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Earlier published studies and unpublished GCR site reviews (L. Haynes, pers.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 northeast) 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 Southwest 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 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 sometimes 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 crosscut 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 wolfratnite 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 infiu 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.

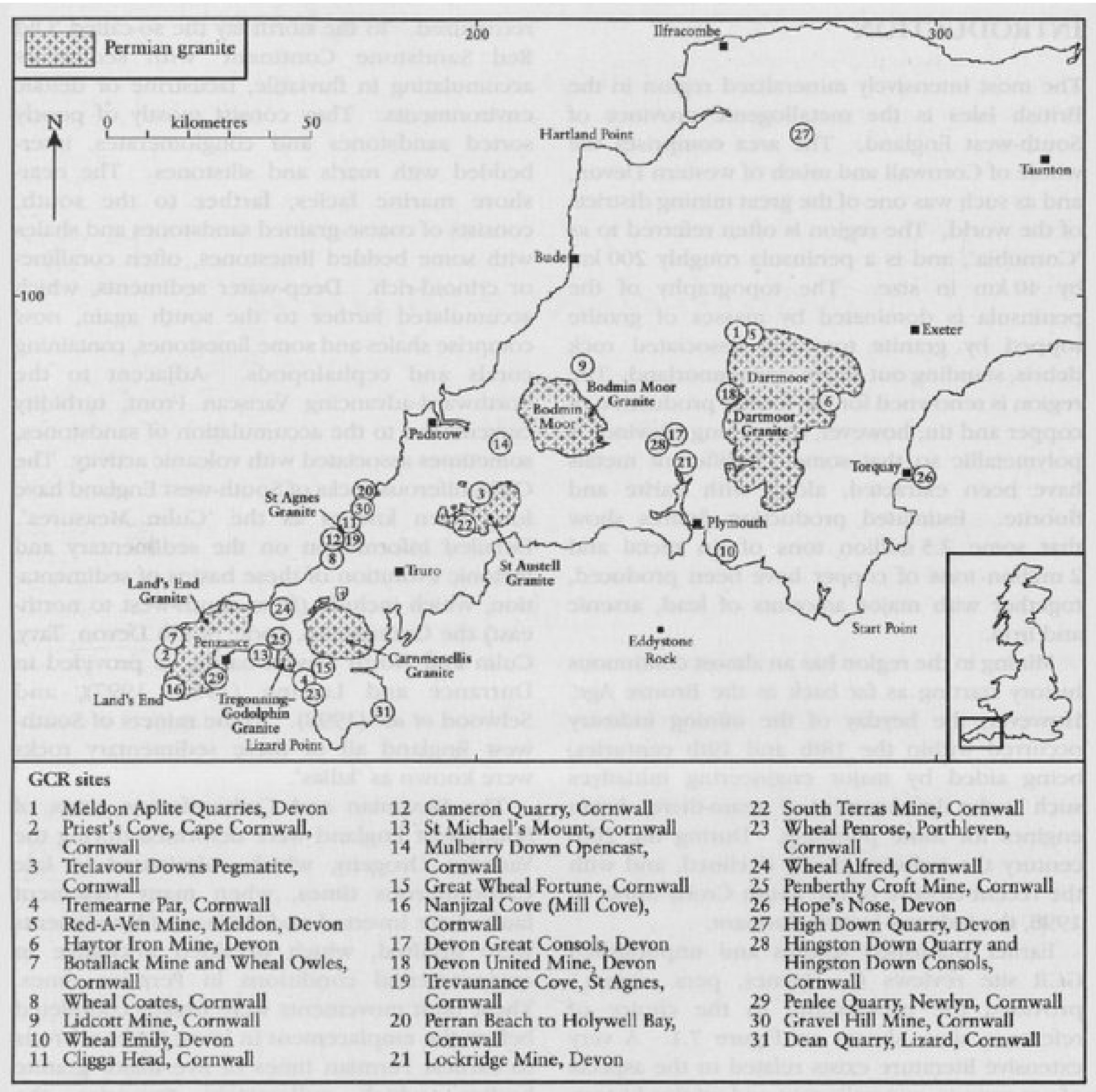
Secondary alteration, particularly of the base-metal sulphides above the water-table (see (Figure 7.5)), was extensive throughout the ore-field region. With only a few exceptions, however, these zones of leaching and enrichment (oxidation and reduction) have been removed by erosion or worked out by mining 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 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 selepide 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.

