by the tramming level beneath the quarry floor.

The dressing plant, historically known for its multiple heads of stamps, was in the valley 400 m west of the opencut. It was connected by two adits to the workings. The Shallow Adit connects with the middle of the western face of the quarry about halfway between the surface and the quarry floor. This adit is now overgrown and blocked by rocks. The Deep Adit commenced 90 m north-west of Shallow Adit and connected to the floor of the pit, towards the northern end of the quarry, with the tramming level, which ran the full length beneath the opencast. Other adit workings are recorded but all are now not available; some stoping is recorded to have occurred on these. Blocks of rubble of tourmalinized killas can be found in areas around the perimeter of the opencast.

Interpretation

Hosking (1964) believed the Mulberry deposit to be of high-temperature hydrothermal origin and to represent paragenetically early mineralization representative of the upper part of the tin zone, and to be of Hercynian age. Both mineralization and consequent greisenization were hosted by the killas rocks. Some workers, for example Edmonds *et al.* (1975), have commented on the apparent distance from the nearest granite outcrop. However it has been suggested that the Mulberry stockwork is a sheeted-vein complex related to a Li-mica granite at depth, similar mineralization being recorded to the south. The structure and mineralization could be related to north–south granite ridges in the roof of the batholith at depth.

Such mineralized stockworks and sheeted-vein swarms may be separated structurally from mineral lode tin deposits but they may well be related to the same mineralizing event. Alderton (1993) classified the Mulberry deposit as being an example of an 'exogranitic' stockwork belonging to the 'main-stage' mineralization. Vein swarms are generally associated with the fracturing of granite cusps and usually occur within the granite (for example at the **St Michael's Mount** and **Cligga Head** GCR sites), but in places they extend for a considerable distance into the overlying metamorphosed sedimentary rocks, as in the case at Mulberry (see Edmonds *et al.*, 1975). Such vein swarms carry numerous sub-parallel, steeply dipping thin veinlets. These are generally bordered by greisen and carry cassiterite, wolframite, and arsenopyrite. Stockworks comprise an intricate network of veinlets usually too small to be worked individually but of economic importance if worked by opencast methods. They are generally found in the sedimentary strata above such granite cusps, and are usually structurally similar to a vein swarm although not always associated with greisenization. Interestingly most of the other north–south structures in the

Bodmin area are believed to be of a late, low-temperature, cross-course Fe- (or Pb-Zn-) rich mineralization.

The deposit at Mulberry Down used to be compared to the stockwork seen in the workings at Wheal Prosper, 800 m west of Lanivet, but this is not now available for study. At the latter locality it is recorded that the trend of the mineralized belt was E 10°N and characterized by very thin veinlets of quartz and cassiterite, the killas close to veinlets being impregnated with cassiterite. This is probably a distal equivalent of Mulberry Down as regards the nature of the mineralizing fluids.

Conclusions

The Mulberry Down GCR site can be seen to be complimentary to the **St Michael's Mount** and **Cligga Head** GCR sites and also other described Cornish stockworks, but at the Mulberry Down site the stockwork structures and greisenization occur in killas rather than in granite ('exogranitic'). This allows the effects of mineralization and greisenization on various lithogical units of the country rock to be studied. The interpretation of the north–south trend in relation to granite distribution warrants further study.

GREAT WHEAL FORTUNE, CORNWALL (SW 627 289)

Introduction

Great Wheal Fortune was an ancient mine. Cunnack (unpublished ms) reported an inscribed date of 1760 from the 80-fathom level, probably on Carnmeal Lode, located on the east side of a valley 0.8 km ENE of Breage, near Helston. Several lodes branch into a stockwork near the surface where they have been worked opencast. These are known as the 'Conqueror Branches', and can still be studied. Earlier mine-workings have been exposed in the later open-pit excavation. It is a relatively narrow excavation, being 10 m in length and some 18 m in depth.

The stockwork consists of nearly vertical minute tin-bearing cracks. Mineralization is in the Devonian Mylor Slate Formation meta-sedimentary rocks ('killas'), which are also cut by a series of quartz-feldspar porphyry ('elvan') dykes.

The workings of Great Wheal Fortune are mainly east of the stream which drains out of Porthleven harbour, which follows the course of the Great Fluccan (see below). The deposit lies to the east of the Tregonning–Godolphin Granite (see Figure 7.13), in an area where many lodes are displaced over a distance (up to 1 km) southwards by a NNW–SSE-trending fault known locally as the 'Great Fluccan' (Dines, 1956). Normally in Cornish mining terms a 'fluccan' is a clay- and iron-oxide-filled but unmineralized cross-course. However, a few kilometres to the south, near Porthleven, the Great Fluccan becomes a focus for lead mineralization at the **Wheal Penrose** GCR site. The lodes on the east side of the Great Fluccan are important metal producers, thousands of tons of cassiterite and much copper ore having been recovered.

Recorded outputs for Great Wheal Fortune between 1855 and 1868 are 2569 tons of 'black tin' (unrefined tin ore) and 322 tons of copper ore. Tributers (the miners) worked the opencast in later years, and Collins (1912) recorded 423 tons of black tin being recovered between 1873 and 1896. In later years some arsenic and wolframite were raised as well as 3.5 tons of silver ore in 1880. Last output records are for 1896.

Description

The opencast Great Wheal Fortune is divided into two parts by the road track to Carnmeal Downs. The whole area is now much overgrown, especially at the south-western end, where the near-vertical faces are hard to view. The larger part of the opencast north-west of the road can be viewed from various access points, and access can be made to the open-pit floor by a steep path along the northern face. From the floor of the open-pit facing south large stopes can be seen following a mineralized structure trending east–west. To the north of the opencast, thin greisen-bordered veins and stringers trend ENE–WSW. The stoped-out feature is believed to follow a very altered elvan dyke, which has been extensively mineralized.

Great Wheal Fortune, south of Wheal Vor, is interesting due to the formation of both a stockwork of greisen-bordered veins as well as mineralized lodes, leading to two types of working, namely mining of lodes and open-pit working of greisen veinlets. Dines (1956) reported that five lodes have been worked to considerable extent and two other lodes tried.

From the north the chief lodes are Carnmeal Lode (coursing E20° and dipping 40°S), Blueburrow Lode (coursing E30°N, with a slight southerly underlie), Copper (Middle) Lode (coursing E33°N and underlying steeply north), Main (Engine) Lode (coursing north-east and underlying up to 15°S) and New Lode (coursing E35°N and underlying 26°S). Dines (1956) also reported that westwards New Lode joins the hangingwall of Main Lode, which beyond the juncture splits towards the surface to form a stockwork known as 'Conqueror Branches'.

The lodes listed above were worked by a large number of shafts, some of which can be seen fenced and capped amongst the present-day vegetation. A number of elvan dykes have been reported throughout the workings, although because of the extensive vegetation it is not now possible to be sure of the position of these.

Interpretation

Dines (1956) reported that the Great Wheal Fortune ore occurs as light yellowish-grey crystals of cassiterite in veinlets or joints up to *c.* 2.5 cm or so wide (Collins, 1912), with quartz, 'gilbertite' (muscovite mica), tourmaline and some topaz. The killas between the joints is tourmalinized and carries some cassiterite. An elvan dyke crosses the main mineralized belt, and is said to heave the veinlets about 9 m horizontally. It looks here as though some of the mineralization at least post-dates the elvan intrusion, although Collins (1912) regarded the latter as having been formed after tourmalinization of the killas but before the infilling of the mineralized joints. There is still considerable discussion of this age relationship, especially as to whether Dines (1956) quoted Collins (1912) correctly. Hosking (1964) believed that Collins observed that the veinlets were distinctly cut by a quartz porphyry dyke and displaced by it. Unfortunately most of the exposures described by Collins (1912) are either overgrown or not now available.

There is the possibility therefore that there are two distinct phases of mineralization, one pre-elvan intrusion and another post-elvan intrusion. Discussion was focused on the evidence of the opencast sheeted-vein complex, which appears to be similar mineralogically, and indeed petrologically, to those associated with Li-mica granite intrusions elsewhere in Cornwall, although here the veinlets are within the killas. This vein complex is reported to be displaced by a mineralized elvan dyke. However, of considerable interest is the fact that the underground workings strike along a lode system, which is recorded as intersecting an elvan dyke, and which causes refraction of the lode system.

Time relationships and the nature of elvan intrusion and mineralization at Great Wheal Fortune clearly warrant further research. However, it may be that the lode system follows an earlier stockwork in the area and some of the late hydrothermal tin mineralization is derived from such a stockwork. From the observations of various workers, the sequence of events leading to the deposits of Great Wheal Fortune appears to have been as follows:

1. intrusion of Li-mica granite (Tregonning Granite) into a type-C biotite granite (Godolphin Granite), as described in the **Tremearne Par** GCR site description;
2. formation of the ENE-trending sheeted-vein complex with some greisenization above the roof of the Tregonning Granite (tourmaline-topaz-'gilbertite'-cassiterite);
3. displacement of this vein complex by an elvan dyke, in a fissure trending east–west;
4. main-stage hydrothermal tin vein mineralization, superimposed within lines of weakness associated with earlier mineralization, with the tin derived from these earlier structures. Where the hydrothermal vein intersects elvan dykes it is refracted and the dykes mineralized (i.e. the elvan dykes could have acted as channel-ways to mineralizing fluids; and finally
5. formation of Great Fluccan, causing down-faulting to the east and preservation of the mineralization.

Conclusions

This very old, and now much overgrown, opencast is still potentially important in demonstrating mineralization in the Mylor Slate Formation metasedimentary rocks close to the Tregonning Granite. Most interestingly the mineralization occurs in several different environments, namely:

1. a stockwork of greisen-bordered veins;
2. in true lode structures;
3. mineralized elvans.

However, further studies are needed to clarify the age relationship of these phases of mineralization, although certainly the tin mineralization of Great Wheal Fortune is of two generations, namely a sheeted-vein complex within killas probably directly associated with granitic intrusion, and hydrothermal veins closely associated with elvan dyke intrusion. Unfortunately, observations of many of the most interesting features of the structures and mineralization at Great Wheal Fortune are now obscured by rockfall from the faces and intense vegetation.

NANJIZAL COVE (MILL COVE), CORNWALL (SW 357 236)

Introduction

Nanjizal Cove or 'Mill Cove' is located south of Land's End, and exhibits partially mineralized veins within the Land's End Granite in fine cliff and wave-cut beach sections. The mainly quartz-tourmaline veins are situated well within the granite with no evidence of a country rock contact or roof zone. The veins are recorded as carrying only a little cassiterite and wolframite.

The rocks of the Land's End Granite in the cove are cut by numerous small parallel veins resembling a sheeted-vein complex, although carrying quartz and tourmaline this southern area of the granite is only weakly mineralized. No large mines or workings are recorded in the area, although some stoping along the wider veins can be found as small trial pits.

The general granite landscape features are similar to other coastal exposures elsewhere in the Land's End Granite in which very regular and rectilinear patterns of joints give rise to a castellated appearance to the cliff sections.

A recent important detailed paper reports a re-examination of the Nanjizal mineralization by a team from the Camborne School of Mines (Leboutillier *et al.*, 2002).

The Land's End Granite has been studied in detail, and the extensive literature includes the works of Exley and Stone (1964, 1982), Exley *et al.* (1983), Booth and Exley (1987), Goode and Taylor (1988), and Floyd *et al.* (1993).

Description

On the extreme southern side of the cove the granite is well exposed in a series of cliff sections which are cut by numerous near-vertical mineralized fractures similar to a stockwork. The inner parts of the veins contain quartz, which is lined by black tourmaline. Rare, small crystals of cassiterite can be found in the central part of some veins but otherwise the veins contain no ore minerals. The fractures/veins strike across the beach and out to sea. The faulted structure consists of a series of discrete fractures within a zone some 3–5 m wide. Marine erosion along this trend, which is a line of weakness, has caused the formation of parallel rock crags and a spectacular narrow arch (see Figure 7.35). Elsewhere, some of the tourmaline-quartz veins trend around 160°–170°. Areas of the granite where veining is most intense are often reddened, probably due to the alteration of feldspar. The footwall of the major lode outcrops in a waterfall, and the associated cliff section consists of brecciated and tourmalinized granite with tourmaline-quartz veins resembling a sheeted-vein complex. Preferential weathering between the granite and the veins (of various widths up to 60 cm across but mostly a few centimetres) has caused a hummocky surface to the rocks on the beach.

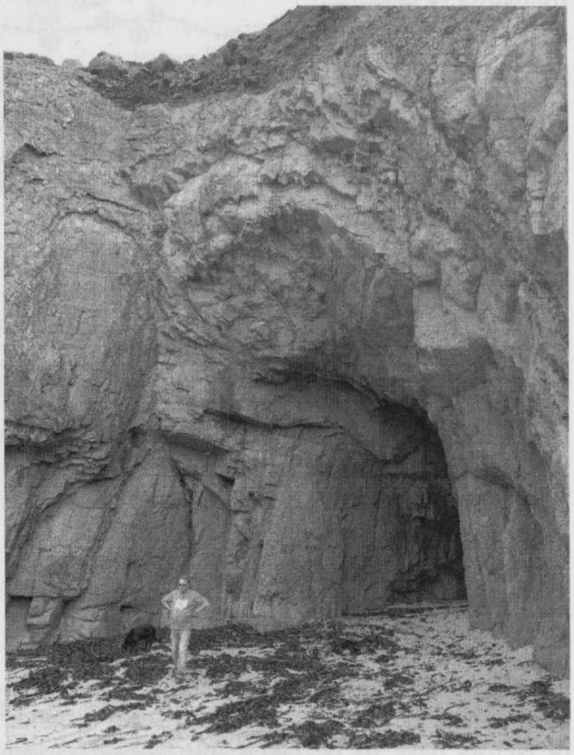

Figure 7.35 Nanjizal Cove. (Photo: Steve Parker.)

The tourmaline-bearing fractures are cut by some small to large cross-course veins. It can be seen that the cross-course trend is the youngest, but in most instances the tourmaline-quartz veins are not noticeably displaced. These cross-courses form a few major structures (*c.* 0.5 m), which contain breccia structures noticeably with crusts of crystalline quartz. These are similar structures to those seen at the **Penlee Quarry** GCR site, on the eastern coast of the Land's End peninsula.

The granite in places grades into a relatively course variety rich in K-feldspar megacrysts, which sometimes show a rough alignment. The feldspars are often a few centimetres in length. Areas of a finer-grained granite can also be recognized.

Narrow veins of black tourmaline with quartz are common in the granite, along with a few nodular patches of tourmaline rock. Around the stockwork area the granite contains a large number of tourmaline-lined miarolytic pockets.

The brecciated structures are formed around unmineralized granite blocks; these appear to have acted as centres for the growth of layers of both quartz and chalcedony. The areas between the granite clasts are heavily reddened by hematite.

Interpretation

High-temperature hydrothermal (hypothermal) quartz-tourmaline veins within the Land's End Granite are well exposed at Nanjizal Cove. At Nanjizal there were several small trial mineral workings similar to others throughout the southern exposures of the Land's End Granite between Land's End and Porthgwarra, although these are all recorded as showing poor contents of ore minerals. To the north of Land's End relatively rich veins are recorded immediately south of Cape Cornwall and to the east towards Sancreed. However the mines and trial workings on these veins produced only low tonnages of ore and are relatively unimportant compared to the major ore production lodes located between Cape Cornwall and Pendeen (see Dines, 1956 for detail of outputs).

In discussing the distinct variation in the mineralization between the northern and southern areas of the Land's End Granite, a large number of factors have to be taken into consideration and the reasons are complex. It is possible that the closeness to country rocks or to the roof zone of the granite, or the presence of metabasic rocks in the succession are fundamentally important to the source of metals, and that deep within the granite perhaps there is little tin and other metals available. Certainly it would seem that the southern Land's End Granite is remote from an emanative centre.

It has been noted that structural parameters might be important; certainly there is a change of joint pattern from the northern to southern outcrop of the Land's End Granite. The major fracture pattern carrying the essentially tourmaline-rich granite veins is north-east–south-west. The rich mineral veins in the Land's End Granite to the north-west, in the Cape Cornwall to Zennor area, have a north-west–south-east trend, whilst to the east the regional trend tends towards east–west. Such changes in pattern can be seen on a local scale at **Cligga Head** in the sidewall of a granite cusp, and possibly the Land's End Granite is related to a later, concealed granite below the present-day erosion levels. However, more likely is a variation in the local stress regime at the time of granite consolidation, emphasizing one direction greater than another.

Geological interpretation of the Land's End Granite by various authors has shown some considerable differences in texture and chemistry. The difference of textural, mineralogical and chemical types of the granite needs further study and interpretation. This leads to discussion of the comparison in the use of textural classifications such as that of Dangerfield and Hawkes (1981) compared with the mineralogical and chemical classification of Exley *et al*. (1983).

Mount (1985) has speculated that the separate evolution and proximity of a fine-grained granite at depth in the Pendeen area has contributed towards the extent of mineralization in the Geevor Mine complex. Perhaps the southern part of the Land's End Granite represents the true metallic potential of type-B megacrystic granite, in comparison to a Li-mica granite which may be present in the Botallack–Geevor area.

Conclusions

The excellent exposures at Nanjizal Cove demonstrate the nature of mineralized veins within the Land's End Granite mass. However the ore mineralization is weak and sporadic.

Two distinct trends of veining can be studied, namely an early phase of tourmaline-quartz-cassiterite mineralogy and a later cross-course mineralization characterized by weathered iron oxides. Within the more pronounced fractured zones in the granite, cassiterite is sparingly found. Some of the veins and associated rocks are noticeably brecciated, with inclusions of blocks of non-mineralized granite (cockaded breccia structures).

The Nanjizal Cove area of the Land's End Granite demonstrates the weak nature of mineralization within the granite (away from contact or roof zone) which can be directly compared with the granitic rocks and contact areas to the north, in the Cape Cornwall–Pendeen area.

The lower-temperature cross-course type of mineralization is characterized by distinctive breccia structures, cockaded structures formed around unmineralized blocks of granite.

DEVON GREAT CONSOLS, DEVON (SX 431 735)

Introduction

The largest mines of Devon were situated in the Gunnislake–Tavistock area, and their output of copper, arsenic and pyrite dominated the mineral production of the county. By far the largest producer was Devon Great Consols, north of Gunnislake, on the Devon County bank of the Tamar. A shipping quay was constructed at Morwellham, on the Tamar, and linked to the mine by an inclined railway track.

The five mines of the group, which constituted Devon Great Consols, were from west to east Wheal Maria (SX 416 737), Wheal Fanny (SX 420 734), Wheal Anna Maria (SX 427 735), Wheal Josiah (SX 428 733), and Wheal Emma (SX 435 735) (see Figure 7.36). The amalgamated mines worked the largest sulphide lode in South-west England. The east–west Main Lode has been proved for almost 4 km and varies between 2 m and 10 m in width. It has been

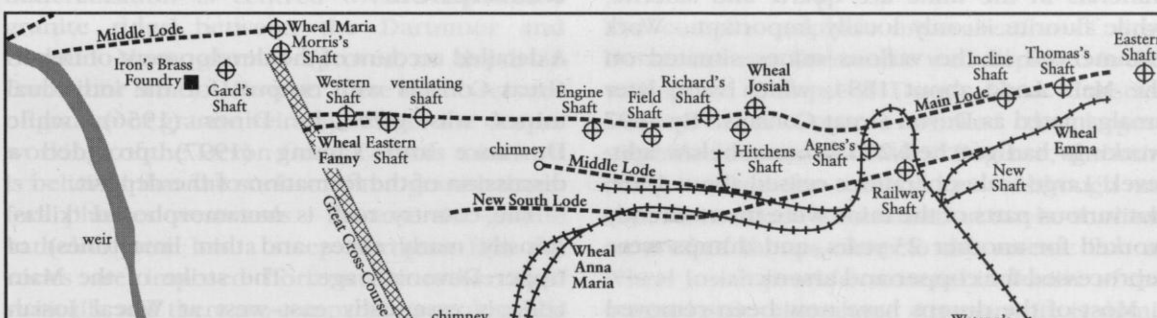

Figure 7.36 Plan of Devon Great Consols Mine.

stoped continuously for much of the 4 km length. Several other lodes have been proved to the south. Throughout the length of workings on the Main Lode there are about 12 shafts to various depths. Details of the mine development are presented in Dines (1956).

Virtually all the surface features of the mines have been obliterated, although the line of the Main Lode can be ascertained by a succession of depressions. Much of the surface debris is calcined waste. By the time of final closure of the mines most of the copper ores had been worked out, but it is reported that a considerable amount of arsenopyrite still remains on the walls of the veins.

Between 1845 and 1906 the mines produced over 0.75 million tons of 6.5% copper ore, 70 000 tons of crude arsenic, and 10 000 tons of pyrite.

During the life of the mines demand for arsenic fluctuated considerably, and at times arsenic was left in the stopes or thrown away on the dumps. As a result, dumps can still be found which are extremely rich in arsenopyrite, which oxidizes relatively slowly. The main gangue minerals in the mine are quartz and siderite, while fluorite is only locally important. Work commenced in the various mines situated on the Main Lode about 1884, which were later amalgamated as Devon Great Consols. By 1897 workings had reached 200 fathoms below adit-level. Large-scale operations ceased about 1902, but various parts of the mine were intermittently worked for another 23 years, and dumps were reprocessed for copper and arsenic.

Most of the dumps have now been removed or reworked for arsenic and fluorspar. The flues and surrounding area at Wheal Anna Maria (SX 427 735) still contain some arsenolite (As_2O_3). The whole area is now part of the Tavistock Woodlands Forestry Scheme, with the exception of part of Wheal Josiah, north of Hawkmoor House Farm (SX 433 735) and the eastern part of Wheal Emma around Thomas's Shaft (SX 440 737).

A well-preserved dump has been located in the general area of Wheal Josiah (see Figure 7.37), specimens from which are typical of the primary mineralization seen on the Main Lode and the South Lode (a loop of Main Lode). The dump contains a lot of massive arsenopyrite and comby quartz, the latter containing well-crystallized siderite and francolite (a variety of apatite). Large blocks of siderite are also plentiful.

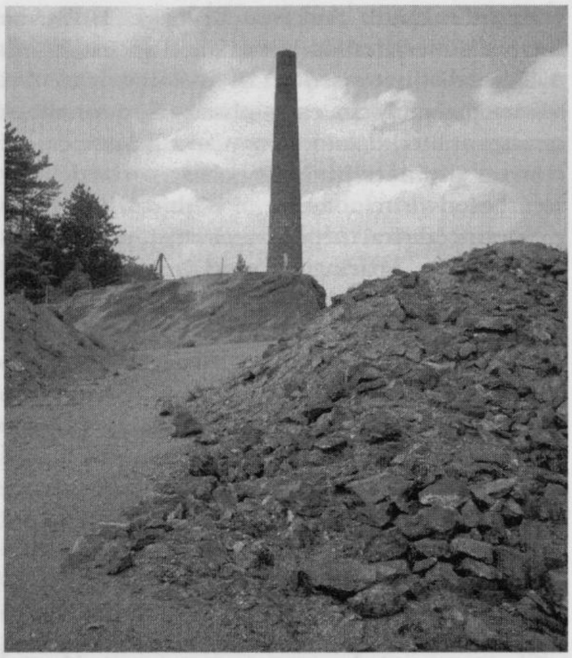

Figure 7.37 Wheal Josiah, showing the mine dump. (Photo: R.F. Symes.)

Description

A detailed account of the development of Devon Great Consols with outputs for the individual mines was given by Dines (1956), while Durrance and Laming (1997) provided a discussion of the formation of the deposit.

The country rock is metamorphosed 'killas' (mostly marly slates and thin limestones) of Upper Devonian age. The strike of the Main Lode is essentially east–west at Wheal Josiah within the Wheal Josiah sett, and the strike then changes from east–west to E12°N. The Main Lode had a gossan, which extended to depths of 20–40 fathoms, and at depth the lode typically varied from 5 m to 9 m or more in width. In some areas rich ore-shoots 12 m wide carried chalcopyrite and arsenopyrite. The deepest shaft was Richard's Shaft at Wheal Josiah, 300 fathoms below surface. The major drainage cross-cut was known as the 'Blanchdown Adit'.

In the Gunnislake–Tavistock area the lodes are cut by late NW–SE-trending cross-courses, some displacing the earlier veins by several metres. In Devon Great Consols, the Great Cross-Course heaves the Main Lode some 225 m in a right-lateral (dextral) sense. Most of the cross-courses dip westwards at moderate to steep angles but carry only a little galena and sphalerite mineralization.

The lodes all have strikes between ESE–WNW more-or-less paralleled by the associated quartz-feldspar porphyry ('elvan') dykes, and mostly dip steeply either north or south. At Devon Great Consols the central parts of the lodes rich in copper were worked first and the outer parts worked later for arsenopyrite. Some of the arsenopyrite occurred in large lensoid bodies up to 2 m thick.

Surface alteration of the veins is a marked feature of this area and extends to considerable depths. Dines (1956) recorded gossans in Devon Great Consols from 75 m to 110 m.

Interpretation

The mineralization at Devon Great Consols is of hydrothermal origin, and only traces of cassiterite are present, the recorded total output for Devon Great Consols being 21 tons of 'black tin'. Discussion of the formation of the deposit has always focused on the depth of granite below the mine. It is believed that major mineralization is centred over a concealed granite ridge between the Dartmoor and Bodmin Moor granites (proved at depth in Frementor Mine). However there are no records of granite or granite veining even in the deeper workings of the Devon Great Consols mines. It is believed that the surface of the granite therefore plunges westwards. Because the granite batholith here has a steep northern face the zones are imposed horizontally rather than vertically, and there are comparisons geologically between this area and the Botallack area of west Cornwall. The presence of siderite in the gangue, rather than hematite, reflects the calcareous nature of the host rocks. The slates are marly, and thin limestones are often present.

The question of mineral zonation provides much interest in this area, as the expected tin reserves at depth were not realised at Devon Great Consols. It was believed originally that the tin zone was always present below the copper zone, and several attempts were made to find tin in the lower depths of the mines. It was assumed that the rich copper areas would give way at depth to tin-rich horizons (see Barclay, 1931). The Richard's Shaft of Devon Great Consols was tested to 550 m depth. A well-defined lode of quartz, chlorite and tourmaline was found to carry only trace amounts of tin. In fact there is little evidence for mineral zonation (as compared to Cornwall) in this area. The tin zone is present in the granite area to the south, at Gunnislake. There is no so-called 'emanative centre' in the vicinity, so hypothermal tin was rarely found, and the mine is a good example of how an incomplete understanding of the zonal scheme of mineralization could lead to loss of capital.

Four major phases of ore emplacement are recognized, namely:

1. an earliest phase that caused intensive tourmalinization of the killas around the main fractures and the introduction of disseminated fine cassiterite;
2. fracture infilling of quartz and some chlorite, with cassiterite, wolframite and abundant arsenopyrite;
3. re-opening, and further infilling of chlorite, quartz, chalcopyrite and arsenopyrite; and
4. finally, infilling of all cavities and fractures, and sealing with fluorite and extensive siderite.

Conclusions

The complex sulphide mineralization of west Devon and east Cornwall is well displayed in the widespread dumps of Devon Great Consols. Devon Great Consols worked the largest sulphide lode in South-west England, the vein being worked for some 4 km. Although no exposures of vein mineralization can be studied, an area of dumps close to the arsenic flue at Wheal Josiah provides material indicative of the original vein mineralogy. Arsenopyrite is dominant while chalcopyrite is poorly represented. Vuggy quartz, siderite and francolite complete the assemblage. Surprisingly few secondary minerals have been recorded considering the depth of gossan originally present.

DEVON UNITED MINE, DEVON (SX 521 795)

Introduction

The Mary Tavy mining area stretches for some 9.5 km along the Tavy and Lyd valleys to about 1 km north of Lydford, and has an east–west breadth of about 4.75 km. It is situated on the western side of the Dartmoor Granite (see Figure 7.38), and the country rock ('killas')

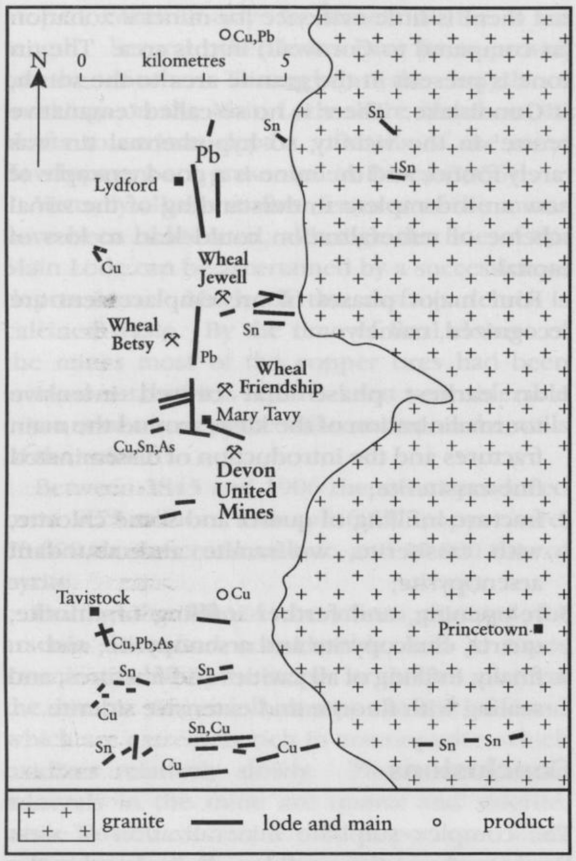

Figure 7.38 Location of the Devon United Mine GCR site on the north-west edge of the Dartmoor mining area. After Durrance and Laming (1997).

consists of metamorphosed grits and shales of Carboniferous age with extensive intrusion of greenstones (altered basic igneous rocks).

Within this area the east–west lodes of Wheal Friendship and Devon United Mine were worked mainly for copper and arsenic, whilst small amounts of tin (cassiterite) and tungsten (scheelite) are also recorded from some of the mines.

The former chief producer in the area was Wheal Friendship (SX 508 794), which is located on the northern fringe of the village of Mary Tavy. Overgrown dumps in open ground containing chalcopyrite and other ore minerals are still accessible from a small road opposite Wheal Friendship House. At the northern end of this orefield the Wheal Betsy north–south lead lode (a 'cross-course') has been proved for some 6.5 km and worked to a depth of 310 m. This mine (SX 510 812) yielded lead- and zinc-ores, the lead ores containing substantial silver. The Wheal Betsy engine-house and surrounding dumps are preserved (see Figure 7.39).

The Devon United group of mines were all situated on the south and east side of the River Tavy (therefore strictly in the Peter Tavy parish). The mines were North Devon United Mine (SX 520 790), Central Devon United Mine (SX 520 790) and South Devon United Mine (SX 513 786). The mines were worked initially for copper, and later for tin and arsenic. Virtually the entire infrastructure of the mines has long gone, but there are several overgrown dumps at various sites especially within the wooded area on the east bank of the river.

It is the dumps associated with the former North Devon United Mine that comprise this GCR site, which are located in small woods close to the river bank and the Horndon footbridge. The footpath from the village of Horndon to the bridge passes across the leat built to serve the mines. Much of the dump material is of 'killas' with pieces of white vein quartz. However, some small dumps have recently yielded an interesting

Figure 7.39 Wheal Betsy Engine House, Devon United Mine. (Photo: Markles55.)

mineralogical assemblage, mostly of vein quartz but with abundant scheelite, native bismuth and well-crystallized arsenopyrite. Other rare minerals have recently been reported by Rumsey and Savage (2004), including the first British occurrence of the rare nickel bismuth sulphide parkerite. It has been suggested that scheelite has probably developed rather than wolframite due to the calcareous nature of the feldspars associated with the greenstones and calc-flintas of Lower Carboniferous age. Scheelite is also found with arsenopyrite at the nearby Wheal Friendship. This mine worked similar lodes on the north-west side of the River Tavy.

The mines were described by Dines (1956), and Hamilton Jenkin (1981). Some details of both Wheal Friendship and the Devon United mines are given by Durrance and Laming (1997).

Production, from figures presented by Durrance and Laming (1997) from the Mary Tavy area, was dominated by the output from Wheal Friendship, which according to Collins (1912) and Dines (1956) was at least 160 000 tons of copper ore, 18 000 tons of arsenopyrite, 165 tons of tin, and 7053 tons of pyrite. At various times amalgamation occurred of Wheal Friendship with the Devon United mines and also Wheal Jewell (SX 528 813). Recorded production figures may therefore be somewhat confused, but it is believed that the Devon United mines produced 15 000 tons of copper ores, 1500 tons of refined arsenic and 373 tons of tin concentrates.

The beginnings of mining are obscure. Wheal Friendship is known to have been working in the late 18th century (Barclay, 1931), and along with the Devon United group of mines continued in production periodically until 1925.

Description

The main workings of Wheal Friendship occurred within a series of interlaced lodes and branches, extending for about 1.6 km westward from the Tavy Valley, and underlie the Tavistock to Okehampton road. To the west of this road, the Main Lode (varying from 0.5–9 m in width) courses E30°N but eastwards changes to nearly east–west; both portions underlie 45°N. Along the course of the worked lodes there were 11 shafts and two inclined planes. The deepest shaft was Taylors, just west of the main road, which was sunk vertically to the 90-fathom level. An important north–south cross-course heaves the lodes from 10–30 fathoms to the left. Filling is mainly of 'fluccan' (clay-gouge), but with a little galena and sphalerite. This cross-course is believed to be the southerly extension of the Wheal Betsy structure. Barclay (1931) recorded the mine as paying dividends before 1790 and being actively worked by various companies up to 1925. At a later date the dumps were worked over for tin, arsenic and tungsten.

The Devon United group of mines includes three separate mines, namely the North Devon United (also known as 'East Wheal Friendship'), the Central Devon United and the South Devon United. East Wheal Friendship was developed as a southern extension of one of the northern lodes of Wheal Friendship. Work had started here before 1835, and in 1846 the property was taken over by a London company. The sett consisted of two parts. The major portion, 600 fathoms in length, lay east of the river in the parish of Peter Tavy. The smaller section, 50 fathoms long, lay west of the river. About this time East Wheal Friendship was incorporated into the Devon United setts. The East Friendship lode was developed in North Devon United Mine, 550 m north of Cudliptown, and in the period 1846–1850 returned a production of 14 271 tons of copper ore (Dines, 1956). The workings consisted of an adit and two shafts. The lode was said to average 3 m in width.

Central United Mine was situated 550 m south-west of Cudliptown and worked a nearly vertical east–west lode called the 'Main Central'. A shaft was sunk near the river to 26 fathoms below adit, the 10-fathom level extending 140 fathoms and the 26-fathom level extending 90 fathoms east of the shaft. Barclay (unpublished manuscript) recorded that the lode varied from 30 cm to 90 cm in width and was filled with quartz, chlorite and brecciated killas (an assemblage commonly found on the dumps). The ore-rich parts of the lode consisted mainly of arsenopyrite with small amounts of cassiterite and occasional chalcopyrite bunches. The lode walls were of altered killas with small tongues of greenstone.

South Devon United Mine was situated east of the Tavy, 900 m south-west of Cudliptown, and was sited on the east–west, N-dipping Main South Lode. Engine Shaft, 65 m from the river, is said to be 50 fathoms deep. Adit level, commencing 26 fathoms west of the shaft, follows the lode for 290 fathoms to the east. The last period of activity ended in 1922. During the last working the Main South Lode was the most important. It averaged 9 m in width, and was recorded as consisting of quartz and chlorite, as well as carrying cassiterite and arsenopyrite. The ground is heaved by several small cross-courses. Values of cassiterite are said to have run to 30 lbs per ton in places.

The Devon United group of mines started working copper about 1820, and between 1842 and 1862, and 1882 and 1884, were worked in conjunction with Wheal Friendship. South Devon United Mine was re-opened mainly for tin in 1904, and Central Devon United Mine mainly for arsenic in 1909, the two continuing producing up to 1922. The outbreak of war in 1914 gave an added impetus to arsenic production, but subsequent depression led to closure in 1923.

Interpretation

The mineralized lodes of the area are interconnected between the east and west banks of the Tavy, and therefore connect the mining setts of Wheal Friendship and Devon United. Their origin is therefore common. The area is one of hydrothermal sulphide veins with predominant or significant contents of copper sulphide ore minerals, and generally fits the main-stage hydrothermal mineralizing event. The mineralization is fairly typical of the tin-copper zone boundary. As has already been stated, the presence of scheelite rather than wolframite may be due to the availability of calcareous rocks in the immediate vicinity.

The outstanding feature of the relatively small Mary Tavy–Peter Tavy mineral area is the rich development of arsenopyrite in association with the copper ores. Similar mineralization is relatively rare and is seen only on a similar or greater scale in Devon Great Consols and the Botallack area of Cornwall (see **Botallack Mine and Wheal Owles** GCR site report, this chapter). It is therefore suggested, from the evidence of such areas, that the controlling factor for such rich copper-arsenic deposits is the presence of mafic intrusive rocks (epidiorites or greenstones) within thermally metamorphosed sedimentary rocks on the gently dipping flanks of a granite mass.

Conclusions

This GCR site, especially the shaft area of the original North Devon United Mine, still provides dump material important for studies of the main-stage copper-arsenic mineral assemblages of South-west England, which were integral in the evolution of the Cornubian Batholith. All three Devon United mines worked typical hydrothermal east–west lode structures. The dominance of copper and arsenic mineralization provides particular interest.

An interesting mineral assemblage of chalcopyrite, arsenopyrite and cassiterite in vein quartz-chlorite lodes can still be collected. Quartz vein material with abundant scheelite, native bismuth and arsenopyrite, along with the first British occurrence of parkerite, has been recorded from dump specimens of veinstone.

Evidence of north–south lead-bearing cross-course mineralization 'heaving' earlier structures can be found in the neighbourhood of the copper-bearing lodes, especially in the Wheal Friendship mining sett, suggesting main-stage mineralization for the Devon United Mine. The presence of cassiterite in the lodes indicates tin-copper zone mineralization.

TREVAUNANCE COVE, ST AGNES, CORNWALL (SW 723 517)

Introduction

In the northern section of the cliffs of Trevaunance Cove, through to Trevellas Porth, well-exposed examples of N-dipping tin-bearing lodes and S-dipping copper lodes associated with the Cligga Head and St Agnes granites can be studied. In the south-west cliff section old adits are still partially accessible. These adits were driven on the Trevaunance Lode of the Polberro Mine (see Figure 7.30) of the St Agnes mining region (Dines, 1956).

Old prints show the cliffs surrounding Trevaunance Cove to be the sites of considerable mining activity, with images of engine houses, water wheels and ore-processing sheds, the latter seemingly immediately above the cliff edge. Few traces of this mining activity now remain, although some dumps are still in place, along with leats and the occasional wheel pit. To the south-west of the cove there was an interesting small harbour (rebuilt many times) which served the mines and local mining community. Unfortunately between 1915 and 1934 a series of storms slowly destroyed the piers of the harbour, leaving only the granite foundations now exposed at low tide.

Around the granite outcrop of St Agnes Beacon a number of important mines were worked. The greatest and richest concentration lay on the north-east side of the St Agnes Granite, between the village of St Agnes and the sea. Here the major mines were West Wheal Kitty, Wheal Friendly and the Polberro mines. For a time the Polberro sett was the biggest tin producer in Cornwall. East of St Agnes village the plateau between Trevaunance Cove and Trevellas Coombe was also extensively mined. The two most important mines were Penhalls and Wheal Kitty, which amalgamated in 1907, closed in 1919, but then were reworked in the period 1926–1930. Towards the southern end of Trevellas Coombe lay the Blue Hills Mine, which worked tin from many old mining setts which were active throughout most of the 19th century. The most northerly of the lodes cut through the Trevaunance Cove cliffs. Specialized small-scale tin streaming is still active in Trevellas Coombe at the Blue Hills Tin Streams (see Stanier, 1998). Production figures for the various mines are presented in Table 7.2.

Washings brought down from Wheal Kitty stamps and processing plant ended up on the beach at Trevaunance Cove. Sands on the shore of Trevaunance Cove still today contain detrital cassiterite, including 'wood tin', which after a heavy storm can be concentrated so as to be of sub-economic proportions. Samples are recorded to have given a recovery of up to 8 lbs of 'black tin' (unrefined ore) per ton. Up until

Table 7.2 Output of representative St Agnes mines. Based on Mines of West Cornwall, and Dines, 1956).

Mine outputs		
	Black tin (tons)	**Approximate period**
West Wheal Kitty	10 070	1881–1915
Wheal Kitty	9510	1853–1918
Polberro	4300	1837–1895
Penhalls	3610	1834–1896
Blue Hills	2120	1858–1897

1940 the deposit was exploited and treated in a small mill near the beach.

Dines (1956) gave detailed coverage of the mines and minerals of the St Agnes area, and further information is presented in Barton (1963). Of many research papers those by Bromley and Holl (1986), and Alderton (1993) are the most valuable.

Description

The importance of the readily accessible lode examples in Trevaunance Cove are best understood by considering their local mineral and mine environment. Polberro, like so many other large mines, was an amalgamation of various ancient smaller workings, some of which are known to have been at work in the 1600s. In the 1830s the concern employed 480 persons, and in 1846 the mine was visited by Queen Victoria, being thereafter known as 'Royal Polberro Consols'. In 1864 the workings had reached a total depth of 100 fathoms. Underground work ceased shortly before 1900, although the sett was subsequently incorporated with those of other St Agnes mines. Wheal Friendly, whose engine house stands on the west side of Trevaunance Cove, survived until 1895 when it was 195 fathoms deep. It then became part of West Wheal Kitty, whose levels extend beneath St Agnes village. West Wheal Kitty had been started in or about 1863 and closed during the First World War. The Kitty and Penhalls sett is bounded on the west by Trevaunance Cove and on the east by Trevellas Coombe. The Penhalls section is to the north, close to the shore of Trevaunance Cove. The mines are very ancient; Kitty is mentioned by Borlase (1758), and other parts of the sett by Pryce (1778). The lodes trend roughly ENE, the most important being 'flat' lodes dipping 50° near-surface and becoming progressively flatter in depth. Pike (1866) described some remarkable 'heaves' or throws in Penhalls Mine.

The Trevaunance Mine, now long abandoned, was very profitably worked for tin from the middle of the 18th century. One of many mines around the St Agnes area, it eventually became part of the larger Polberro Mine in the 19th century, and later part of St Agnes Consols.

Polberro Mine is known for very rich deposits along the Trevaunance Lode. Very important mineralogically were the remarkable crystallographic 'habits' of the fluorite specimens obtained from these mines. Although not now available within today's small number of exposures, good specimens can still be studied in major collections. Specific aspects of the fluorite and their importance to mineralogical studies were described and figured by Embrey and Symes (1987). As described, a great many old setts were later incorporated into the Polberro group, including Wheal Trevaunance and the Pell Mine, which yielded fine specimens of fluorite, with crystals showing the 'four faced cube' form to perfection. West Wheal Kitty was a group of some 30 older setts, one of which was Wheal Rock where Raspe found the first stannite specimens in 1785. Many old specimens of superbly crystallized chalcopyrite found in collections are believed to have come from the mines of the West Kitty group.

The country rocks of the St Agnes district are Lower Devonian 'killas' containing prominent grit bands. At both **Cligga Head** and St Agnes Beacon there are two small granite outcrops where the country rocks are thermally metamorphosed. Quartz-feldspar porphyry ('elvan') dykes coursing ENE–WSW are recorded from some of the mines. The general lode trend is ENE, in some cases nearly vertical, while others have a flat northerly dip of between 20° and 35°. The area is traversed by numerous fault-fissures which tend to heave the mineral-bearing lodes so as to cause the flat N-dipping lodes to be repeated, occurring as a series of N-dipping sections (Dines, 1956). The 'flat' lodes have yielded mainly tin from contorted and crushed killas that is highly tourmalinized and impregnated with cassiterite. The vertical lodes are normal fissure-veins. Several north–south, nearly vertical quartz-filled later cross-courses are also reported from the mines.

North of the beach at Trevaunance Cove, and along to Trevellas Coombe, cliff exposures of a typical S-dipping copper lode are present. Although only 0.5 m wide, it can be seen to contain brecciated killas, veined and lined by quartz. Chalcopyrite can be recognized along with pyrite and chlorite, and it is reported that the vein also carries some tin.

In the north cliffs of Trevaunance Cove a complex system of lodes is exposed, dipping both north and south and bifurcating in places. Two of the thin structures, only a few centimetres in width and about 1.5 m apart, dip to the north at about 35°–40°. Small trial adits can be seen on one of these N-dipping veins where it has been offset by a small fault. It is difficult to follow the veins on the beach as large boulders obscure the in-situ rock sequence. The vein is cut by a small nearly horizontal vein which further complicates the sequence, although this cannot be followed through the rock sequence. The near-horizontal lode appears to be the earliest of the complex. The N-dipping lodes can be seen to be brecciated and tourmalinized and clearly 'moved' by S-dipping lodes. This area therefore provides small-scale evidence for the believed nature of the complexity of early to late tin mineralization and copper lodes in the St Agnes area, as described by Dines (1956).

The Trevaunance Lode is exposed in the cliffs of the southern side of Trevaunance Cove, which, when reasonably exposed, can also be seen to be brecciated. The vein can be followed by a line of overgrown pits towards the Polberro Mine.

Interpretation

Veins in the Cornish orefield are commonly vertical or steeply inclined, dipping at 60° or more, although flatter structures do occur. Many of these flatter, near-horizontal veins occur in the St Agnes district. Structural evidence seems to indicate that some of these structures are associated with thrust planes.