References

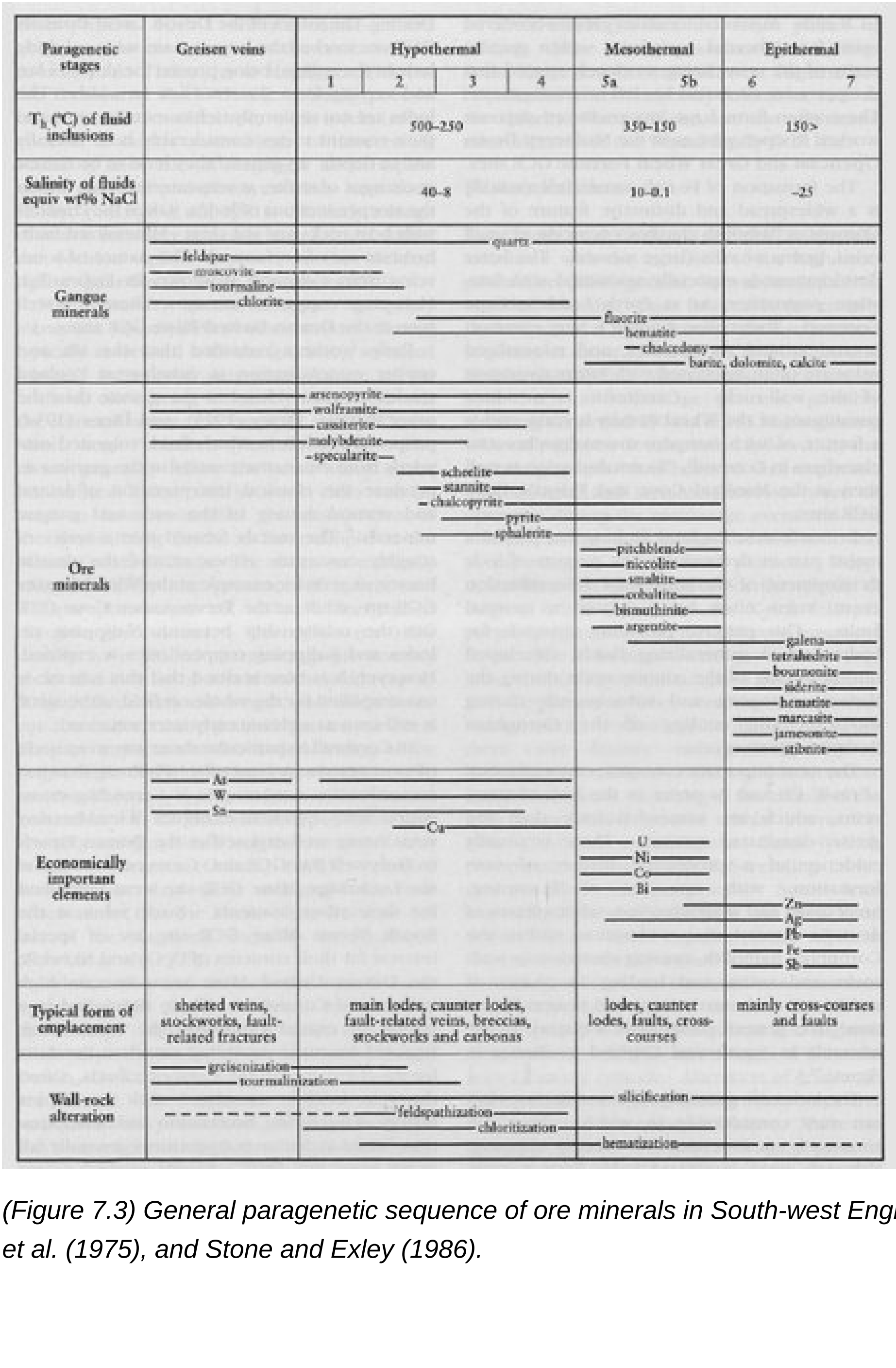


(Figure 7.1) Map showing the locations of the GCR sites in South-west England.