As in the case of a cooling magma, the fall in temperature is probably the most important physical change, along with pressure consideration, which controls crystallization of the different minerals. The deposits of the St Agnes region demonstrate the control of decreasing temperature on mineralization. This is exhibited on a large scale in the metalliferous deposits inland from the north Cornish coast at St Agnes Head and Cligga Head (see Alderton, 1993, fig. 6.30), where distinct mineral zones occur. Higher-temperature tin-tungsten mineralization occurs nearer the coast, followed inland by copper and then lower-temperature lead-zinc mineralization (see Figure 7.40). In the St Agnes region some of the lead-zinc veins appear to have similar trends to both the higher-temperature copper and tin lodes, which is not normally the case in South-west England, as they typically form cross-course veins.

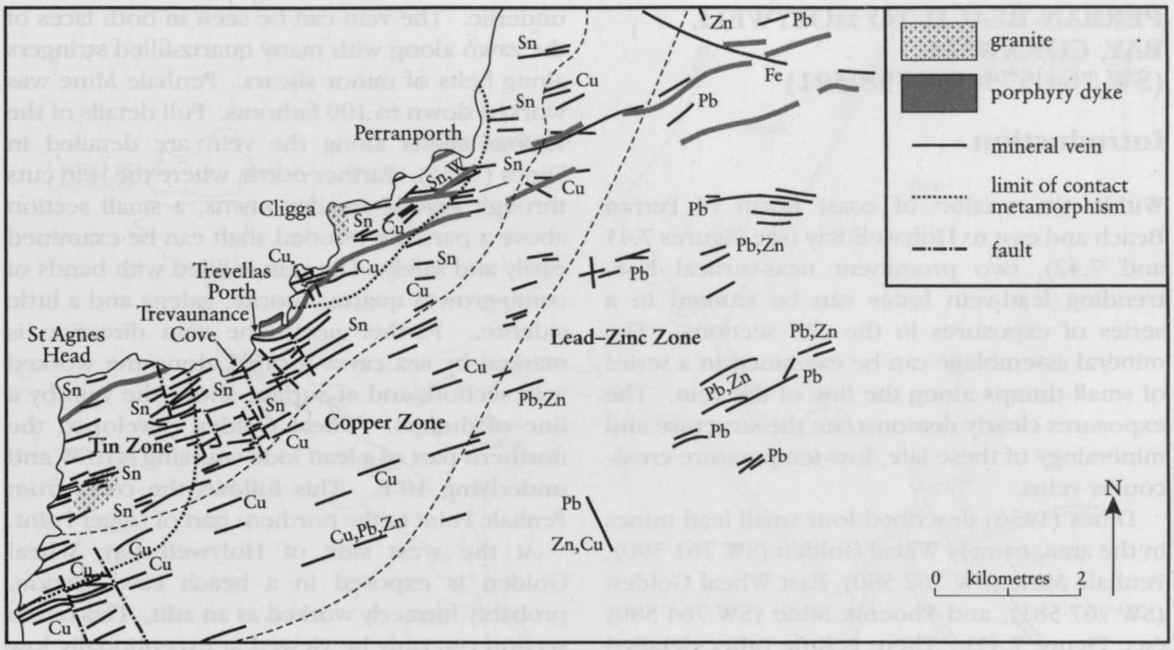

Figure 7.40 Mineral zonation in the St Agnes–Cligga area. After Alderton (1993).

Adjacent to the Turnavore Shaft of Polberro Mine, veins were described as containing a topaz-cassiterite-pyrite-sphalerite assemblage (Dines, 1956). The following paragenesis was determined by Dines (1956):

1. quartz-topaz-cassiterite;
2. brecciation and development of clay by 'topaz' replacement; and
3. sphalerite-pyrite-arsenopyrite.

As such there are some similarities to the **Cameron Quarry** GCR site mineral assemblage. Essentially, mineralization is of main-stage hydrothermal origin associated with intrusion of the St Agnes Granite, which is part of the main Cornubian Batholith. It has been pointed out that Trevaunance Cove is approximately equidistant from the two principal areas of Li-mica granite seen at Cligga Head and Cameron Quarry. At Trevaunance, however, there is no evidence of the greisenization associated with this type of granite as seen at the **Cligga Head** and **Cameron Quarry** GCR sites, although in the Polberro Mine, immediately south of the cove, topaz is recorded as being a prominent early mineral in the vein paragenesis. It is therefore concluded that the apparent differences in the sequence of events at Wheal Coates and Trevaunance Cove are attributable to the presence or absence of early faulting associated with Li-mica granite intrusion. Where faults were present they acted as channel-ways for an early phase of tin-topaz mineralization, followed by superimposed hypothermal tin mineralization; where they were absent the hypothermal mineralization occurred in two stages, conforming to the regional pattern seen around the St Agnes–Cligga Head granite ridge.

Conclusions

Exposures between Trevaunance Cove and Trevellas Porth demonstrate the relationships between early N-dipping tin lodes (brecciated and tourmalinized) and later S-dipping copper lodes. The site therefore demonstrates in microcosm the lode systems of the St Agnes area in terms of their mineralogical and structural characteristics, and evidence seen at the nearby GCR sites at **Cligga Head**, **Cameron Quarry** and **Wheal Coates** for understanding the main-stage mineralizing events related to the Cornubian Batholith, in particular the lateral zonation of the various tin, copper, and lead-zinc mineral lodes.

PERRAN BEACH TO HOLYWELL BAY, CORNWALL (SW 764 575–SW 758 591)

Introduction

Within the section of coast north of Perran Beach and east to Holywell Bay (see Figures 7.41 and 7.42), two prominent near-vertical N–S-trending lead-vein lodes can be studied in a series of exposures in the cliff sections. The mineral assemblage can be examined in a series of small dumps along the line of the vein. The exposures clearly demonstrate the structure and mineralogy of these late, low-temperature cross-course veins.

Dines (1956) described four small lead mines in the area, namely Wheal Golden (SW 761 590), Penhale Mine (SW 762 580), East Wheal Golden (SW 767 581), and Phoenix Mine (SW 764 580) (see Figure 7.41). There is little other detailed geological literature except for much earlier references by Pryce (1778), and Collins (1912).

The line of the veins can be studied traversing from Penhale Point in a southerly direction. The outcrop of the Penhale Lode is clearly seen in a series of cliff sections across the various coastal indentations ('zawns') of the Holywell promontory. The Penhale Lode is best observed from above the major collapsed shaft (above the beach) near to the renovated mine buildings, the line of the lode being marked by bifurcating quartz veins.

Description

The country rock ('killas') to the mineralized veins is Lower Devonian slates and grits, although the eastern part of the traverse from Perran Beach to Holywell Bay is covered by blown sand. The mineral lodes are characteristically marked by the development of banded comby quartz with fluorite, galena and some siderite.

In 1849 Penhale Mine produced 100 tons of 8% copper ore, and between 1849 and 1870 raised 1270 tons of lead ore, realising 7150 oz of silver, and 7060 tons of brown hematite (the latter may have come from the Perran Iron Lode). The Penhale Lode is best exposed in the head of the inlet, along the zawn north of Penhale. The lode has a N10°W strike and 10°E underlie. The vein can be seen in both faces of the zawn along with many quartz-filled stringers along belts of minor shears. Penhale Mine was worked down to 100 fathoms. Full details of the various shafts along the vein are detailed in Dines (1956). Farther north, where the vein cuts through several smaller zawns, a small section above a partially wooded shaft can be examined easily and safely. The vein is filled with bands of comb-growth quartz, fluorite, galena and a little siderite. Farther north the vein direction is marked by sea caves formed along the worked vein section, and at surface above the vein by a line of dumps. Wheal Golden developed the northern part of a lead lode coursing N10°W and underlying 10°E. This follows the coast from Penhale Point to the northern part of Ligger Point.

At the west side of Holywell Bay, Wheal Golden is exposed in a beach cave section, probably formerly worked as an adit. This beach section can only be viewed at exceptionally low tidal conditions. The lode here is 0.8 m wide and filled with comby quartz, fluorite and siderite. Young's Shaft (of Wheal Golden) was sunk partway down the cliff, 230 m east of Penhale Point. The mine is believed to have been active in the 18th and 19th centuries and was to intersect the richest parts of the lode 70 fathoms deep at the time of abandonment. Output records for the period 1849 to 1855 are listed as 2560 tons of lead ore and 24 200 oz of silver. In the cliffs on the south-western side of Holywell Bay a further three small sections of a lode structure are exposed, within a shear belt zone. Again erosion and tidal colouring has caused the features to be poorly exposed, but the section appears to be ferruginous and of a vuggy nature.

The East Wheal Golden shaft was sunk on a section of lode paralleling the Wheal Golden Lode (365 m to the east). The shaft is 18 m from the cliff edge at the south end of Holywell Bay. A yield of 15 tons of lead ore and 180 oz of silver is recorded for 1861.

Dines (1956) described the Phoenix Mine as being on the East Wheal Golden Lode, 365 m east of Penhale Mine. Between 1873 and 1876 the mine raised 77 tons of lead ore and 282 oz of silver. It is believed that the lode continues southwards, and is probably the quartz-rich vein described as intersecting the Perran Iron Lode at depth.

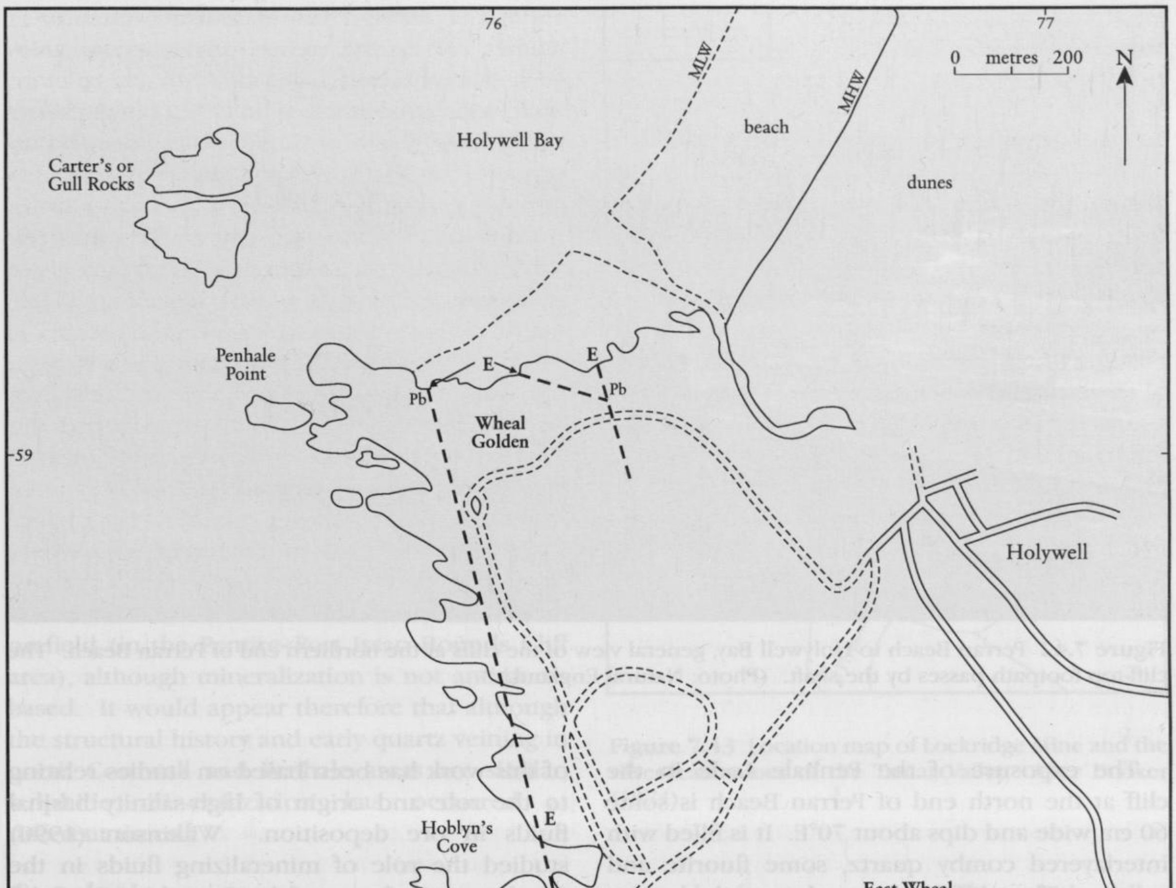

Figure 7.41 Perran Beach to Holywell Bay. (E) represents exposures of the lodes within the area (Penhale Lode, Perran Iron Lode, Wheal Golden Lode and East Wheal Golden Lode).

Figure 7.42 Perran Beach to Holywell Bay, general view of the cliffs at the northern end of Perran Beach. The cliff-top footpath passes by the shaft. (Photo: Natural England.)

The exposure of the Penhale Lode in the cliff at the north end of Perran Beach is some 60 cm wide and dips about 70°E. It is filled with interlayered comby quartz, some fluorite and galena. The cliff here, on the southern part of Ligger Point, is cut by many quartz-filled tension gashes and quartz stringers. This section can only be reached at low tidal conditions, similar to the situation at the northerly cliff section of the Wheal Golden lodes in western Holywell Bay.

The Perran Iron Lode of the **Gravel Hill Mine** GCR site is reported to be intersected south-east of the mine by at least two north–south veins, yielding a little lead and silver in the iron workings. To the north-west of Gravel Hill Mine continuation of the Perran Iron Lode has probably determined the line of the cliffs. Erosion along this line has removed much evidence, but in places evidence of iron mineralization can still be seen. The probable intersection point of the Penhale Lode with the continuation of the Perran Iron Lode has also been eroded out.

Interpretation

Several authors have detailed fluid-inclusion studies based on cross-course mineralization in South-west England (see Alderton, 1993). Much of this work has been based on studies relating to the role and origin of high-salinity basinal fluids in ore deposition. Wilkinson (1990) studied the role of mineralizing fluids in the development of parts of the Cornubian Orefield, considering especially evidence from mineral veins in south Cornwall. This work confirmed the fluids to be of high salinity, similar to basinal brines, with the ore minerals being deposited at about 140°C. However, it was also recognized that low-salinity fluids (at *c*. 200°C) were contemporaneously mobilized in E–W-trending normal faults, and these sporadically infiltrated the cross-courses at structural intersections. The formation of a mineral assemblage such as galena, sphalerite, chalcopyrite, quartz and siderite can be accounted for by the mixing of the two fluid types. Differences in paragenesis within the orefield may be dominantly a result of different mixtures of two or more fluid types. If comparisons with this model can be made it may be that there has been a major contribution of this fluid type at Penhale–Wheal Golden. The galena-fluorite-quartz mineralization in the north–south lodes of the Perran Beach to Holywell Bay area may result from mixing of low-salinity metamorphic fluids with a highly saline brine derived from a Mesozoic (offshore) basin. Elsewhere in Cornwall cross-course mineralization contains either of these fluids but not usually both.

Although small-scale north–south lead-silver veins intersect the Perran Iron Lode, which contains siderite and sphalerite as reported by Henley (1971), it is believed to have been filled at about the same time, the north–south veins being slightly later. South of the Perran Iron Lode, virtually all the lodes course NNE–SSW and carry tin, copper and lead. Some may be re-opened fissures originally carrying older tin and copper ores and further filled by lead ores.

The north–south lodes of the Penhale–Wheal Golden area occur within a belt of shearing of a similar trend, in which quartz stringers are prominent. Research on lead-antimony mineralization in north Cornwall (Clayton *et al.*, 1990) has shown that en-echelon vein systems are related to shear zones, quartz deposition often being contemporaneous with shearing. The Penhale–Wheal Golden structural situation would seem to be similar to the north Cornwall orefield (in the Pentire–Port Issac–Bounds Cliff area), although mineralization is not antimony-based. It would appear therefore that although the structural history and early quartz veining in north Cornwall and Penhale areas are similar, sulphide mineralization has occurred at different times.

Conclusions

The Perran Beach to Holywell Bay area provides fine exposures of cross-course mineralization where exposures along the vein can be studied and samples also collected from vein dumps. Although underground access to the cliff sites of in-situ mineralization is not easy, exposures of the Perran Iron Lode can still be viewed, and exposures of some parts of the cross-courses are still available.

LOCKRIDGE MINE, DEVON (SX 438 664)

Introduction

The Lockridge Mine GCR site, near Bere Alston, Devon (see Figure 7.43), is a dump site located south of Lockridge Farm road. A minor hillock reveals a quite substantial mineral-rich tip, while immediately to the south of this a fenced open shaft probably represents the working from which the material was obtained. The surface of the tip is kept relatively fresh by undercutting

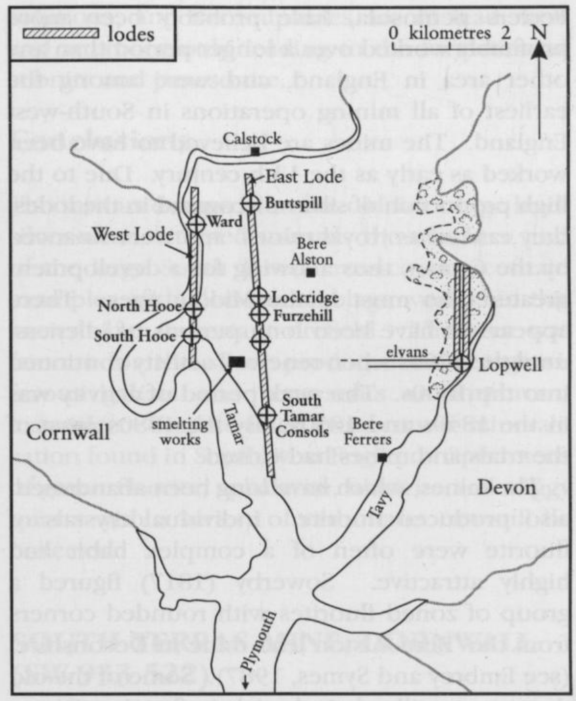

Figure 7.43 Location map of Lockridge Mine and the silver-lead mines of the Tamar Valley. After Booker (1974).

caused by the stream running through the valley bottom, and good specimens of the ore assemblage can be collected. Sphalerite is common, in specimens banded with quartz (often chalcedonic), with a little galena, while recently wurtzite has been identified forming intergrowths with sphalerite showing 'ice-fern' texture (Grguric and Nickel, 2006). Light-green massive fluorite can also be found. Some quartz specimens show bands of casts from well-crystallized fluorite.

Quartz, fluorite, sphalerite, wurtzite and some galena mineralization can also be collected from the extensive but compressed dumps which form part of the hill-slope at SX 438 664. These overgrown dumps extend along the whole of the wooded area alongside the road to Lockridge Farm. At the western end they surround old mine buildings and the chimney of Lockridge Mine. The start of the dumps can be found just to the west of the railway bridge. Fenced shafts on this site, which are in a dangerous condition, can be traced southwards along the line of the mineralized cross-course.

The silver-lead mines of the Tamar Valley (see Figure 7.43), lying on the Bere Alston–Bere

Ferrers peninsula, have probably been more profitably worked over a longer period than any other area in England, and were among the earliest of all mining operations in South-west England. The mines are believed to have been worked as early as the 13th century. Due to the high proportion of silver discovered in the lodes, they ranked as 'royal mines' and were financed by the Crown, thus allowing for a development greater than most in the Middle Ages. There appears to have been long periods of idleness, until the 1780s when renewed activity continued into the 1800s. The peak period of activity was in the 1840s and 1850s. By the 1880s most of the trials and mines had closed.

The mines, which have long been abandoned, also produced fluorite. Individual crystals of fluorite were often of a complex habit and highly attractive. Sowerby (1817) figured a group of zoned fluorites with rounded corners from the 'Bere–Alston lead mine in Devonshire' (see Embrey and Symes, 1987). Some of the old dumps are still relatively rich in fluorite (Dines, 1956).

At the present time fluorite found on the dumps occurs as purple to light-green cubes with quartz and chalcedony within and on slates. It is reported that green and colourless fluorite was worked from the dumps of Lockridge Mine in 1942.

There is only a limited literature on the mine. It was discussed and recorded by Dines (1956), and figured in the historical industrial descriptions of the Tamar Valley by Booker (1967), and Hamilton Jenkin (1974), with further mention by Durrance and Laming (1997).

The mine represents an example of cross-course mineralization, which trends almost normal (roughly N–S) to the main-stage veins in South-west England. These veins developed late in the history of mineralization associated with the Cornubian Batholith.

Description

A strip of country about 1.5 km wide alongside the Tamar and extending about 6.5 km southwards from Calstock consists of Devonian country rock ('killas') (shales at Lockridge) with some outliers of 'Culm Measures' shales at the northern end. The country rocks are traversed by two N–S-trending (E-dipping) cross-course lodes. These have yielded important amounts of lead and silver.

The eastern cross-course, about 1.2 km east of the western lode, is barren beneath Calstock but has been worked almost continuously from Buttspill Mine (SX 437 677) southwards through the Tamar Valley on to Lockridge Mine (SX 438 664), Furzehill Mine (SX 436 654), and the South Tamar Consols (SX 437 645), a proven 3.5 km length of productive ground. The mines were known collectively as 'Bere Old Mines' or as 'Tamar Valley Mines'.

The Lockridge Mine was also known as 'Goldstreet Mine', and is situated 1.6 km south-west of Bere Alston. Dines (1956) gave some details of the mine, noting that an adit was driven 450 fathoms east by north from its portal, 165 m north-east of Whitsam (SX 430 662). Two dumps may mark the course of the lode, but shaft sites are now obscured. Dines (1956) recorded that the northern dump, 825 m north-east of Whitsam, was estimated to contain 700 tons of slightly pyritous shales, much vein quartz, some fluorite and a little sphalerite. The other dump, 230 m to the south, probably of around 1000 tons, contains more fluorite and was worked over in 1942.

Dines (1956) recorded that the dumps of the South Tamar Consols extended down to the River Tamar just north of Clamoak Quay (SX 438 645). They were extensive but of little mineralogical interest. The workings of Furzehill Mine extend much farther south than is indicated by Dines (1956), and are almost continuous with those of South Tamar Consols. They occur adjacent to the site of an engine house and shaft above the Bere Alston to Weirquay road. Today there seems to be little of mineralogical interest, although Dines noted that the dump contains some green fluorite.

Lode-filling within the cross-course is quartz, along with sphalerite, fluorite and galena, while some siderite is also present. In many of the Bere Alston mines galena was rich in silver near surface (up to 100 oz per ton of lead), although at depth the content fell somewhat. The silver content, however, was the chief value of the mines. The area was also one of the main producers of fluorspar in South-west England, although the specific output of the Lockridge Mine is not recorded. Production statistics are incomplete for the mine, but the recorded output of the valley mines as a whole is some 25 000 tons of lead ores, yielding 18 900 kg of silver.

Interpretation

North of the Tamar Valley the two parallel, north–south cross-course veins of Lockridge Mine cut the Gunnislake tin-tungsten-copper lodes. The mineralization and style of formation are typical of the cross-courses of South-west England. The hydrothermal assemblage, comprising galena, sphalerite and sometimes argentite, is indicative of low-temperature (200°C) mesothermal mineralization, in zone 5b of Hosking (1964).

As noted above, the early, near-surface workings were particularly rich in silver but the content diminished with depth. This seems to suggest some enrichment by the action of percolating surface water.

The Lockridge and related mines were essentially lead-silver producers, with the silver being contained in galena. However, in lower-temperature epithermal deposits the temperature of formation of the galena is lower, and also lead is often complexed with antimony. This leads to a situation in which silver can no longer be fully contained in solid solution and silver minerals may form directly from the ore solutions. Some mines in South-west England have been worked for native silver and/or silver-bearing minerals, for instance Wheal Brothers at Gunnislake, and Wheal Herland near Hayle (see Embrey and Symes, 1987). Other mines, notably in North Cornwall, have produced silver associated with antimony and copper minerals. The formation and nature of typical cross-course mineralization has been described at other GCR localities, such as the **Wheal Penrose** GCR site. In summary, there is a gradual change in the mineralogical composition between zones 5(b) and 6 of Hosking (1964). Near the top of zone 5(b), zinc, in the form of sphalerite, becomes a subsidiary or accessory ore mineral. Silver minerals often separate from the lead ores and complex with available copper and antimony, forming minerals such as pyrargyrite and stephanite (as at Wheal Newton, in Cornwall). In zone 5(b) subsidiary amounts of copper may be present as chalcopyrite or cupriferous pyrite, but in the lower part of zone 6 complex sulphosalts such as bournonite and tetrahedrite are the prominent copper-bearing minerals. Famous localities for the formation of these minerals in Cornwall are Wheal Boys and the Herodsfoot Mine. In the upper part of zone 6, copper is eliminated from the residual ore-bearing solutions, and the sulphides are of lead, iron and antimony only, leading to the formation of stibnite and jamesonite.

Conclusions

The various dumps from the old Lockridge lead-silver mine, situated towards the northern end of the large South Tamar cross-course, contain examples of the lode assemblage worked in this ancient but important orefield. The area was famous for the silver produced from argentiferous galena and represents an important example of the late-stage cross-course mineralization found in South-west England. Specimens of green fluorite, sphalerite, wurtzite and vuggy quartz with a variety of carbonates can still be collected.

SOUTH TERRAS MINE, CORNWALL (SW 933 522)

Introduction

The South Terras Mine (also known as 'Resugga and Tolgarrick Mine' and sometimes 'Grampound Road') lies in the valley of the River Fal about 1.5 km south-west of St Stephen (see Figure 7.44), and approximately 8 km west of St Austell, at the southern margin of the St Austell Granite. South Terras Mine was one of the few mines in Britain that was worked commercially for uranium, and in the final period of activity, in the 1920s, the main product was radium.

At the present time it is the dumps containing minerals from the various South Terras lodes which are of considerable mineralogical interest (see Figure 7.45). Small but good samples of uranium secondary minerals and some uraninite (pitchblende) can still be found in the dumps. A further suite of unusual and rare nickel and cobalt minerals also occur on the various dumps, including, for example, rammelsbergite, smaltite, skutterudite, gersdorffite and the bismuth mineral bismuthinite. The rare nickel arsenides aerugite and xanthiosite have also been reported (Davis *et al.*, 1964). However, Ryback *et al.* (2001) have demonstrated that the late A.W.G. Kingsbury falsified the localities of numerous rare mineral species. This deception affects a number of locations in the South-west

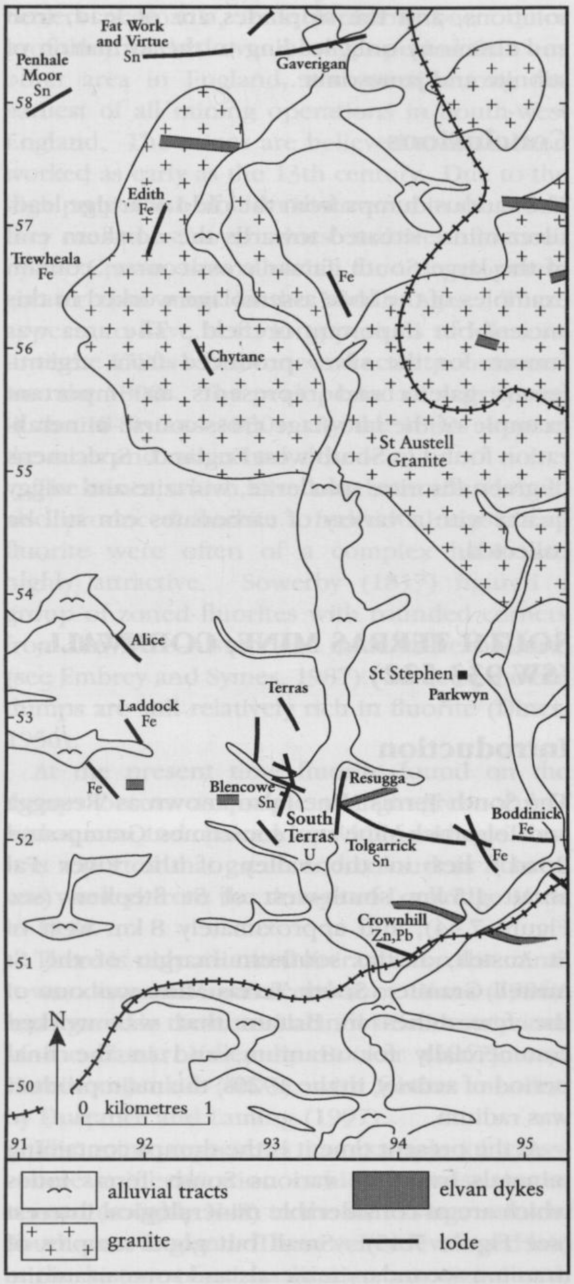

Figure 7.44 Map showing the position of South Terras Mine. After Dines (1956).

England, including South Terras Mine. Therefore care should be exercised when considering claims by Kingsbury which have not been substantiated or duplicated by subsequent collectors.

The South Terras Mine has attracted much interest over the years and has been described by Collins (1912), and Robertson and Dines (1929), while a detailed summary was provided by Dines (1956). The site also represents an example of the U-Co-Ni-Bi-As-Ag suite of deposits recorded by Alderton (1993).

Description

South Terras Mine was sited in country rock ('killas') (Meadfoot Group) of Lower Devonian age, which also contains greenstones (altered basic igneous rocks), recorded at a depth of 37 m. It is reported also that the rocks were cut by a quartz-feldspar porphyry 'elvan' dyke. Records indicate (Dines, 1956) that mine workings intersected three mineralized structures, namely a uranium lode trending approximately north–south (N10°W), a tin lode trending N15°E, and a lode of iron ore (magnetite) ranging E30°S. These were reported to intersect about 115 m south by east of Tolgarrick Mill.

Nothing is known of the nature of the tin lode or of its workings, and the earliest workings appear to have been on the iron lode. The iron lode is recorded to have been up to 3 m wide with rich ore in the centre, being poorer near the walls. The lode was partly in killas and partly in intrusive greenstone, and the country rocks appear to have been partially metamorphosed by the intrusion.

Near the surface the iron lode ore is weathered to ochre (to 50 fathoms depth), and is reported to contain, in addition to magnetite, some tourmaline, cassiterite, chalcopyrite, arsenopyrite, sphalerite and some silver ore. Where the lode cuts greenstone the arsenate minerals scorodite, pharmacosiderite and olivenite have been recorded. Workings on the iron lode encountered the uranium lode in 1873. Stoping on the latter commenced in 1878. The South and North shafts were sunk shortly afterwards.

The uranium lode is recorded as being up to 1 m wide running approximately north–south with a westerly underlie of about 60°. Quartz generally occupied most of this width. During mining there was evidence for several stages of vein infilling, and areas of crushed killas also occur in the vein. The age of this late-stage cross-course mineralization has been given at 225 Ma, but a much younger age of 47 Ma has also been recorded (see Alderton, 1993). According to Collins (1912) the secondary uranium minerals autunite, torbernite and zippeite occurred at high levels in the lode, and

Figure 7.45 Photograph of a dump area at South Terras Mine (Photo: JNCC.).

at depth massive uraninite (pitchblende). The chief ore minerals were uraninite, and the secondary minerals torbernite and autunite. Uranium ore appears to be late stage in the veins. The uranium-bearing fissure-vein is said to have extended some 18 m. Richest ore was found at the 240-fathom level, although even here ore was sporadic, forming irregular ore swells of a few centimetres. Traces of chalcopyrite, pyrite and galena can be found on the dumps, and nickel, cobalt, bismuth and chromium ores were also reported from the mine associated with the uranium lode. In the 1920s uranium ore was shipped to France for treatment. However, at this time (1922–1925), a treatment plant at the mine site continued to recover radium. Total uranium production has been estimated at 736 tons of uranium ore, including 286 tons from the dumps.

True 'caunter' lodes, that is lodes at a trend to the main lodes of the area forming fissure systems to the recorded elvan dykes, appear to be the latest phase of mineralizing activity, forming a bifurcating and altered ore-bearing fissure. The recorded elvan dykes intersect the country rock from east to west, and the elvans sometimes carry cassiterite. It is thought possible that where the lode cuts through the killas it is rich in uranium, but in granite it is barren; this is certainly indicated by the evidence from specimens on the dumps.

Interpretation

The South Terras Mine is perhaps the most important of several recorded uranium and Ni-Co-As orebodies associated with the southern margin of the St Austell Granite. Locally, at Egloshellen Mine (SW 950 528), Dines (1956) reported uranium mineralization, and during the exploration programme by the Geological Survey Atomic Energy Division in the 1950s, uranium mineralization was discovered at the Resugga Lane-End site (SW 942 519). In addition, uranium mineralization is relatively widespread throughout the South-west England orefield and reported from many other parts of the mining field, for example Geevor Mine, St Just, Old Gunnislake Mine near Calstock, and Kings Wood Mine near Buckfastleigh.

The mineralization of the uranium lode, in common with that of other similar low-temperature cross-course mineral veins in South-west England, is of the nickel-cobalt-arsenic-bismuth-silver-uranium type. The long list of minerals recorded from the South Terras

Mine dumps is representative of a complex mineralization history. Three groupings of minerals probably reflect the varied mineralized lodes, namely: a primary association of uranium with chalcopyrite and pyrite altered by supergene enrichment to Cu-As-U secondary minerals; an association of minor Fe-Ni-Co-Bi-As mineralization, forming a suite of unusual and rare minerals; and an association of the iron minerals of the iron lode (magnetite). A detailed study of uranium mineralization in South-west England was presented by Ball *et al.* (1982). In this study they cited two localities where Ni-Co mineralization and uraninite are actually intergrown. The relatively frequent association of uranium with Cu, Ni, and Co has led some workers to believe the source of uranium to be associated with the greenstones (uranium mineralization has been found associated with greenstones). However, it might be that the greenstones are merely suitable hosts to hydrothermally-derived uranium deposits. Alteration processes associated with the St Austell Granite may be of importance to supplying uranium into convective fluids and precipitation into late-stage cross-course veins. Alderton (1993) noted these alternatives, but also added the underlying Permian alkaline volcanic rocks and associated lamprophyres as a potential source.

The nature of the iron lode (magnetite) is not fully known, but the described mineral assemblage might mean that it is a sulphur-poor magnetite skarn. The actual source of the uranium at South Terras Mine is probably the St Austell Granite, whereas the Ni-Co-Bi-As may be derived from the earlier iron-rich phase of mineralization.

Ball and Basham (1979) strongly emphasized that uraninite was earlier than the associated sulphides in most uranium occurrences, including South Terras Mine. The models of mineralization for uranium put forward by Ball and Basham (1979) are important to developing a paragenetic scheme. The uranium mineralization can be seen as related to two discrete episodes. The first was a phase of cross-course mineralization where convective circulation affected both the killas and granite, and the main sites of mineralization were the cross-courses. Uranium was leached from local wall-rocks and earlier higher-temperature mineralization. In the second phase, uraniferous solutions generated by kaolinization or radiogenically driven cirulation were directed outwards from the granite until dammed by a suitable barrier, such as the elvans. It could be that the elvans present in the South Terras area might well have been an important feature responsible for mineralization forming along the N-dipping hangingwall of the elvans. However, there are a variety of models that can be used to first generate and then precipitate uranium in the cross-course veins and a variety of adjacent country rocks.

Conclusions

The nature and structural situation of the South Terras Mine uranium deposit, located at the southern magin of the St Austell Granite, is of considerable interest to gaining an understanding of uranium and cross-course mineralization in South-west England. From the specimens that can still be collected from the dumps, and material in museums and private collections, some idea of the structure and paragenesis of the South Terras Mine cross-course mineralization suite can be determined.

It is a conclusion that the site still provides considerable potential for scientific research. The variety of rare and unusual minerals reported to occur on the dumps makes this site one of considerable mineralogical interest. Recent biological work on the uptake of uranium by lichens found coating part of the dumps has been reported by McLean *et al.* (1998).

WHEAL PENROSE, PORTHLEVEN, CORNWALL (SW 634 252)

Introduction

Wheal Penrose is a former lead-zinc mine situated 400 m east of Porthleven. The lodes occur in partly metamorphosed country rock ('killas') of Devonian age (Mylor Slate Formation).

The dumps above Porthleven Sands lie within and alongside a triangular plot formed by the minor roads traversing south-west from Penrose Hill. This site is focused on some of the still available dumps of Wheal Penrose. The dumps mostly carry sphalerite, although galena and other sulphides are also still present, along with some important secondary minerals, which can still be collected. Slippage of the dump causes loose blocks to litter a small area of the field alongside the wall.

Wheal Penrose is said to have been exploited in Roman times, it was known to be working in the 17th century and was then worked intermittently, finally ceasing work in 1872. Dines (1956) has provided the most complete reference to this mine, and reported an output for the period 1843–1844 of 175 tons of lead ore, although large quantities of siderite were obtained from the dumps after the mine was abandoned. During the period 1868 to 1869 it is recorded that many fine specimens of secondary minerals were collected from the mine workings at a level just above the adit.

The former large dump of the neighbouring Wheal Rose Mine (SW 638 247) originally stood beside the track from Porthleven to Loe Bar. These dumps originally contained ore specimens and many rare secondary minerals. These dumps have now been removed and the area levelled.

Description

Three more-or-less parallel base-metal-mineralized cross-course veins are found in the vicinity of Porthleven, these being the Porthleven Lode (which cuts through the harbour area), the Wheal Rose Lode and the Wheal Penrose Lode (see Figure 7.46). The Wheal Rose and Wheal Penrose lodes are considered in this site description. A series of quartz veins containing siderite and occasional sulphides outcrop in the low cliffs between Porthleven and Loe Bar. At the former Wheal Rose site, the main lead-vein trends NNW and occupies a major fault structure, extending from the coast at SW 639 245

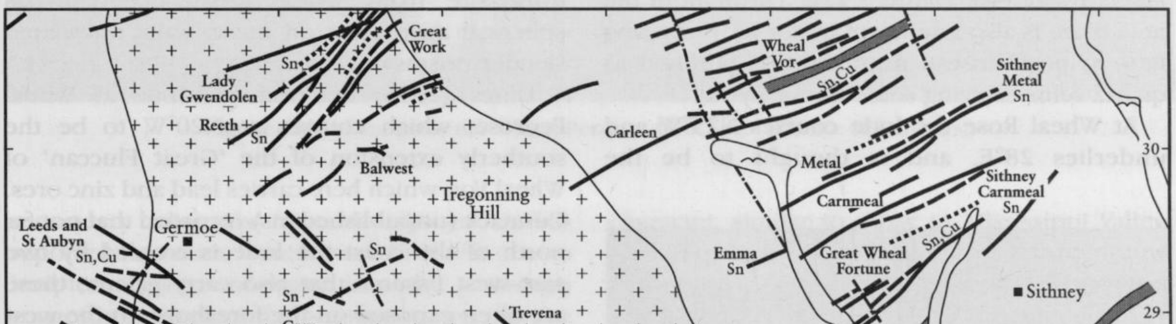

Figure 7.46 Sketch map of part of the Mount's Bay District, showing the Porthleven, Wheal Rose and Wheal Penrose lodes to the east. After Dines (1956).

as far as Great Wheal Fortune at Breage (SW 627 290). Although a major structure, mineralization is recorded as being intermittent.

A vein parallel to that at Wheal Rose occurs a short distance to the north-west and is believed to be the mineralized southerly extension of the 'Great Fluccan', a large, partly mineralized NNW–SSE-trending tear fault, which cuts off the lodes at the westward end of Great Wheal Fortune and Wheal Vor, and which may extend across Cornwall from the north to south coast (Dearman, 1963).

Gleeson *et al.* (2000) suggested that contact of all three Porthleven veins with their host lithologies varies from sharp and planar to irregular and brecciated. Wall-rock fragments are often incorporated into the vein. The vein mineral assemblage is dominantly of siderite and quartz, along with galena, sphalerite, chalcopyrite and arsenopyrite (see Figure 7.47). Throughout the area there is also a series of minor E–W-trending late- to post-Variscan normal faults outlined as quartz veins carrying some minor pyrite.

At Wheal Rose the lode courses N25°W and underlies 28°E, and is thought to be the continuation of the Woolf's Cross-course of Wheal Vor. Although the detail of mine development is not well-known, Dines (1956) stated that development was carried out from the New Engine Shaft, on the cliff edge about 550 m north-west of Loe Bar (SW 639 245). The lode consists of galena with pyromorphite, sphalerite, siderite, pyrite and quartz. The galena yielded silver to the amount of 60 oz per ton of lead. Cunnack (unpublished ms) stated that two parallel lodes were worked but this does not agree with available mine plans. Siderite is said to have constituted most of the lode material. Russell (1944) recorded a range of secondary minerals, including anglesite, while phosgenite, laurionite and paralaurionite are present at Wheal Rose. In the Russell Collection, now in the collections of the Natural History Museum, is a specimen of the rare lead carbonate mineral dundasite from Wheal Rose, occurring as spherical aggregates on quartz with associated slender prisms of cerussite.

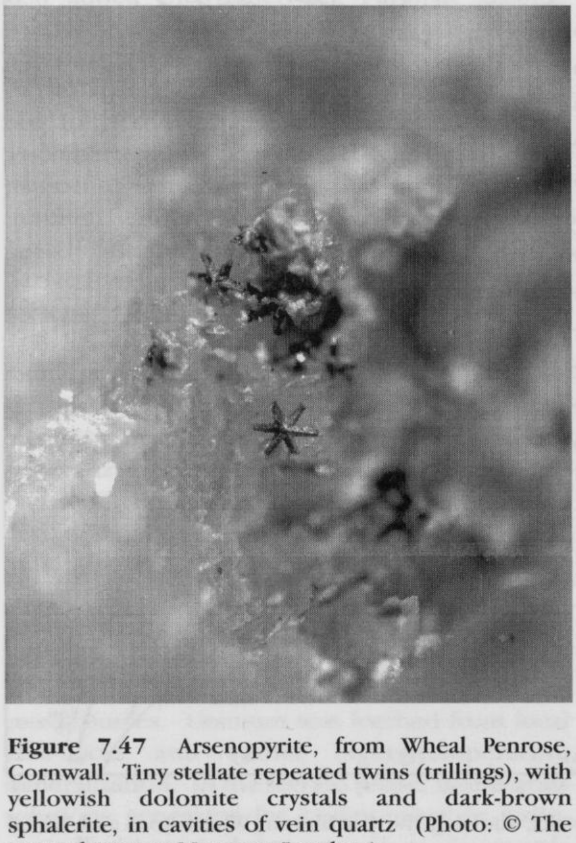

Figure 7.47 Arsenopyrite, from Wheal Penrose, Cornwall. Tiny stellate repeated twins (trillings), with yellowish dolomite crystals and dark-brown sphalerite, in cavities of vein quartz (Photo: © The Natural History Museum, London.)

Dines (1956) believed the lode at Wheal Penrose, which courses at N20°W, to be the southerly extension of the 'Great Fluccan' of Wheal Vor, which here carries lead and zinc ores. Cunnack (unpublished ms) recorded that not far north of the coast the lode is crossed by two east–west fissures that also carry galena; these are often exposed on the foreshore, to the west of the mine when the sand has been removed by storms. There are no plans of the workings, only a longitudinal section dated 1841 which seems to show the lode being worked from various shafts. The major shafts on the lode were Thomas's Engine Shaft, 140 m from the cliff edge, Flat Rod Shaft and Highburrow Shaft. Dines (1956), quoting Cunnack, gave details of several more shafts along with the mine development, most of the surface evidence for which has now been obliterated.

Interpretation

The dumps at the Wheal Penrose GCR site (see Figure 7.48) are now much smaller than previously, but are still of considerable mineralogical interest as they contain most of the secondary lead minerals (especially lead chloride minerals) found formerly at Wheal Penrose and recorded from Wheal Rose. These also include notable specimens of cerussite, anglesite, and mimetite. There is some discussion as to how the

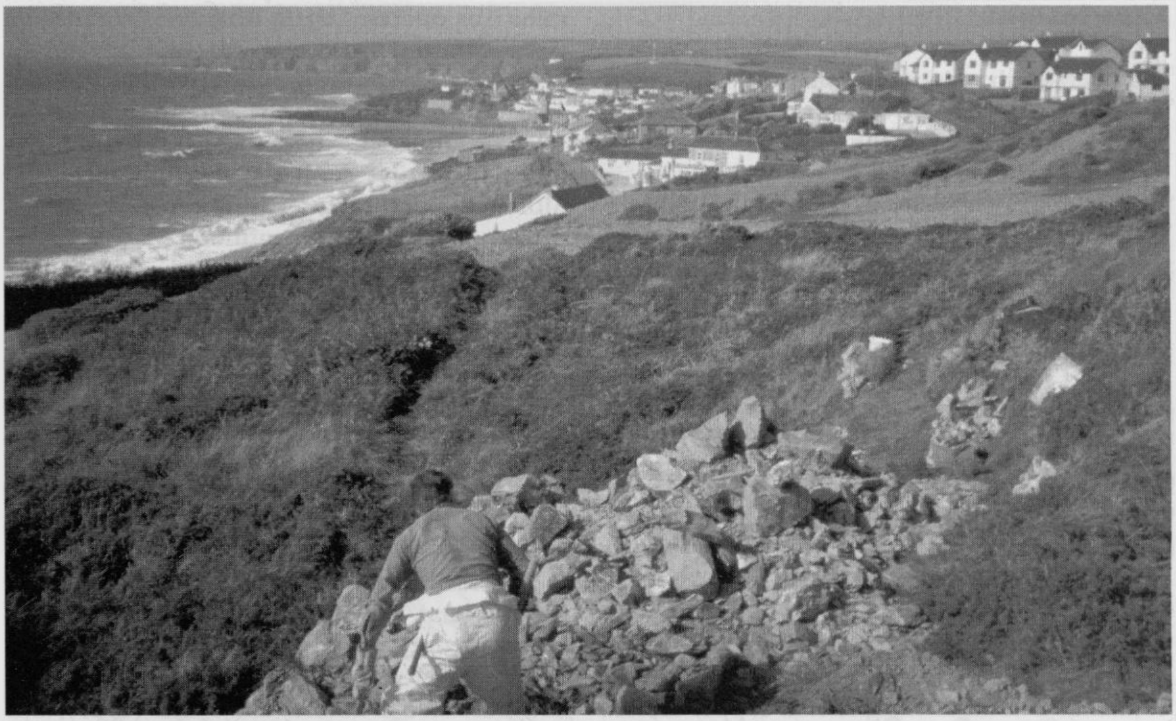

Figure 7.48 Dumps at the Wheal Penrose GCR site. (Photo: R.F. Symes.)

secondary minerals formed. Dines (1956) reported that mine waters were brackish due to incipient leakage of water into the workings, suggesting therefore that seawater action on the vein led to the formation of the secondary assemblage. Other authors have suggested sea-spray action on dump material as being responsible for generation of the lead chloride minerals. It would seem that normal secondary enrichment (supergene) processes have not been involved in the formation of these minerals.