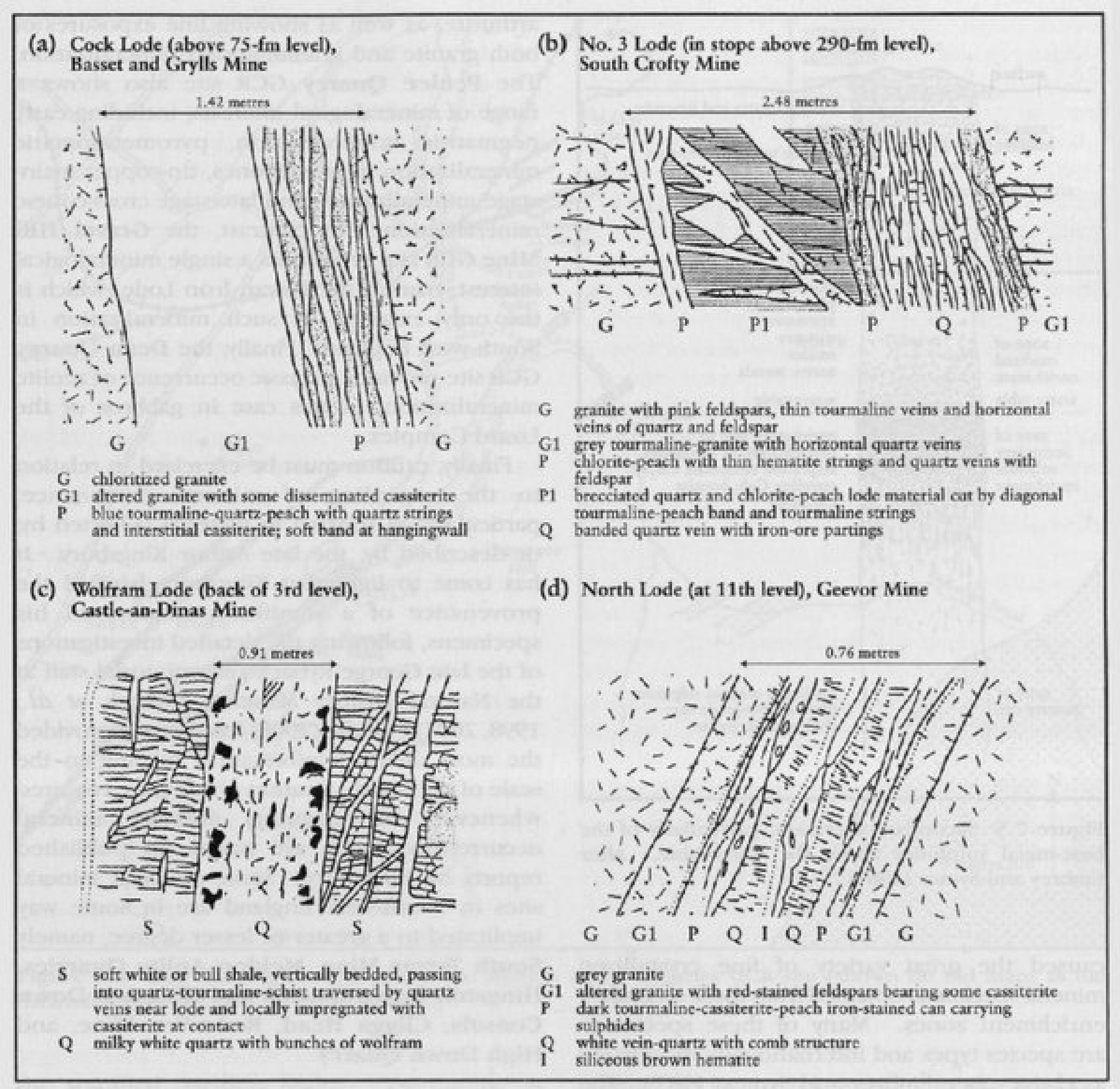
Type	Variety	Pl:Or	Plagioclase type (vol%)	Micas	Accessories[a]	Occurrence
A	basic microgranite	Pl > Or	Olig – And (amount varies)	Bi >> Musc	Hb	as inclusions in B
B	coarse-grained megacrystic biotite granite	Or > Pl	cores An 25–30 (22%) rims An 8–15	Bi > Musc	T	dominant variety
C	fine-grained biotite 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.