Throughout the areas of main-stage granite-related Sn-W-Cu high-temperature hydrothermal deposits of South-west England, most of the metal production came from large numbers of E–W-trending (varying to SW–NE-trending) veins (lodes). Distinct to these structures were a suite of N–S-trending to NW–SE-trending Pb-Zn-Fe lodes, which are known as 'cross-courses'. These veins tend to cross-cut the main lode system, and were therefore interpreted as being later than the granite-related mineralization. It was concluded that these structures must represent the final stage of granite-related mineralization. However, later studies, such as those by Sawkins (1966b), and Alderton (1978) determined from fluid-inclusion studies that the metal-bearing fluids were of low-temperature and high-salinity character, similar to those in Mississippi Valley-type deposits. Subsequently, Shepherd and Scrivener (1987) suggested that the fluids were related to basinal brines expelled from surrounding sedimentary basins.

Gleeson *et al.* (2000) recently presented detailed results from a fluid-inclusion investigation in relation to fluids derived from basinal brines. Samples for this study were collected from cross-course mineralization veins in the Porthleven and Menheniot areas of Cornwall, which were then compared to those obtained from Permo–Triassic sedimentary rocks from the Western Approaches Basin. The micro-thermometric data indicate that the cross-course fluids have a similar composition to the saline fluids present in the Permo–Triassic basinal sequence. It has been suggested that fluids moved laterally from the basin into the Palaeozoic host-rocks along repeatedly re-activated structures, where they were heated by the Cornubian Batholith to produce the observed temperatures of the base-metal mineralizing fluids. There is limited evidence for fluid mixing between the dilute east–west (main-stage) fluids and the cross-course mineralizing fluids, which may have played a part in the precipitation of base-metal sulphides.

Conclusions

Although much reduced in volume, the dumps at the Wheal Penrose site still provide evidence of the ore assemblage and the important secondary minerals at this site. The ore assemblage is typical of cross-course mineralization, thought to have been derived from basin-generated fluids, although there is a suggestion that the lodes appear to be directly related to other major structures in this area of the South-west England orefield. The site is also noted for the occurrence of a suite of rare, secondary lead chloride minerals.

WHEAL ALFRED, CORNWALL (SW 580 370)

Introduction

The area to the east of Hayle and the St Erth river contained a number of significant copper mines. Collins (1897) stated that in 1800 Alfred Consols was second only to Dolcoath as a copper producer. The Wheal Alfred GCR site is situated about 1.6 km due east of Hayle and consists of a sett of east–west lodes. Several mines were worked in this specific area, namely Alfred, Alfred Consols, North Alfred, South Alfred, West Alfred Consols, Mellanear and West Alfred (see Figure 7.49). Although a major copper producer, the mine is known internationally for the complex Sn-Cu-Zn-Pb mineralization associated with an important suite of secondary minerals, including pyromorphite-mimetite and agardite.

At Wheal Alfred several dumps of considerable size are present (see Figure 7.50), but it is the large dumps north of Lower Treglissan Farm that have yielded the most important specimens of pyromorphite-mimetite and associated agardite. The dumps still yield a range of ore and secondary minerals, although of small and poor quality compared to earlier times. However, the minerals found, often associated with the sugary quartz veinstone, are pertinent to the origin of the deposit.

Believed to be on the site of a much older tin mine, Wheal Alfred was prosperous as a copper mine in the early part of the 19th century. A description and sketch plan by Phillips (1814) show that several veins intersected and mineralization is therefore complex. Output records show that lead and tin were also produced. The mine was operated again from 1851 to 1862 as Great Wheal Alfred, but was unsuccessful in producing major ore.

The port of Hayle grew considerably at the start of the 19th century partly due to the servicing of ores from the Wheal Alfred area. Although the fortunes of Wheal Alfred plummeted, Hayle continued as a most important centre of the Cornish engineering industry. The Harvey foundry was famous for the exporting of pumping engines worldwide. The last of the Cornish copper smelters, at Copperhouse, Phillack, ceased work in 1819, shortly after the (first) closure of Wheal Alfred.

Many of the mines had commenced before the 19th century, most had ceased operation soon after the 1850s, and all finished before the 20th century. Dines (1956) described in detail the various mines of the sett, their general geology and recorded outputs. Surprisingly there is only a limited research literature. Specimens from Wheal Alfred were described and illustrated in Embrey and Symes (1987), and some mining details are described by Hamilton Jenkin (1959).

Description

The country rocks of the Wheal Alfred sett are mainly 'killas' with some altered basic igneous rocks ('greenstones') east of St Erth. Old mine plans show that several quartz-feldspar porphyry ('elvan') dykes also occur in the area, trending ENE–WSW. Dines (1956) gave a full detailed description of the structures of the mines in the Wheal Alfred sett. At Wheal Alfred the main east–west lode (Main Lode) has been worked over a distance of nearly 1 km and to a depth of over 450 m. It is crossed by four other lodes, Middle Lode (trending about N40°E), South Lode (which courses E35°N), and North Lode (where it courses E10° to 40°N), Branch and Weekses Lode (which courses E20°N), and finally the western extension of Alfred Consols Lode. Main Lode was worked from Copper House or Taylors Engine Shaft.

Main Lode is crossed at Cherry Garden Shaft by a 18 m-wide elvan that trends E 40°N and dips 45°NW. Main Lode is intersected by a fluccan (clay-filled fault), coursing N5°W and by a cross-course trending N15°W. The fluccan does not appear to throw the lode, but the cross-course heaves it about 5 fathoms. The interesting variety of differing mineral structures within the mines of the Wheal Alfred sett gives rise to the

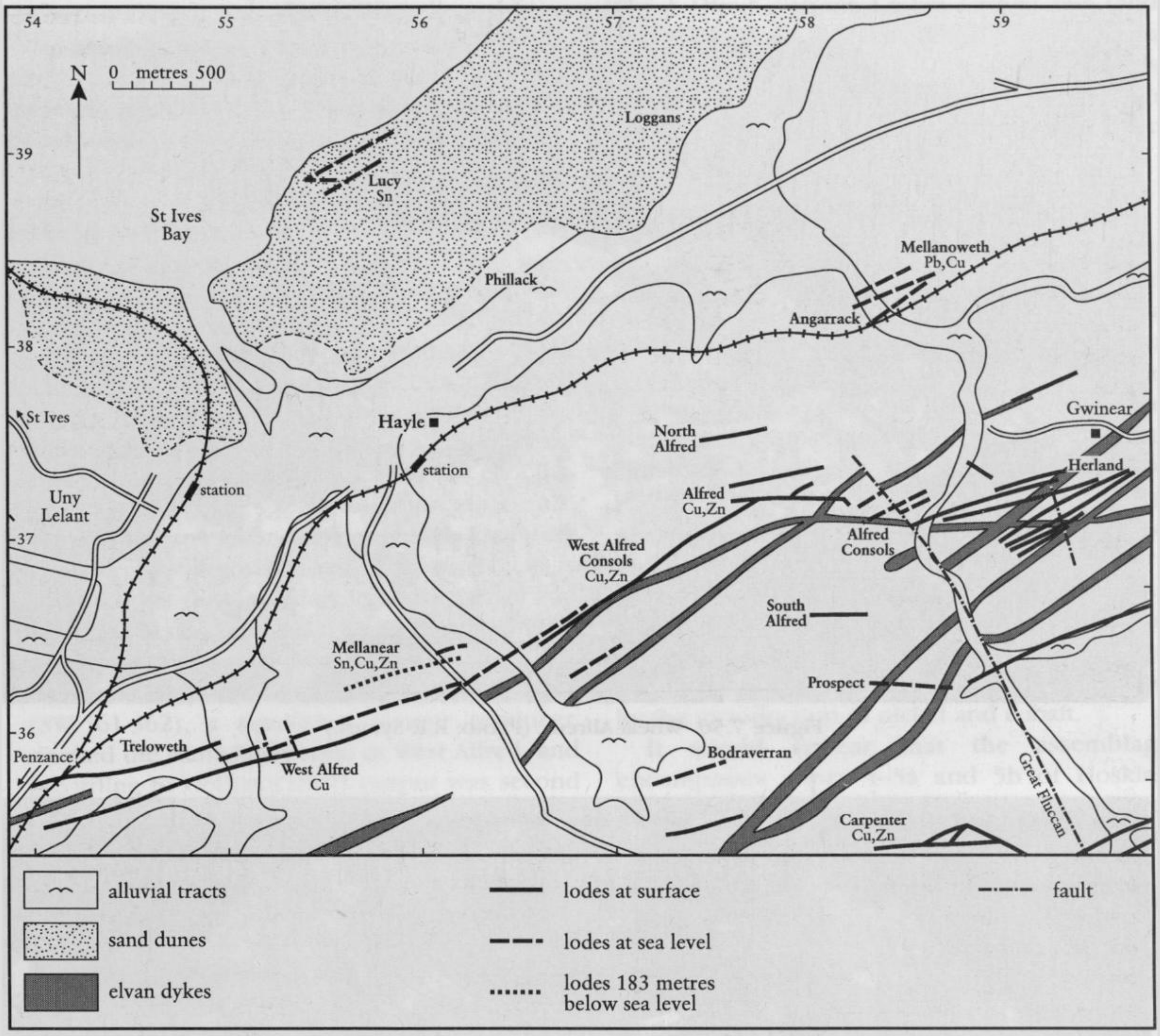

Figure 7.49 Sketch map of the Wheal Alfred setts. After Dines (1956).

complex record of primary ore minerals and derived secondary minerals. Minerals present were various copper ores, arsenopyrite, siderite, cerussite, smithsonite, argentite, cerargyrite and pyromorphite-mimetite.

Between 1801 and 1864, more than 170 000 tons of copper ore averaging about 7% were produced, but the mine was in operation before this time, and Collins (1897) stated that in 1800 it was the second largest copper producer in Cornwall. Considerable quantities of galena and cerussite ($PbCO_3$) were raised before 1814, and 245 tons of sphalerite were also mined.

Wheal Alfred has long been known as the locality for exceptional specimens of pyromorphite (see Figure 7.51). These are seldom of the usual bright-green colour and are often almost colourless or earthy, perhaps indicating that calcium is present. The finest specimens are often found as tapering, yellowish-green crystals, sometimes hollow and up to 5 mm across, and which occasionally form barrel-shaped crystals. They are normally found on iron-stained sugary quartz. Pyromorphites from this locality are the finest found in Cornwall but it is still not known from which part of the mine they were derived. The best locality for pyromorphite at surface is the large dump north of Lower Treglisson Farm marked by a telegraph pole. Extensive vein quartz still occurs in this dump.

Small pale-green sprays of the rare REE arsenate mineral agardite are sometimes found with the pyromorphite-mimetite. EDX analysis

Figure 7.50 Wheal Alfred. (Photo: R.F. Symes.)

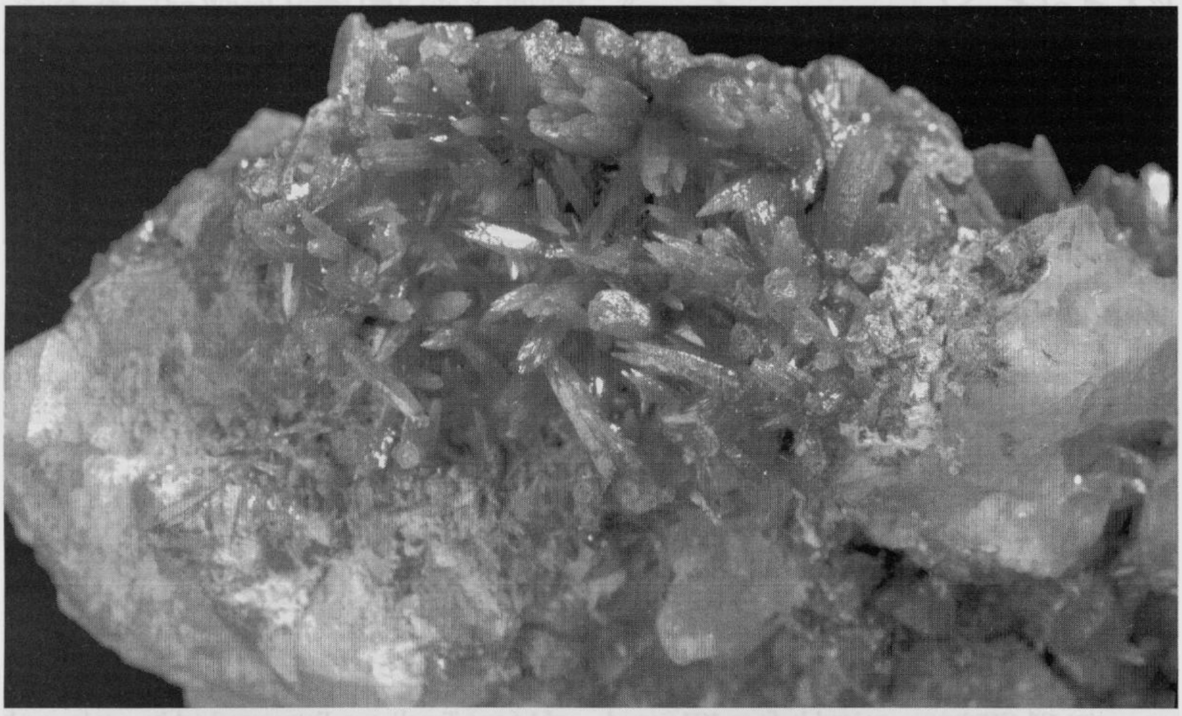

Figure 7.51 Pyromorphite from Wheal Alfred, Phillack, Cornwall. Tapering crystals, some hollow and up to 4 mm across, on iron-stained quartz. Pyromorphite specimens from this locality are the finest found in Cornwall, but it is not known from which part of the mine they came. (Photo: © The Natural History Museum, London.)

of various specimens of agardite collected from Wheal Alfred shows cerium to be the dominant rare-earth-element (REE) present, but lanthanum, neodymium and calcium were all also shown to be present. In terms of Levinson's rule for nomenclature of REE minerals these should be seen as the cerium variety of agardite, according to Nickel and Mandarino (1988), namely agardite-(Ce).

Dines (1956) recorded that the lodes in Alfred Consols Mine (the eastern extension of Wheal Alfred) contained considerable amounts of lead mineralization, and therefore the mixed mineral assemblage may be very similar to that at the **Penberthy Croft Mine** GCR site and Wheal Gorland. The eastern part of the mine contains cobalt and nickel in north–south structures, giving rise to secondary minerals including annabergite, erythrite and bieberite. It is believed that the secondary bismuth, nickel and cobalt minerals may have formed at the intersections of lodes with cross-courses.

Interestingly, the important Mellanear Mine (SW 561 362), a significant copper producer, worked the same Main Lode as West Alfred, and according to Collins (1897) output was second only to Devon Great Consols between 1879 and 1888. The mineral assemblage at Mellanear Mine (Dines, 1956) appears to have included some cassiterite, sphalerite, arsenopyrite and pyrite. West Alfred Consols records show lesser outputs of copper, zinc ore and small amounts of silver.

Alfred Consols lay just east of Wheal Alfred (see Figure 7.50), and here the lodes of the sett are traversed by the 'Great Fluccan' cross-course, which trends N30°W and underlies 10°W in killas, although most of the country rock is greenstone. Both of these are cut by elvan dykes. The Main Lode here was developed from Daveys Shaft, and the outcrop of the cross-course is recorded as passing through Daveys Shaft. The lodes developed in Alfred Consols were said to average 76 cm wide, but have been recorded up to 7 m. The recorded mineral assemblage is chalcopyrite, chalcocite, bornite, tetrahedrite, cuprite, galena, cerussite, pyromorphite-mimetite, sphalerite and cerargyrite. The two mines were large copper producers; for instance output between 1857 and 1864 was 18 500 tons of copper ore (at Alfred Consols), and between 1852 and 1863 21 510 tons of copper ore for Wheal Alfred. About 1.6 km farther east (and east of the Great Fluccan) Wheal Herland again worked part of the Main Lode. This mine is famous mineralogically for a remarkably rich pocket of native silver found at a cross-course intersection.

Interpretation

The area of mineralization worked at Wheal Alfred and associated mines appears to be a mixture of main-stage mineralization and a later cross-course assemblage. Very little is available in the literature for a full interpretation of the mineralogy at this important mining sett. From old records and the detailed description of Dines (1956) it would appear that primary, essentially east–west copper lodes of main-stage hydrothermal mineralization are crossed by later lead-zinc-bearing cross-courses. Silver was probably carried as argentiferous galena. In areas of the lodes a mixed mineral assemblage has therefore formed which is further complicated by the introduction of nickel and cobalt.

It would appear that the assemblage encompasses zones 4–5a and 5b of Hosking (1964). The presence of tin in the western parts of the sett would indicate higher hydrothermal temperatures of between 300°C and 500°C. However, several cross-courses are present in the workings, including the 'Great Fluccan', and these have added even more variety to the ores, particularly in the eastern part of the mine. The importance to the mineralizing process of elvan dykes more-or-less parallel to the trend of main veins is not fully understood.

Supergene enrichment has been important at this site, especially on the lead mineralization areas, where carbonate, phosphate and arsenate species have formed. Accordingly, considerable amounts of cerussite, pyromorphite-mimetite and cerargyrite are recorded.

Conclusions

Wheal Alfred and associated mines show a complex assemblage of primary ore minerals and related secondary minerals which indicate the occurrence of both main-stage and later cross-course veins. Wheal Alfred has yielded the finest examples of pyromorphite in Cornwall, which sometimes is associated with agardite-(Ce).

PENBERTHY CROFT MINE, CORNWALL (SW 553 324)

Introduction

Penberthy Croft Mine is situated approximately 1.5 km from the village of Goldsithney, in the parish of St Hilary, Cornwall (see Figure 7.52). The importance of the site at the present day is purely mineralogical, being a prolific source of unusual and rare secondary minerals, of which the Cu-Pb-Fe arsenates are the best known. Virtually all of these have been collected from the extensive dumps which cover a large area of open ground at the site (see Figure 7.53). However, five main areas on these dumps have been identified as containing the richest and most diverse assemblages of mineral species: Dukes Shaft (the richest area at Penberthy Croft Mine) has 52 confirmed species; Daws Shaft has 51 confirmed species; Ducketts Shaft has 48 confirmed species; the pharmacosiderite dumps have 41 confirmed species; and the birnessite dumps have 39 confirmed species (Betterton, pers. comm., 2010).

Copper- and tin-mining took place at Penberthy Croft Mine to a maximum depth of 53 fathoms below adit; small amounts of lead ore were also raised. In recent times, when tin prices were at a high, the dumps were sampled to evaluate their tin content.

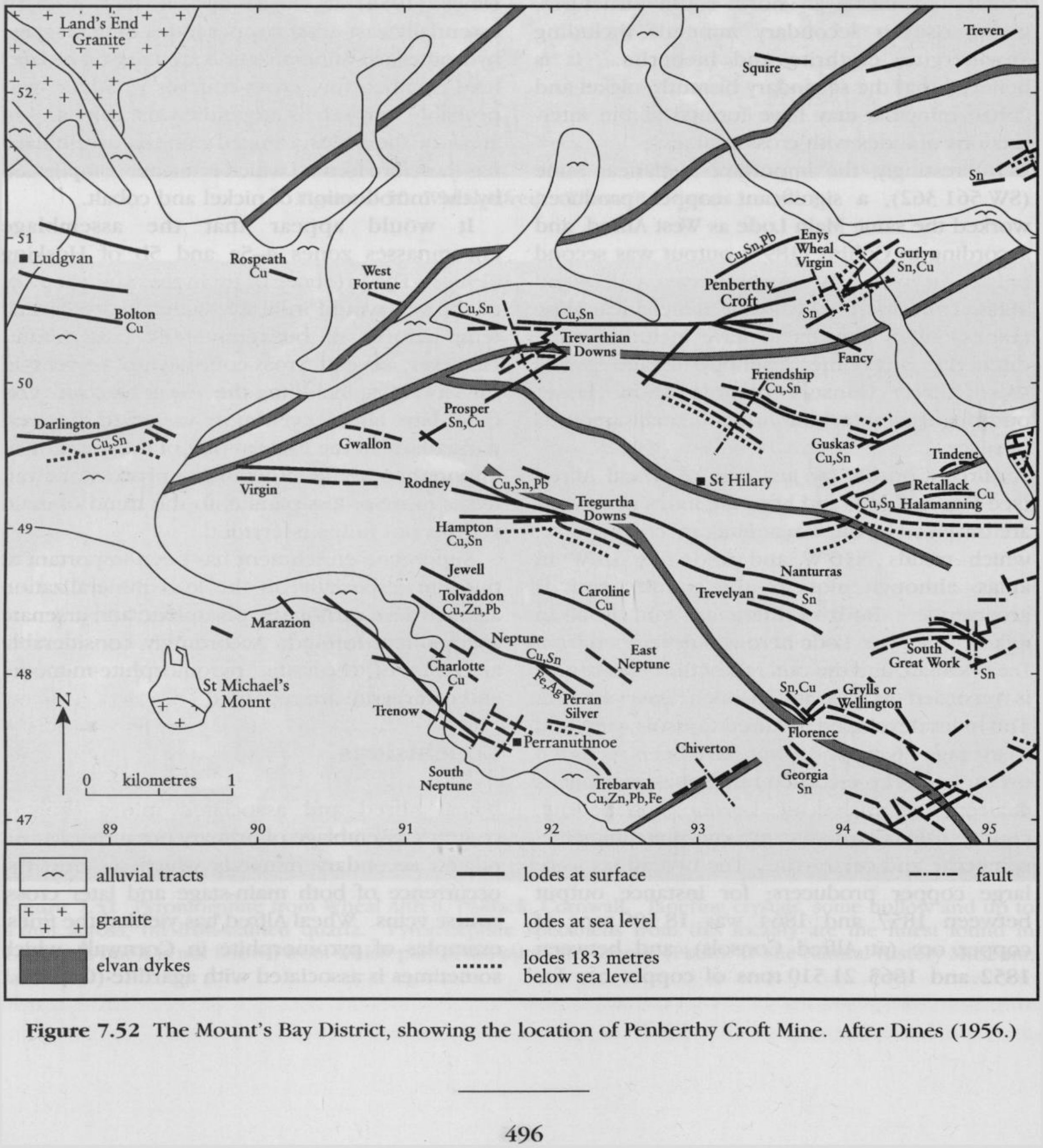

Figure 7.52 The Mount's Bay District, showing the location of Penberthy Croft Mine. After Dines (1956.)

Figure 7.53 View across the main area of spoil heaps, Penberthy Croft Mine. The fenced area is Daws Shaft, the type locality for bayldonite. (Photo: H. Townley, Natural England.)

Penberthy Croft Mine was noted as a locality for pyromorphite and mimetite in the mid-19th century. The copper lead asenate mineral bayldonite is ubiquitous at Penberthy Croft Mine and although originally described as from the St Day area, Kingsbury (1964) and others have stated that the original material came from Penberthy Croft Mine, which is considered to be its type locality. Recent studies have shown Penberthy Croft Mine to be the first recorded site in the British Isles for segnitite (Betterton, 2000), and the joint first recorded site for jeanbandyite and natanite (the other being Hingston Down Quarry) (see Betterton *et al.*, 1998).

Other rare minerals recorded from the dumps are carminite, pharmacosiderite, plumbogummite, wroewolfeite, monazite-(La) and mansfieldite. Altogether some 96 authenticated species have been reported from the locality, and Betterton (2000) has recently made a comprehensive review of the species present (see Table 7.3).

Description

Penberthy Croft Mine is believed to be very old, although historical records of output are sparse. Dines (1956) gave recorded outputs of 8700 tons of 7% copper ore, 60 tons of 'black tin' (unrefined ore) and 1.25 tons of 60% lead ore during the years 1818, 1824 and between 1881 and 1883. The mine was said to be producing very little in 1840, and was believed to be have been closed in the late 1840s. Dines (1956) provided details of the mining sett, while the detailed history of the mine has been recorded by Hamilton Jenkin (1965).

The Main Lode courses east–west, parallel to a quartz-feldspar porphyry ('elvan') dyke which lies some 140 m to the south of the lode. The outcrop crosses Long Lanes 530 m south of Penberthy Cross, and the lode has been worked for about 280 m east and 830 m west of the lane. Various other important lodes course away from the Main Lode, for example Longclose Lode courses E28°N and leaves the footwall on Main Lode 600 m west of Long Lanes. Canant Lode strikes W35°S and leaves the hangingwall of Main Lode 120 m west of Long Lanes. The total worked distance is around 3 km.

The Main Lode is either a double lode or the mineralization is telescoped, because tin, copper and lead minerals are all present within the dump material. However, the lead mineralization may be carried by small-scale cross-courses.

Table 7.3 List of minerals recorded at the Penberthy Croft Mine GCR site. Mineral species in **bold** (96 species) have been confirmed; those in *italics* are fradulent, suspected or cases of analytical errors. 'UKPC2' and 'UKPC3' refer to 'Unknown Penberthy Croft' 2 and 3 – further research on these minerals is required. After Betterton (2010).

Adamite	**Cassiterite**	**Jarosite**	**Pseudomalachite**
Agardite-(Ce)	*Ceruleite*	**Jeanbandyite**	**Pyrite**
Agardite-(La)	**Cerussite**	*Jordanite*	**Pyromorphite**
Alloclasite	**Chalcoalumite**	**Langite**	**Quartz**
Anatase	*Chalcocite*	**Laurionite**	**Redgillite (UK PC1)**
Anglesite	**Chalcophyllite**	**Leadhillite**	*Rosasite*
Ankerite	**Chalcopyrite**	**Libethenite**	**Scheelite**
Annabergite	*Chlorargyrite*	**Linarite**	**Schulenbergite**
Apatite-(CaF)	**Chrysocolla**	**Liskeardite**	**Scorodite**
Aragonite	**Clinochlore**	**Malachite**	**Segnitite**
Arseniosiderite	**Connellite**	**Mansfieldite**	*Serpierite*
Arsenolite	**Copper (native)**	**Mattheddleite**	**Siderite**
Arsenopyrite	**Corkite**	**Millerite**	**Silver (native)**
Atacamite	**Cornubite**	**Mimetite**	**Smithsonite**
Aurichalcite	**Cornwallite**	**Mixite**	**Sphalerite**
Azurite	**Covellite**	**Monazite-(La)**	**Stannite**
Bayldonite	**Cuprite**	*Mottramite*	**Stilpnomelane**
Beaverite	**Cyanotrichite**	**Muscovite**	**Stolzite**
Beraunite	**Devilline**	**Natanite**	**Sulphur (native)**
Beudantite	**Dolomite**	**Olivenite**	**Tenorite**
Bieberite	**Duftite**	**Orthoclase**	*Tyrolite*
Birnessite	**Erythrite**	*Paratacamite*	**UK PC2**
Bismuthinite	**Galena**	**Parnauite**	**UK PC3**
Bismutite	**Goethite**	**Pharmacosiderite**	**Varlamoffite**
Bornite	**Gypsum**	**Philipsburgite**	**Woodwardite**
Brochantite	**Halite**	**Phosgenite**	**Wroewolfeite**
Calcite	**Halloysite**	*Pitticite*	**Zincolivenite**
Caledonite	**Hidalgoite**	**Plumbogummite**	
Carminite	*Hornblende*	*Plumbojarosite*	

The mining sett is in Devonian metasedimentary rocks consisting of low-grade greenschist-facies killas, mostly slates, and is situated between the Land's End and Carnmenellis granite masses. The slates belong to the Mylor Slate Formation, usually a series of siltstones and mudstones with occasional impersistent sandstone layers (Goode and Taylor, 1988). Some interbedded metabasites strike east–west through the sett.

The primary mineralization is multi-stage, polymetallic and hydrothermal in character. The deposit appears to consist (from evidence of material collected mostly at surface) of several but distinct overlapping assemblages. The early main-stage mineralization is of high-temperature hydrothermal Sn-Cu-W-As veins, followed by a later-stage lower-temperature mesothermal to epithermal Pb-Zn mineralization, and a final late-stage Fe-Mn mineralization. As with all hydrothermal mineralization, fracturing, brecciation, silicification and chloritization of the vein material is common.

Supergene weathering and oxidation processes led to the formation of complex gossans with oxide and supergene enrichment zones. These processes led to the formation of a prolific suite of secondary minerals, such as pyromorphite and many secondary copper minerals. However, a further phase of mineral formation dates from post-mining times, both underground and certainly on the dumps, resulting in increased mineral species representation, including for example, birnessite. The abundance of the various species groups present is roughly in the decreasing order arsenates, arsenates-sulphates and phosphates.

Most of the supergene minerals are found in cavities associated with strongly oxidized gossan in vein quartz, or as small crystalline crusts on the slates. Today most specimens occur as euhedral to subhedral micro-crystals.

Interpretation

Other than the description by Dines (1956), little is known of the mineralization and structure of the underground workings, and any paragenetic sequence has to be derived from past-collected samples in museum or private collections and the evidence of species in the dumps.

The origin of the primary mineralization of the Penberthy Croft area is directly associated with the main-stage hydrothermal mineralization of South-west England, of a late Carboniferous to Permian age and formed under similar conditions to the granite-driven models of convective mineralizing fluids (Simpson *et al.*, 1979). In such models mineralization is phased both in space and time. Early tin mineralization may be associated with the pink propylitic alteration of feldspars in the granites; however at Penberthy Croft the main-stage high-temperature vein mineralization seems to be the most important. At upper levels a chalcopyrite-dominated assemblage is found with arsenopyrite and associated sphalerite, while at depth arsenopyrite dominates, with cassiterite and minor scheelite and stannite present. It could be that rich tin mineralization occurs at some depth below Penberthy Croft.

In addition, minor, burial-related quartz-albite-anatase-monazite veins of a pre-tectonic, metamorphic origin can be found. This phase of mineralization is very minor, but has also been found at other Cornish mines (Betterton, pers. comm.).

A later stage of mineralization associated with lead-bearing hydrothermal fluids is found in the cross-course lodes. This led to an assemblage of galena, sphalerite, pyrite and minor chalcopyrite. Some nickel, bismuth and cobalt minerals have been found at Penberthy Croft, indicating a possible later phase of nickel mineralization associated with the cross-course assemblage. A phase of low-temperature mineralization (siderite) led to an assemblage of iron mineralization.

The diversity of the supergene minerals arises from the range of primary sulphides present and the prolonged and complex history of weathering and erosion under a variety of climates. Modification of the water-table over time has also played an important part in this process. The presence of 'boxwork' supergene specimens, with goethite, emphasizes the episodic nature of supergene and oxidation processes.

Conclusions

The Penberthy Croft mining area worked a number of metalliferous epigenetic veins hosted by 'killas' of Upper Devonian age. The mine is an important mineralogical site for the variety of primary, secondary and tertiary mineral species that occur on the dumps. Especially noteworthy are the secondary copper and lead minerals, present as arsenates, sulphates and phosphates.

HOPE'S NOSE, DEVON (SX 949 636)

Introduction

Hope's Nose forms a promontory on the northern side of Torbay, Devon, and comprises a steeply sloping headland bounded by low cliffs, about 3 km east of the centre of Torquay. The Hope's Nose GCR site consists of the seaward exposures on this promontory (see Figure 7.54). At Hope's Nose, the Middle Devonian (Eifelian) beds form a wave-cut platform below a small cliff. The platform is some 100 m long and roughly 25 m wide, and is mostly covered under tidal or storm conditions. The mineralized veins of interest are located on either side of a major outfall pipe.

Gold-bearing carbonate veins cut the Middle Devonian limestones of the wave-cut platform, and also contain rare palladium and selenium minerals. The mineralization is believed to result from hydrothermal activity. Stanley *et al.* (1990a) described a low-temperature epithermal environment for the mineralization, associated with the Lundy–Sticklepath–Lustleigh–Torquay Fault System.

Description

The geology of this part of south Devon is complex and, because there are so few inland exposures, it is poorly understood. The area lies in a roughly east–west tectonic belt made up of Devonian to Lower Carboniferous sedimentary rocks, typically marine shales and sandstones together with interbedded lavas and tuffs (see Figure 7.54). During Middle to Upper Devonian

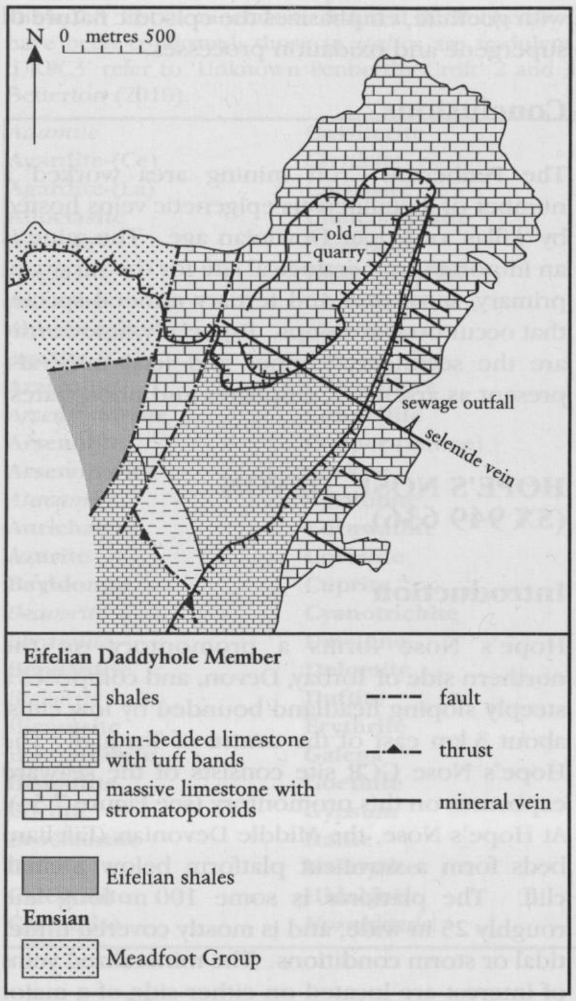

Figure 7.54 Sketch map of Hope's Nose, showing the geology and the location of the principal gold-bearing veins. After Stanley *et al.* (1990a).

times extensive carbonate platforms developed within a predominantly marine sequence, and the Tor Bay reef complex, of which the limestones at Hope's Nose are a part, formed on the eastern margin of one of these platforms. During the Variscan Orogeny this sedimentary succession was deformed and has been referred to as a 'thrust and nappe terrane' (Chandler and Isaac, 1982).

Today, a variably developed wave-cut platform provides most of the coastal exposure in the northern part of Hope's Nose. In these exposures, and in a small disused quarry on the headland to the east, massively bedded, hard and fossiliferous limestones are overlain, apparently disconformably, by a thin to poorly bedded dark-grey and shaley limestone with interbedded tuff horizons. This sequence has been assigned to the Daddyhole Member of Eifelian age, the earliest of the three members of the Middle Devonian Torquay Limestone Formation (Scrutton, 1978; Goodger *et al.*, 1984).

The massive limestones are cut by a number of calcite veins and stringers (see Figure 7.55) for about 50 m north-east and south-west of the outfall. The veins are steeply dipping and trend roughly N70°W. Some of them show slickensides and most have been subject to faulting, although they display little vertical displacement (Scrivener *et al.*, 1982). Wall-rock alteration around the veins is restricted to patchily developed hematization.

The veins vary in colour and texture, commonly consisting of coarse, purple and yellowish ferroan calcite enveloping clasts of the host limestones, as well as biscuit-coloured, anhedral calcite and dolomite, often with a saccharoidal texture. These veins often have voids filled with iron hydroxides. It is these calcite veins that seem to be most commonly associated with gold.

Gold was first found in these veins by Gordon (1922), and was fully described by Russell (1929) who reported arborescent sprigs of gold in five distinct calcite veins to the north of the outflow. However, since the locality was 're-discovered' in the 1980s gold has also been found in veins south of the outfall. Some of the gold was found to be palladian by electron-probe micro-analysis and to be associated with the palladium antimonides isomertieite and mertieite-II (Clark and Criddle, 1982) (see Figure 7.56).

Subsequently, specimens from close to the outfall and also from the western side of the quarry were found to contain a suite of selenide minerals (Stanley *et al.*, 1990a). The full assemblage is calcite, hematite, dolomite, pyrite, chalcopyrite, gold, palladian gold, isomertieite, tiemannite, trüstedtite, tyrrellite, penroseite, umangite, fischesserite, eucairite, naumannite, clausthalite, klockmannite, cerussite, malachite, aragonite and goethite.

Additional material was collected at a later date from a vein about 50 m north-east of the 'selenide vein' of Stanley *et al.* (1990a), and further selenide minerals were found. Subsequent studies led to the identification of the new mineral chrisstanleyite ($Ag_2Pd_3Se_4$), a mineral similar to oosterboschite. In addition,

Figure 7.55 One of the remaining areas of vein mineralization at Hope's Nose. The vein cuts the massive limestone beds. (Photo: H. Townley, Natural England.)

two unknown minerals of composition $PdSe_2$ and $HgPd_2Se_3$ (Paar *et al.*, 1998) were identified. The former mineral has been identified subsequently as the new mineral verbeekite (Roberts *et al.*, 2002), with its type locality being Musoni Mine, in the Democratic Republic of Congo.

Alderton (1993) attributed this episode of mineralization to post-granite emplacement and linked it possibly to a source derived from either Permian red-beds or, perhaps more likely, from Permian alkaline volcanic rocks and lamprophyres.

Interpretation

Fluid-inclusion studies on calcite and quartz from the gold-bearing veins gave a range of homogenization temperatures of 65°–120°C. The fluids were rich in $CaCl_2$, with total gross salinities of 20–23 equivalent wt% NaCl and a $CaCl_2$:NaCl ratio probably with a minimum of 3:1. Such salinities are within the ranges for South-west England Pb-Zn-F mineralization.

Although the mineral association at Hope's Nose is unusual it is not unique. There are distinct similarities between Hope's Nose and the classic selenide deposits in the Harz Mountains. For the Tilkerode and other Harz selenide deposits, Tischendorf (1968) suggested that the metal and selenium contents had been leached from black carbonaceous shale host-rocks, and that solutions from a deeper source, possibly residual fluids from a relatively basic magma, contributed Fe, Ca, Mn and Mg.

Another comparison can be drawn with the overall element package associated with noble metal-bearing shales in the Zechstein of Poland, where a thin black-shale horizon, enriched in Ni, Co, Pt, Pd, Ir, Cu, Se, Hg, Mo, Re, Au, As and Bi, forms a boundary between oxic and anoxic conditions, the metals being fixed by absorption, 'complexation' and reduction by the organic matter (Mountain and Wood, 1988). At Hope's Nose, the high salinities in fluid inclusions, high Ca: Na ratios, and the widespread hematization of the limestone adjacent to the veins all suggest that conditions for complexing could have been

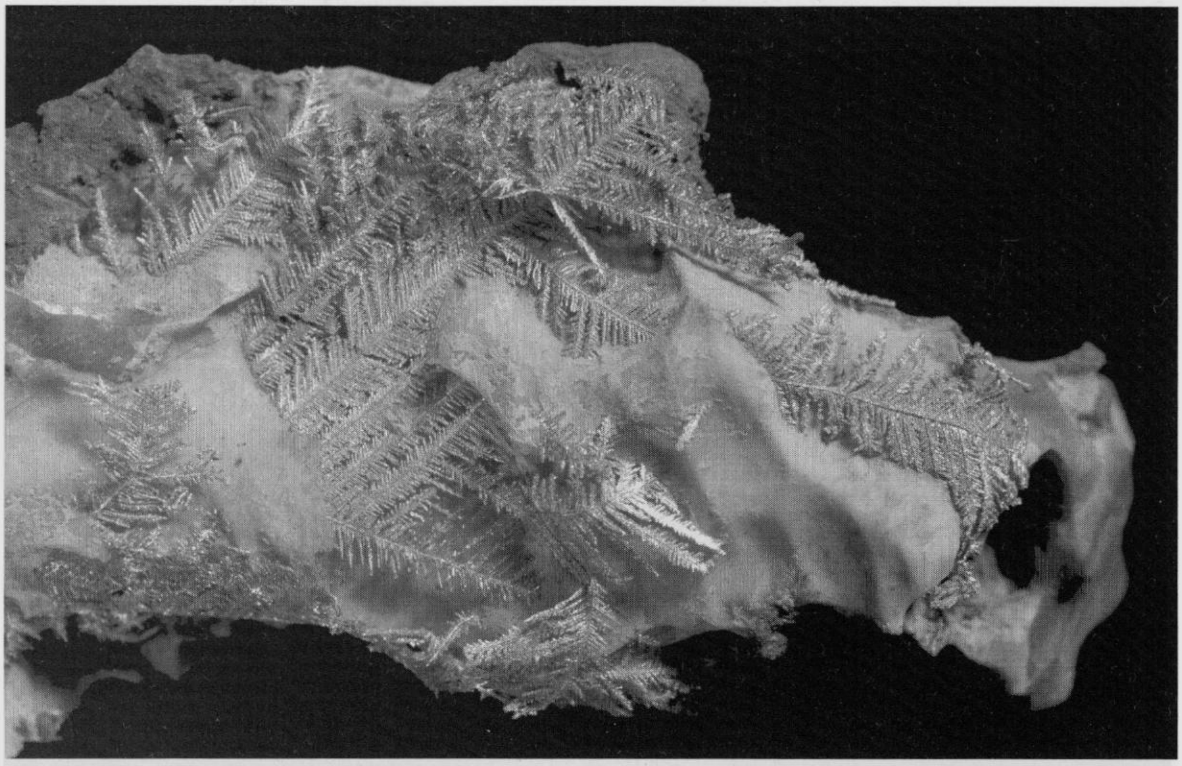

Figure 7.56 Gold, from Hope's Nose, near Torquay, Devon. A beautifully delicate dendritic growth in cream-coloured calcite, with brown-weathered dolomite. Originally wholly enclosed by calcite, the vein has been exposed by acid treatment. The small veins at this locality crop out on the sea coast, near the sewage outfall of Torquay and are remarkable for the palladium minerals isomertieite and mertieite-II which have recently been found there in small amounts. (Photo: © The Natural History Museum, London.)

present. However, as the Daddyhole Member is not notably bituminous, the mechanism for reduction and deposition is less certain. It may be that fluids driven from below ponded against the overlying thinly bedded shaly limestone, were neutralized by reaction *in situ* and could no longer hold their trace-element content in solution.

In any case, the low temperature and low amount of silica in the veins might indicate a relatively shallow and restricted circulatory system since chemically active fluids would be expected to react with any siliceous wall-rocks and pick silica up into solution.

The fracture system into which the fluids were drawn may have been controlled by movements along a major NNW–SSE lineament, the Lundy–Sticklepath–Lustleigh–Torquay Fault System. Local thrusting may also have been important in localizing the deposit (Stanley *et al.*, 1990a). A possible link with nearby shallow intrusive igneous bodies is provided by a significant positive gravity anomaly, while Alderton (1993) has suggested that the source of the gold may have been Permian volcanic rocks and associated lamprophyres.

Conclusions

A rare association of gold-palladium and selenide mineralization occurs in carbonate veins at Hope's Nose. This is the only known occurrence of this mineral assemblage in Britain, and is therefore an internationally important mineral site.

Gold in small amounts is widespread throughout the area, having been recorded from Daddyhole Quarry (Gordon, 1922) and from several 'panned' areas of the River Dart. Recent surveys by the British Geological Survey have shown gold to be distributed in the drainage channels and soils of the area.

Mineralization is thought to have formed by low-temperature hydrothermal remobilization of precious metals, possibly associated with concealed, local mafic igneous rocks, the gold possibly being derived from the underlying

Permian alkaline volcanic rocks and associated lamprophyres. Specimens of delicate dendritic growth of gold in cream-coloured calcite are most attractive; in many specimens the gold has been further exposed by acid treatment (see Embrey and Symes, 1987).

HIGH DOWN QUARRY, DEVON (SS 653 290)

Introduction

The High Down Quarry GCR site, at Filleigh, near South Molton, in Devon, is the type locality of the aluminum phosphate mineral wavellite. This small quarry is situated directly to the north of the minor road between West Buckland and Heddon.

There is considerable interest in the naming of this mineral. The original paper on wavellite was by Davy (1805). The paper was entitled '*An Account of Some Analytical Experiments on a Mineral Production from Devonshire*'; it also stated that a Dr Babington proposed to call the 'fossil' from Devonshire 'wavellite', after Dr William Wavell, the gentleman who discovered it (note, in the original paper 'Wavel' is spelt with one l). An earlier discovery, some time before 1785, by a Mr I. Hill, has been suggested by Sowerby (1811).