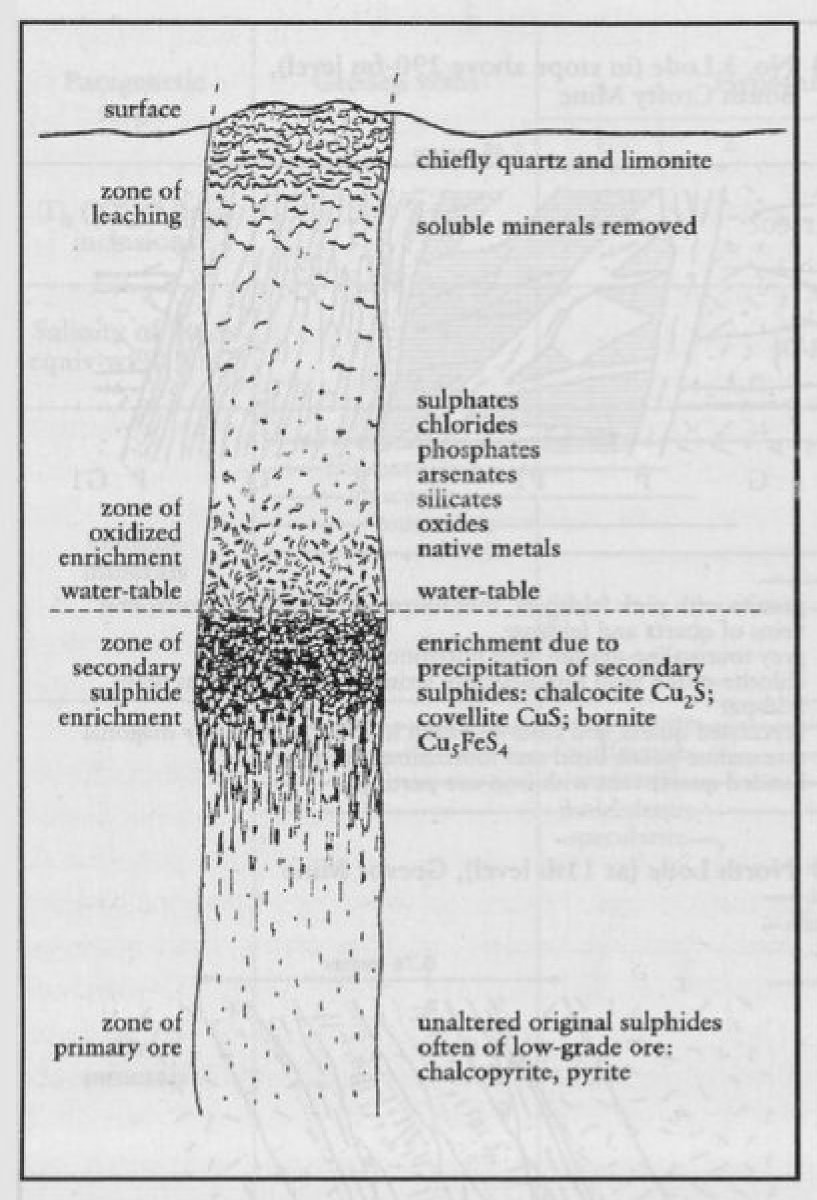
(Figure 7.2) Main granite types of South-west England. Based on Exley (1983), Stone et al. (1988), and Alderton (1993).



(Figure 7.3) General paragenetic sequence of ore minerals in South-west England. Based on Ilosking (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).



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