A specimen of wavellite from High Down Quarry was figured by Sowerby (1806) in his *British Mineralogy*, and listed in Greg and Lettsom (1858). An annotated colour photograph of an excellent specimen of wavellite from High Down Quarry was in Embrey and Symes (1987). Because of its radiating fibrous appearance wavellite was originally thought to be a zeolite, and was known for sometime as 'hydrargillite', and also for a short time as 'devonite'. An excellent description of the discovery of the Barnstaple zeolite (wavellite) has recently been given by Cleevely (2007).

Description

Today it is hard to determine the reason why the quarry was worked, perhaps for material for wall construction for local fields or it may have simply acted as a cattle containment area. The low quarry faces (maximum depth of approximately 3 m) (see Figure 7.57) expose black carbonaceous cherty slates of the Codden Hill Beds (Carboniferous, Lower Culm), with wavellite crystals sparingly present along cleavage and joints.

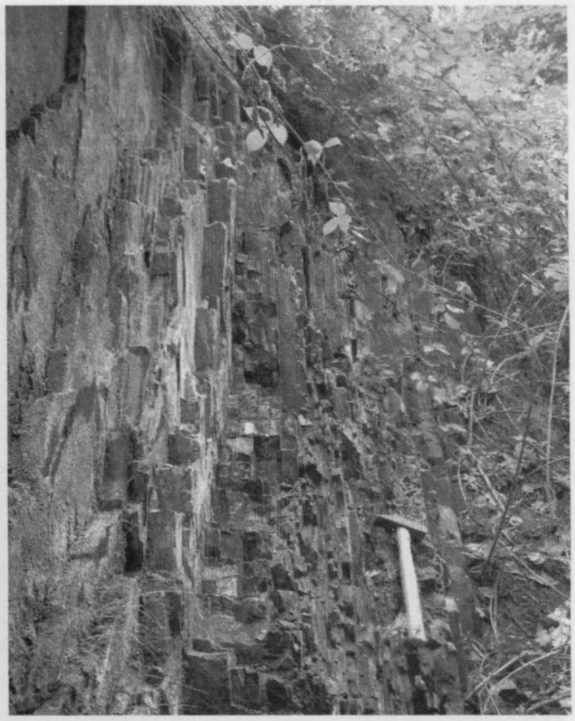

Figure 7.57 Black carbonaceous cherty shales of the Codden Hill Beds, exposed at High Down Quarry. (Photo: Natural England.)

Wavellite appears to be restricted to the southern end of the quarry working, and becomes hard to find in the northern exposures of slate. Fine specimens can still be collected from small dumps on the quarry floor. The wavellite occurs as colourless, white-grey, or light-green acicular crystals forming flat radiating or spherulitic aggregates (average 1 cm in diameter) coating joints or fractures (cleavage planes) in the slates. Exceptional specimens have been described as botryoidal masses of radiating crystals (see Figure 7.58) up to 5 cm in diameter, pale-green in colour, and sometimes blackened by carbonaceous inclusions. The rhomboidal jointing in the black slate is sometimes bleached where mineralization occurs. A further aluminium phosphate mineral, variscite, is sometimes intimately associated with the wavellite. Variscite typically occurs as very small aggregates (hemispherical or globular) associated with wavellite or as thin coatings along cleavage surfaces. The same association of wavellite and variscite is seen in beds of similar age on the Gower Peninsula, in South Wales (Bevins, 1994; Plant and Jones, 2001).

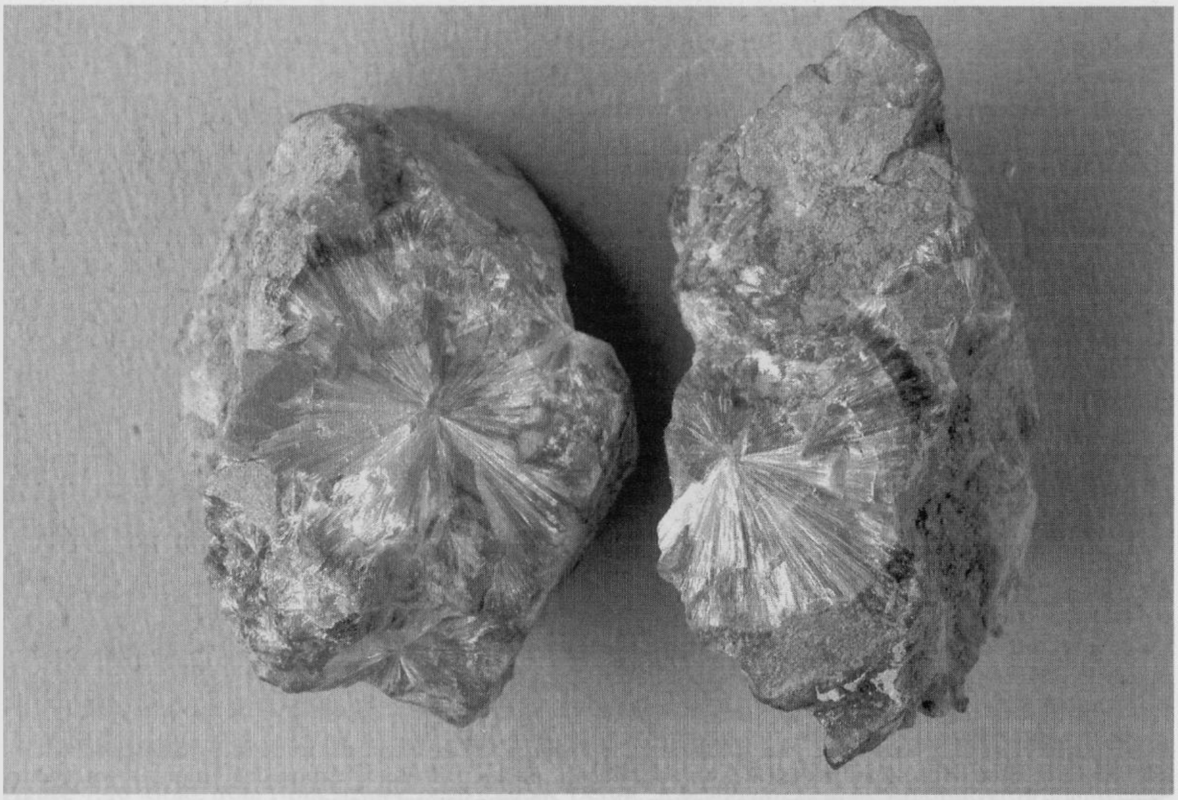

Figure 7.58 Wavellite specimen from High Down Quarry. (Photo: Natural England.)

Interpretation

There are no other mineral deposits in the immediate vicinity of High Down, and there is general agreement that at High Down Quarry wavellite is of supergene or secondary origin, although worldwide it has been described as coating joint-surfaces and sometimes in cavities in low-grade metamorphic rocks, and rarely has been recorded as a late-stage mineral in some hydrothermal veins. The wavellite (and variscite) could have formed from the reaction between aluminous clay-minerals (kaolinite) and phosphorus-bearing waters. The source of phosphorus could have been apatite disseminated throughout the country rocks.

Conclusions

High Down Quarry is the type locality for the aluminium phosphate mineral wavellite, where mineralization can still be seen *in situ* and collected for study from small waste heaps. It occurs with the aluminium phosphate variscite.

HINGSTON DOWN QUARRY AND HINGSTON DOWN CONSOLS, CORNWALL (SX 410 718)

Introduction

Hingston Down Quarry lies approximately 2 km west of Gunnislake, in east Cornwall, and is a large working aggregate quarry. The quarry works the small granite intrusion of Hingston Down, part of a granite ridge situated midway between the Bodmin Moor and Dartmoor granites. The fine-grained biotite granite at Hingston Down is traversed by numerous nearly vertical, approximately E–W-trending veins, and mineralized joints containing various minerals including chalcopyrite, arsenopyrite, sphalerite, molybdenite, wolframite, scheelite and fluorite. The rare beryllium silicate mineral bertrandite was recorded from the quarry (Ward, 1983), and arthurite, the rare copper iron arsenate mineral, has been recorded from the dumps of Hingston Down Consols, and is indeed the type locality for the mineral (Davis and Hey, 1964). A description of Hingston Down Consols Mine and some of the lodes which pass through the quarry was provided by Dines (1956). Further planned development of the quarry will be to the east, where borehole logging is believed to have shown further supplies of good-quality, fine-grained, 'grey' granite.

Description

This GCR site comprises the active quarry at Hingston Down and the adjacent disused mine and spoil tips immediately south and south-west of the working quarry faces (see Figure 7.59). The quarry continues to expose a deep section through the south-western part of the Hingston Down Granite, and the associated mineralized zones. Mineral veins previously worked in the Coxpark section of Hingston Down Consols used to be exposed in the western faces of the quarry. At most times the south-eastern faces of the quarry expose mineralized veins, often quartz-filled and usually associated with a pegmatitic facies of the granite.

The Hingston Down Granite mass is irregular in shape, and although of only a relatively small mass it is similar in character and composition to the major Cornish granite masses. The granite is a mostly grey (tending to brown when weathered), fine-grained biotite granite, sometimes porphyritic and with pegmatitic bodies formed commonly within the granite wall-rock. Tourmalinization occurs at the contact. A detailed description of the granite was given by Ward (1983).

Occasionally, mineralized features occur in the quarry that are sufficiently persistent to be mappable. These minor lodes are rather atypical of others in the area and consist of discontinuous lenticular masses of sulphides (sphalerite, chalcopyrite, wolframite, pyrite and arsenopyrite), which occur either as individual masses or in complex intergrowths. Best exposures are usually in the south-eastern faces of the quarry and across the quarry floor. Where it occurs, mineralization in the lodes tends to pinch and swell and discolours the quarry faces. Mineralization is therefore of a sporadic nature and is rarely traceable for more than a few metres. Many of these minor veins are quartz-filled and good opal specimens are sometimes found.

Hingston Down Consols was originally worked for copper. The various shafts of the Hingston Down Consols group worked several lodes which are mainly in metamorphosed country rock ('killas') at the surface but run into granite at a relatively shallow depth and are reported to pass downwards from a copper zone into a tin zone of mineralization. To the west of the sett an east–west quartz-feldspar porphyry ('elvan') dyke was said to traverse both the killas and granite. The mine has a recorded output

Figure 7.59 Hingston Down Quarry. (Photo: JNCC.)

for the period 1916 to 1919, but ceased working shortly after. Current interest is in the minerals found in the mine dumps. The largest dumps are centred upon the remains of the old engine-house, and much of this area is cordoned off due to possible danger caused by local stoping. However the dumps are sufficiently large to provide good examples of the mineralization. The dump material tends to be variable with no overall production pattern, and both tin- and copper-zone mineralization occurs together with later-stage lead mineralization, the latter tending to fill small fractures in chalcopyrite-rich specimens. It is probable that outputs from various parts of the mine have been mixed on these dumps. Good specimens of arthurite can still be obtained from the dumps, along with scorodite, carpholite, pharmacosiderite, and beudantite, while the rare minerals hidalgoite and carminite have been recorded. In addition, recent studies have shown Hingston Down Quarry to be the joint first recorded site for jeanbandyite and natanite (the other being **Penberthy Croft Mine**) (see Betterton *et al.*, 1998). However, Ryback *et al.* (2001) have demonstrated that the late A.W.G. Kingsbury falsified the localities of numerous rare mineral species. This deception affects a number of locations in the South-west England, including Hingston Down Quarry and Hingston Down Consols. Therefore care should be exercised when considering claims by Kingsbury which have not been substantiated or duplicated by subsequent collectors.

The workings are situated at the south-west corner of the granite outcrop, where there are two major lodes about 30 fathoms apart. The more northerly Main Lode has been developed from Bailey's Shaft and Morris's Shaft. South Lode was opened up by Hitchen's Shaft. On the Main Lode, Morris's Shaft was sunk in granite, but Bailey's Shaft commences in killas and enters granite at about 75 fathoms depth. The record from this shaft describes well the mineralized sequence observed: copper ores and arsenopyrite occupied the highest level, accompanied by some tin and wolframite, while at depth the sulphides die out, although cassiterite and wolframite tend to persist.

Another section of the mine, known as 'Lower Hingston', was opened up by an adit in killas in the Coxpark Valley. The Coxpark Lode used to be exposed in the western face of the quarry (Dines, 1956), but the adit is not now visible and is at present covered by stockpiled aggregate.

Interpretation

At the Hingston Down GCR site there is some mineralization directly associated with the granite, which is related to normal granite processes and often related to the formation of tourmaline. Sometimes cavities occur in slightly greisenized granite containing schorl, fluorite, chlorite and pyrite. It was from an open joint-fissure in the granite that small crystals of the beryllium silicate bertrandite were found associated with fluorite and quartz (Ward, 1983).

Hingston Down Consols originally worked a series of parallel, approximately E–W-trending, Sn-Cu lodes both in granite and killas, and within the pronounced Gunnislake–Hingston–Kit Hill granite ridge. Mineralization is related to, and of the same age as, the main-stage hydrothermal mineralization of the South-west England orefields, but the presence of lead minerals in the assemblage implies a late stage of mineralization associated with north–south cross-courses. Dines (1956) stated that the known cross-courses occurred on the deeper levels of the Main Lode west of Bailey's Shaft. There is some evidence of a reverse zonation of the Sn-Cu mineralization (that is copper in granite and tin in killas), but this still needs to be substantiated and interpreted. Whether this granitic ridge can be interpreted as an emanative mineralization centre is still open to discussion.

Arthurite, the copper-iron arsenate first described from Hingston Down Consols (Davis and Hey, 1964) occurs as apple-green crusts sometimes intimately mixed with pharmacosiderite. It would appear to be a supergene or secondary mineral formed either due to reactions within the mine or on the dumps, copper, iron and arsenic being in plentiful supply in both oxidizing environments.

Beryllium-bearing minerals are rare in South-west England, but have been recorded from Cheesewring Quarry (Bowman, 1911), St Cleer (Russell, 1913) and Trolvis Quarry, Stithians (Hosking, 1954). At all of these localities the bertrandite occurs as a primary phase in fissures in granite and is of late-stage, hydrothermal origin. Analyses have shown that leucogranites at Hingston Down contain up to 33 ppm Be.

It appears that at Hingston Down, beryllium is concentrated in the residual magma, and the frequent association of fluorite with bertrandite in greisenized joints in the granite (and in other

Cornish occurrences), suggests migration of Be in aqueous F-bearing solutions, perhaps as a mobile complex in the hydrothermal stage, with final reaction of the fluids with wall-rocks resulting in formation of bertrandite and fluorite.

Conclusions

Hingston Down Quarry continues to work a granite mass for aggregate, from time to time exposing pegmatitic-hosted mineralization. Lode mineralization is also exposed in the quarry, while the dumps of Hingston Down Consols are still fertile in a variety of mineral assemblages. Hingston Down Consols is the type locality for arthurite, a copper iron arsenate mineral.

PENLEE QUARRY, NEWLYN, CORNWALL (SW 468 278)

Introduction

Quarrying at the Penlee Quarry GCR site (see Figure 7.60), at Newlyn, commenced some 100 years ago, when it was formerly known as the 'Gwavas Quarry'. The crushed roadstone production was given as 120 000 tons in 1982, and at its peak the quarry is reported to have produced over 300 000 tons of roadstone annually. Work ceased in 1991 and although some areas of the quarry have recently seen restructuring of the levels, and therefore fresh exposures, there appear to be no plans for further development as a working quarry. The altered dolerite rock ('greenstone') from Penlee was noted for its high crushing strength, but a low polished stone value (PSV) precluded its use for most road surfaces in the UK.

The quarry provides a variety of mineralization types for study. A north–south vein is of considerable interest to mineralogists as it contains an unusual assemblage of minerals not common elsewhere in Cornwall. This assemblage consists of chalcopyrite, arsenopyrite, löllingite, molybdenite, pyrite, pyrrhotite, quartz and chalcedony. Both molybdenite and löllingite are rare in South-west England.

Dependent on the state of the exposed faces at any time examples of early pegmatitic mineralization and pyrometasomatic mineralization in greenstones (the Gwavas 'metabasite' sill) can be studied. Further, an amethystine-chalcedonic vein has also been revealed in the northern faces of the quarry.

Figure 7.60 Penlee Quarry. (Photo: A. Tyson.)

There is only a limited literature on the petrology and mineralization of Penlee Quarry. The geology of the country around the Penzance area was described by Goode and Taylor (1988) (see Figure 7.61). No details of mineralization were discussed by either Dines (1956), or Hosking (1964).

Quarried roadstone from Penlee was originally transported directly from the quarry by ship. The quarry is large, being in both a north–south and east–west direction close to 800 m. Some faces are old and unstable, and the nature of lode mineralization is often best studied from large loose blocks within the quarry.

Description

Penlee Quarry exposes country rock ('killas') and greenstone located very close to the contact of the Land's End Granite. The Devonian Mylor Slate Formation metasedimentary rocks were intruded by a large dolerite intrusion, the 'Gwavas sill' during Devonian times. It was this greenstone intrusion that was the main component of the quarried stone. The intrusion of the nearby Land's End Granite (290–300 Ma) led to metamorphism of the greenstones, characterized by the formation of copious green acicular actinolite, which tends to overprint the original ophitic texture. Newly created quarry bench exposures to the south of the quarry, along with associated features in some of the old faces, display brecciated infill structures to the veins. These consist of comb-layered, sometimes vuggy, quartz, clasts of brecciated host-rocks, and chalcedonic cemented breccia. Some of the breccia textures are similar to those seen at the **Nanjizal Cove** GCR site, albeit on a smaller scale, and also those described from Wheal Remfry (Allman-Ward *et al.*, 1982). Such cockaded structures have been studied by C. Halls (pers. comm.), and are thought to illustrate the forceful fluid flow along the lode.

Pieces of the country rocks have been broken from the fissure walls and carried forcefully by the fluids. It would seem that fissure-filling was characterized by repeated opening and further deposition. Both within the lode structures and other disseminations, the distribution of mineralization tends to be patchy, but it can also be locally intense. It is dominantly of pyrometasomatic type, and largely restricted to the mafic lithologies. The common assemblage is of pyrite, chalcopyrite, marcasite, arsenopyrite and löllingite all associated with actinolite. A Sn-Cu lode is recorded as crossing the quarry, trending east–west, but is now poorly exposed or obscured completely, although when revealed, this roughly E–W-trending quartz lode carries some interesting mineralization.

The presence of molybdenite in the quarry is of considerable significance. It occurs as coarse crystals in hornfels adjacent to granite pegmatites and veins. It is usually most easily studied and collected in the south-west part of the quarry.

In the north and south faces of the south-west part of the quarry, a prominent north–south lode is exposed, dipping 65° to the west. This structure is often highly ferruginous and brecciated, while some blocks or fresh quarry-face exposures show unaltered sulphides.

Interpretation

Consolidation and subsequent volume contraction of the Land's End Granite (part of the Cornubian Batholith) caused opening of incipient planes of weakness in the killas host-rocks and greenstone units as well as joints in the granite. Circulation of various types of hydrothermal fluids led to the deposition of the identified mineralization assemblage.

The major cross-course structure in Penlee Quarry has the same overall trend as a similar structure at the **Nanjizal Cove** GCR site, and is typical of those seen in the Land's End area, and other areas of Cornwall.

Goode and Taylor (1980) described intrusive and pneumatolytic breccias in South-west England, and mention has been made of Wheal Remfrey by Allman-Ward *et al.* (1982). Halls (1987) described a mechanisitic approach to lode infill. The nature of the metasedimentary rocks (killas) has been described in Goode and Taylor (1988), while Floyd (1983) described the composition and petrogenesis of pre-orogenic basaltic rocks in the region.

Of the mineral assemblage listed, it is molybdenite that may be the most significant, being a relatively rare mineral in South-west England. Hosking (1964) recorded molybdenite occurrences in early greisen-bordered, sheeted-vein complexes, and it has been further recorded associated with granite and granite pegmatites at several localities, including the **Hingston Down Quarry and Hingston Down Consols** GCR site

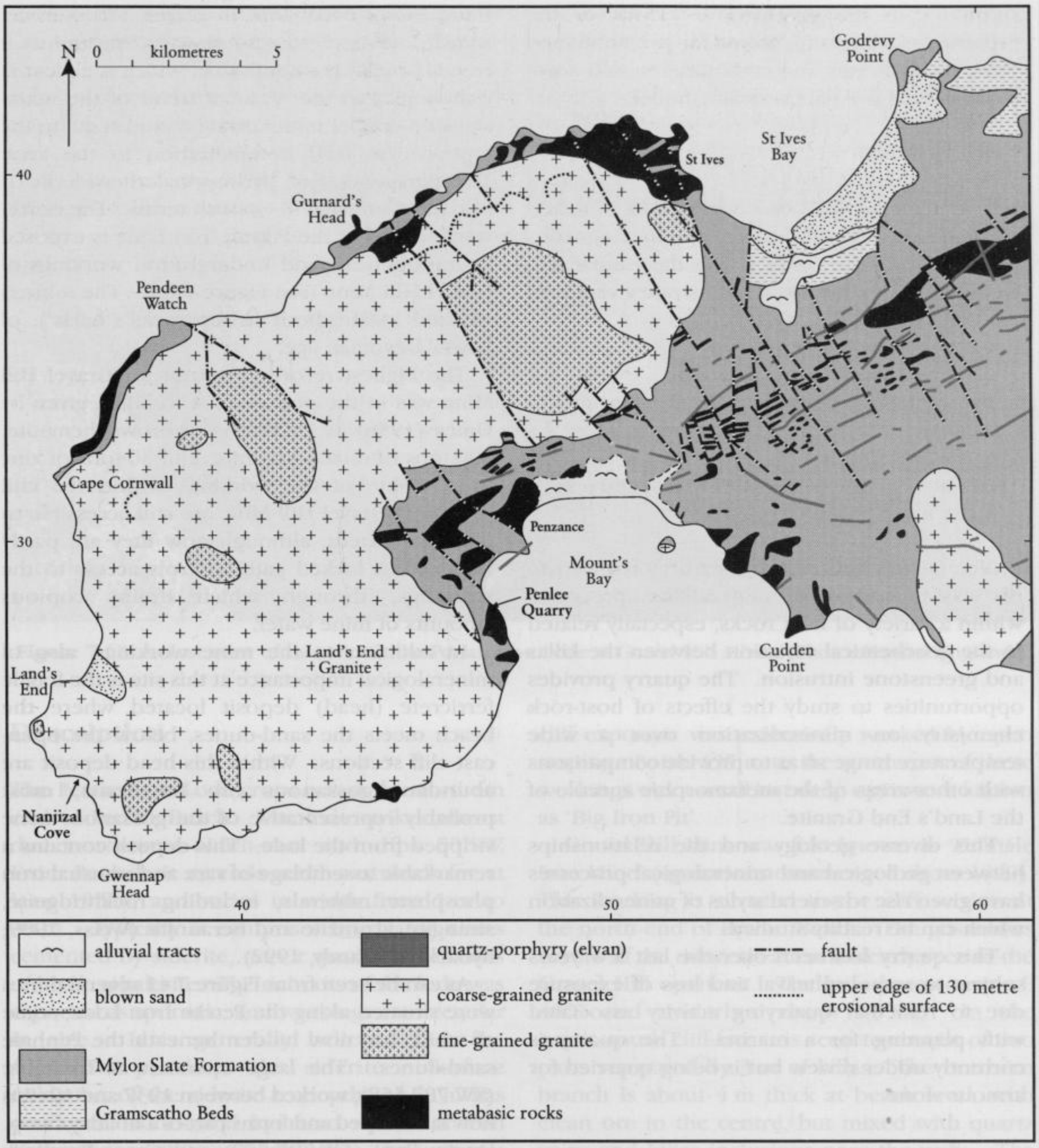

Figure 7.61 The geology of the Penzance area, showing the extent of the Land's End Granite, and the locations of the Penlee Quarry and Nanjizal Cove GCR sites. After Goode and Taylor (1988).

Bromley and Holl (1986) reported interstitial löllingite-arsenopyrite-molybdenite as being present in aplites and comb-layered pegmatites in the Li-mica granites of Tregonning and St Austell.

Further studies need to be made to interpret the paragenesis present in Penlee Quarry. It may be that in the Penlee Quarry there is a combination of a pegmatite paragenesis with that of a normal pyrometasomatic sulphide assemblage, produced by the metamorphism of sulphides in killas and greenstones. Alternatively, metasomatic replacement of the host lithologies by copper mineralization might explain the associated coarse molybdenite aggregates and the patchy distribution of high-temperature sulphides in the greenstone. However the presence of marcasite, abundant pyrrhotite and some iron silicates and carbonates would seem to favour the pyrometasomatic model.

Conclusions

Penlee Quarry has been worked in a mixed sequence of metasedimentary and meta-igneous rocks close to the contact with the Land's End Granite. The exposures demonstrate a variety of mineralization types, namely;

1. early pegmatitic mineralization;
2. pyrometasomatic mineralization in greenstones;
3. a tin-copper lode;
4. essentially east–west quartz lodes; and
4. a late mineralized cross-course.

Penlee Quarry still exposes features relevant to the understanding of mineralizing processes within a variety of host rocks, especially related to the geochemical variation between the killas and greenstone intrusion. The quarry provides opportunities to study the effects of host-rock chemistry on mineralization over a wide temperature range so as to provide comparisons with other areas of the metamorphic aureole of the Land's End Granite.

This diverse geology and the relationships between geological and mineralogical processes have given rise to several styles of mineralization which can be readily studied.

This quarry has been over the last few years subject to some upheaval and loss of exposure due to remedial quarrying activity associated with planning for a marina. The quarry is currently under review but is being quarried for armour stone.

GRAVEL HILL MINE, CORNWALL (SW 764 575)

Introduction

The Gravel Hill Mine GCR site is situated at the north-east corner of Perran Beach (Sands), approximately 3.5 km north of Perranporth. The mine worked the Perran Iron Lode for iron ore.

The Perran Iron Lode is one of the largest lodes in South-west England, having been worked over a distance of 6 km, and with a thickness of over 30 m in places. It is a very unusual structure for South-west England as it trends north-west–south-east, which is almost at right-angles to the regional trend of the main-stage tin-copper mineralization, and at 40° to the cross-course lead mineralization in the area. The paragenesis of pyrite-sphalerite-siderite is also most unusual in Cornish terms. The north-western end of the Perran Iron Lode is exposed in the opencast and underground workings of Gravel Hill Mine (see Figure 7.62). The mine is situated in Meadfoot Group rocks ('killas'), of Lower Devonian age.

The highest recorded output for Gravel Hill Mine was in the period 1874 to 1882, given by Dines (1956) as 7400 tons of brown hematite, 300 tons of mixed limonite, and 30 tons of zinc ore. Some of the workings within the cliff section at Gravel Hill Mine are still accessible to a limited extent, although now they are partly flooded. A locked gate controls access to the workings, through which drains copious amounts of mine water.

In addition to the mine workings, also of mineralogical importance at this site is the fragile ferricrete (head) deposit located where the beach meets the sand-dunes, below the opencast cliff sections. Within this head deposit are abundant gossanous ore fragments, most probably representative of the gossanous zone stripped from the lode. This deposit contains a remarkable assemblage of rare and unusual iron phosphate minerals, including rockbridgeite, strengite, strunzite and beraunite (Weiss, 1989; Ryback and Tandy, 1992).

As can be seen from Figure 7.41 several mines were situated along the Perran Iron Lode, some of which are now hidden beneath the Penhale sand-dunes. The large opencast at Treamble (SW 787 558), worked between 1937 and 1940 is now landscaped and forms part of a holiday camp. Duchy Peru (SW 797 557) and Great Retallack (SW 794 557) were famous for silver minerals, most of which came from north–south cross-course mineralization associated with galena.

There are very few direct references to the mineralization of Gravel Hill Mine, although Dines (1956), and Weiss (1989) did discuss aspects of the mineralogy. Descriptions of the mines were presented by Collins (1912), and Dines (1956). The fault along which the lode is associated was identified as being of regional significance in a structural and mineralogical interpretation by Henley (1971).

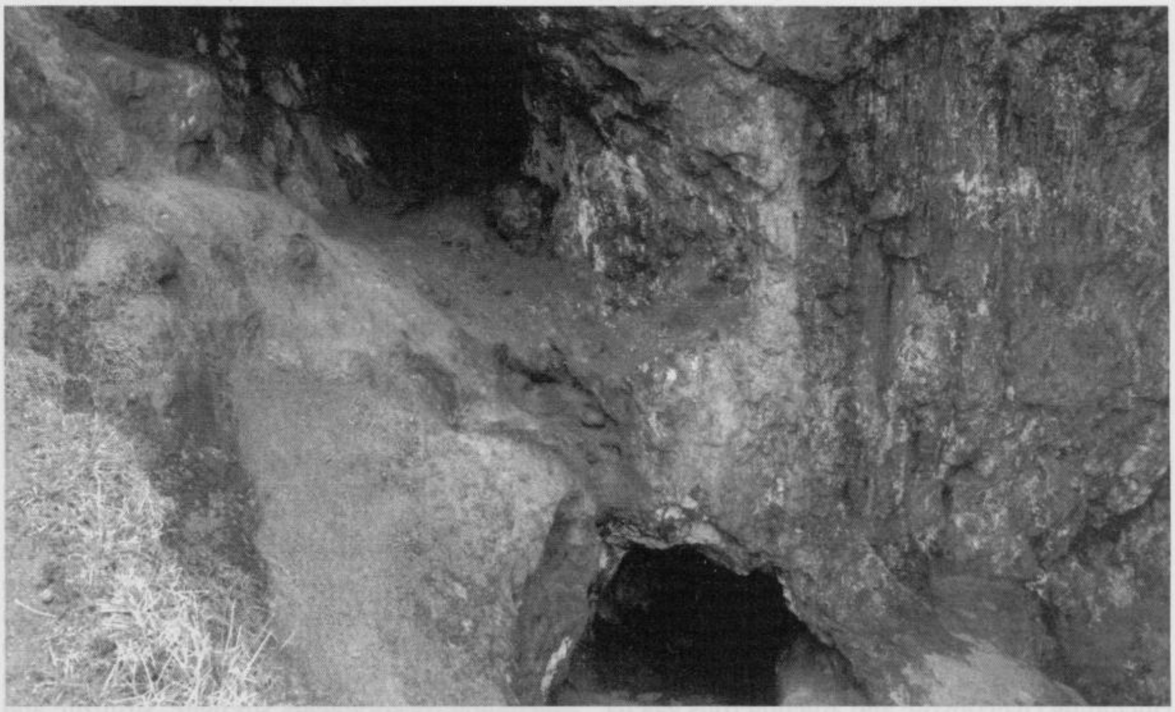

Figure 7.62 A close view of the adits in the Perran Iron Lode at Gravel Hill Mine. (Photo: Natural England.)

Description

The Perran Iron Lode crops out at the northern end of Perran Beach. The lode strikes almost due north-west–south-east and dips 50°SW. From Penhale it extends south-eastwards for at least 10 km, and varies in width from 1 m to 30 m. Typically it comprises brecciated slates cemented by siderite, minor quartz and masses of black sphalerite. The richness of the lode was reported as sporadic, and workings are irregular in size. It is generally believed that the sphalerite pre-dates the siderite. Surface oxidation of the siderite to depths of 60 m has produced oxides and hydrated oxides of iron (hematite, goethite and limonite). The lode was extensively worked for iron ore during the 19th century. The lode is cut in places by later north–south cross-course veins containing pyrite and some argentiferous galena. It could be that the Perran Iron Lode represents a mineralization episode pre-dating granite intrusion (Henley, 1971).

At Gravel Hill Mine the lode is proven to 60 fathoms in depth, and is split vertically into a northern branch (4 m wide) and a southern branch (12 m wide), the two being separated by an area of killas approximately 13 m wide. The cliff exposure was extensively worked by open stoping. Some 155 m to the south-east of these workings was a small but deep openwork known as 'Big Iron Pit'.

Gravel Hill Mine was first known as 'Penhale Iron Mine' (operations commenced about 1840). This working is situated in the cliff section at the north end of Perran Beach. The gossanous nature of the mineralization is clearly seen in the Gravel Hill opencast. The lode here courses E 40°S and underlies about 40°SW. In the north–south cliff-face it is seen to consist of two parts separated by 3 m of killas. The northern branch is about 4 m thick at beach level, with clean ore in the centre, but mixed with quartz veins and killas inclusions near the walls. The southern branch, up to 12 m wide, is mostly formed of limonite with siderite kernels traversed by quartz veins. A quartz-feldspar porphyry ('elvan') dyke occurs a few metres from the footwall of the lode in the cliffs, and trends north of east. The lode has been worked in the cliffs, the stopes on both branches standing as caverns, supported by ore pillars. The base of the oxidized zone is about adit-level. It is stated that at 20 fathoms below adit-level the lode is narrow and consists of fluccan (fault) clay with fragments of blende, galena and pyrite.

The adit level is driven on the northern branch of the lode, and continues 120 fathoms south-east to Borlase's Shaft. Shepherd's Shaft is situated 90 m NNW of Borlase's Shaft. Underground workings are quite extensive, with some especially large open stopes where a north–south lead lode is crossed, (see **Perran Beach to Holywell Bay** GCR site report, this chapter). Today, because the killas between the two lode sections is so altered and impregnated by iron oxides, it is difficult to recognize the difference between lode and killas.

Interpretation

In the Gravel Hill Mine bands of siderite are flanked by brecciated killas, cemented by quartz, other iron oxides and some sphalerite. Where oxidation of the siderite has taken place, black, manganese-bearing minerals coat the surface of the limonite. Elsewhere on the Perran Iron Lode sulphides become more important, including chalcopyrite and argentiferous galena. Henley (1971) believed the Perran Iron Lode to occupy a major structural lineament, on either side of which contrasting fold styles could be recognized. He also suggested that movement along the fault had changed direction over time.

The ore paragenesis is still not fully understood as it is difficult to account for the abundance of siderite. Interpretations, based on the principle of mineral zonation, suggest that at depth the iron should give way to lead and zinc and eventually copper. However, there does not seem to be any evidence for this zonal pattern.

Dines (1956) proposed a temporal scheme for the Perran Iron Lode, which is essentially a low-temperature paragenesis, namely:

1. early brecciation, followed by deposition of quartz and sphalerite in some parts of the lode;
2. formation of north–south lodes and deposition of galena with associated silver minerals;
3. re-opening of the Perran Iron Lode and siderite deposition; and finally
4. further brecciation of siderite ore in some areas, and infillings of clay and sulphides in others.

Henley (1971) believed that the siderite deposition took place in a number of phases, separated by pulses of brecciation. Some of the exposed features described by Henley (1971), and which provided important information for ideas on the origin of the deposit, are now overgrown or covered by sand-dunes.

It could be that in fact calcareous solutions, rather than iron-rich solutions were introduced at a late-stage into areas of the fissure system allowing for the formation of siderite. Siderite formation could therefore have been due to a number of factors including the gossanous oxidation of original sulphides, such as pyrite and some sphalerite, alteration of replacement siderite bodies, or oxidation of an original hematite body.

The origin of the texturally variable ferricrete deposit, which occurs where the beach meets the dunes, is uncertain, but generally it is thought to be part of the gossan zone naturally stripped from the lode (although alternatively it could have been the remains of the gossan stripped before working began). It contains manganese and iron minerals, as well as a remarkable suite of rare phosphate minerals, including rockbridgeite, strengite, strunzite and beraunite. If of natural occurrence, a Pleistocene age has been suggested for its formation.

Conclusions

Gravel Hill Mine is the only working and exposure of the Perran Iron Lode now available for study. The Perran Iron Lode is one of the largest and most extensive lodes in South-west England, having been worked over a distance of 6 km and reaching a width of 30 m in places. It is further remarkable in having a north-west–south-east trend, and is generally believed to be a pre-granite vein deposit.

The beachside ferricrete deposit is of considerable mineralogical interest, containing abundant cemented gossanous ore. This fragile rock formation carries a suite of rare iron phosphate minerals, a number being only known from this locality in the British Isles.

DEAN QUARRY, LIZARD, CORNWALL (SW 804 204)

Introduction

Sections in Dean Quarry, near St Keverne, on the Lizard Peninsula, expose parts of the layered gabbro sequence of the eastern (upper) unit of the Lizard Complex (see Figure 7.63).

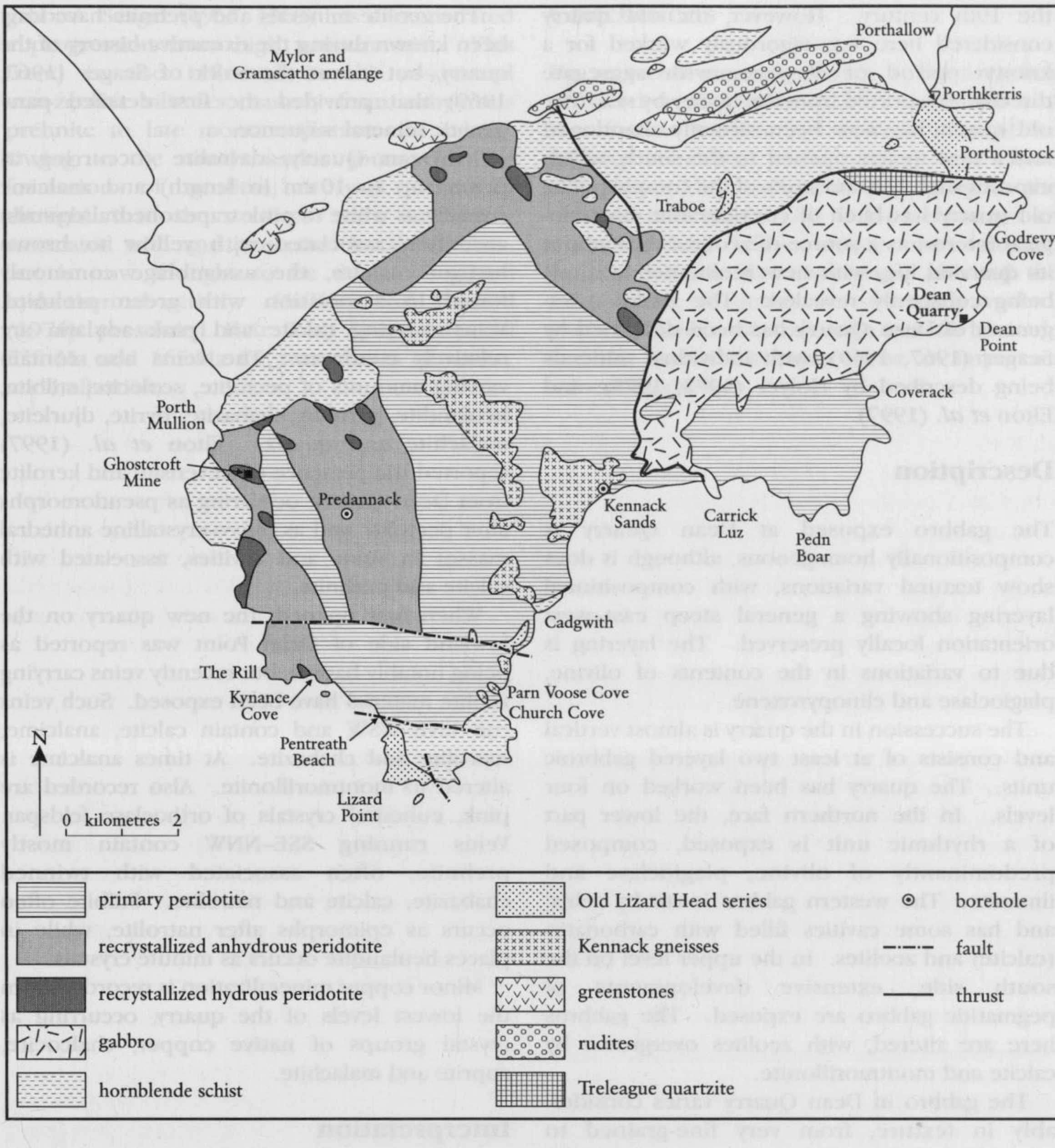

Figure 7.63 Geological map of the Lizard area, showing the location of the Dean Quarry GCR site. Based on Flett (1946), Green (1964), and Styles and Kirby (1980).

In many recent studies it has been proposed that the Lizard Complex represents a deformed and dismembered ophiolite, the gabbros being part of the standard model for oceanic crust, and the idealized ophiolite being formed at mid-oceanic ridges (Styles and Kirby, 1980). Powell *et al*. (1996) gave a re-interpretation of the internal structure of the Lizard Complex.

However, more recently, it has been suggested that the complex peridotites originally formed in a non-volcanic rifted-margin setting, rather than mid-oceanic ridge, the rocks being exhumed from upper mantle to lower crustal depths during a period of early Devonian rifting and break-up. During the late Devonian the Lizard Complex was thrust NNW along major low-angle detachment and became incorporated in a series of Variscan nappes (Cook *et al*., 2000, 2002).

Dean Quarry lies on the coast at Dean Point, where quarrying commenced towards the end of the 19th century. However, the old quarry considered here was vigorously worked for a known period of 30 years, with aggregate directly transported from the quarry by sea. The old quarry has now been virtually abandoned and a new quarry opened to the south, which exposes slightly lower units of the complex. The old quarry has been of considerable mineralogical interest as a source of zeolites throughout its quarried life, with new zeolite-rich sections being constantly revealed. The zeolite paragenesis of Dean Quarry has been described by Seager (1967, 1969), with individual minerals being described by Holyer (1972, 1975), and Elton *et al.* (1997).

Description

The gabbro exposed at Dean Quarry is compositionally homogenous, although it does show textural variations, with compositional layering showing a general steep east–west orientation locally preserved. The layering is due to variations in the contents of olivine, plagioclase and clinopyroxene.

The succession in the quarry is almost vertical and consists of at least two layered gabbroic units. The quarry has been worked on four levels. In the northern face, the lower part of a rhythmic unit is exposed, composed predominantly of olivine, plagioclase and ilmenite. The western gabbro is cut by veins, and has some cavities filled with carbonates (calcite) and zeolites. In the upper level on the south side, extensive developments of pegmatitic gabbro are exposed. The gabbros here are altered, with zeolites overgrown by calcite and montmorillonite.

The gabbro in Dean Quarry varies considerably in texture, from very fine-grained to pegmatitic, and although mostly fresh some areas are altered, even showing a slight schistose fabric. The gabbro is cut in several places by meladiorite dykes.

Zeolite minerals are usually found associated with basaltic rocks, but at Dean Quarry they occur in gabbro in veins trending ENE–WSW and SSE–NNW through the quarry. The development of the zeolite veins is at all times intermittent. Some of the veins are very rich in certain sections, although have been barren for considerable periods of quarrying activity.

The zeolite minerals and prehnite have long been known during the extractive history of the quarry, but it was the work of Seager (1967, 1969) that provided the first detailed paragenetic mineral sequence.

In Dean Quarry, natrolite (occurring as prisms up to 10 cm in length) and analcime (usually as white to pink trapezohedral crystals) are often associated with yellow to brown lustrous calcite, the assemblage commonly found in association with green prehnite. Veins carrying calcite and pink adularia are relatively common. The veins also contain varying amounts of pectolite, scolecite, stilbite, heulandite, gyrolite, chabazite, pyrite, djurleite, malachite and quartz. Elton *et al.* (1997) reported the presence of stevensite and kerolite from Dean Quarry, occurring as pseudomorphs after pectolite and as micro-crystalline anhedral masses in veins and cavities, associated with calcite and prehnite.

When first opened, the new quarry on the lowland side of Dean Point was reported as being notably barren, but recently veins carrying zeolite material have been exposed. Such veins run ENE–WSW, and contain calcite, analcime, natrolite and chabazite. At times analcime is altered to montmorillonite. Also recorded are pink, euhedral crystals of orthoclase feldspar. Veins running SSE–NNW contain mostly prehnite, often associated with twinned chabazite, calcite and natrolite. Stilbite often occurs as epimorphs after natrolite, while in places heulandite occurs as minute crystals.

Minor copper mineralization is recorded from the lowest levels of the quarry, occurring as crystal groups of native copper, chalcocite, cuprite and malachite.

Interpretation

Zeolite minerals are widespread in the Lizard Peninsula, occurring in the gabbros of both Dean and Porthoustock quarries, as well as elsewhere within some of the serpentinites. Dean Quarry is of considerable interest for the nature and significance of the gabbro and especially for the contained zeolite mineralization. The petrology of the gabbro has been described in the papers listed above.

The zeolite minerals occur in a series of pneumatolytic veins running through the gabbro. Seager (1967, 1969) has demonstrated a progression from high temperatures. This trend is also reflected in the associated non-zeolitic silicates, namely from anhydrous prehnite to late montmorillonite and calcite. Owing to the usual basaltic source for the formation of zeolites, it was originally thought that the zeolites were intimately associated with and generated by the gabbro, but is now thought to be due to regional hydrothermal activity. Halliday and Mitchell (1976) presented K-Ar and Ar-Ar dates of 220 Ma and 165 Ma for two phases of zeolite mineralization.

Conclusions

Up to recent times quarrying at Dean Quarry provided fresh exposures of the gabbros and therefore an increase in our knowledge of the gabbros in relation to the origin of the Lizard Complex. This continuous quarrying in the old and new quarry also further enhanced an understanding ofthe major mineralogical features of the zeolitic assemblage. Although the faces of the old quarry are now rarely worked, studies of zeolite mineralization can still be made and the quarry continues to be an important mineralogical site.