Igneous Rocks of South-West England

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Chapter 4

Pre-orogenic volcanics (Group B sites)

INTRODUCTION

The sites covered in this chapter are listed below, and arranged in broad stratigraphic–tectonic groups from west Cornwall to east Devon. The majority are examples of extrusive and intrusive basaltic rocks covering the late Devonian–early Carboniferous period of maximum volcanic activity in south-west England. The actual intrusion age of the large sills is not known, although many in western Cornwall appear to be pre-main-phase deformation, that is, pre-late Devonian (Taylor and Wilson, 1975). Other bodies showing evidence of high-level intrusion, soft-sediment deformation and spatially associated lavas, have an age corresponding with the enclosing sediments. In central south-west England, where faunal evidence of depositional age is good, lavas interbedded with dated sediments are typically Frasnian (for example, Pentire Point pillow lavas), Famennian (for example, Chipley pillow lavas) or Dinantian (for example, Tintagel Volcanic Formation). Lavas within the poorly fossiliferous Mylor Slate and Gramscatho Formations of western and southern Cornwall are probably late Devonian (Turner *et al.*, 1979; Wilkinson and Knight, 1989).

Both the magmatic and superimposed contact-metamorphic features of late Devonian extrusives and closely associated intrusives within the Land's End Granite aureole are described, as these sites often exhibit classic contact effects of high-level granites.

The locations of all sites are shown in Figure 4.1.

LIST OF SITES

Intrusives in parautochthonous late Devonian, west Cornwall:

B1 Porthleven (SW 628254–SW 634250)
B2 Cudden Point–Prussia Cove (SW 548275–SW 555278)

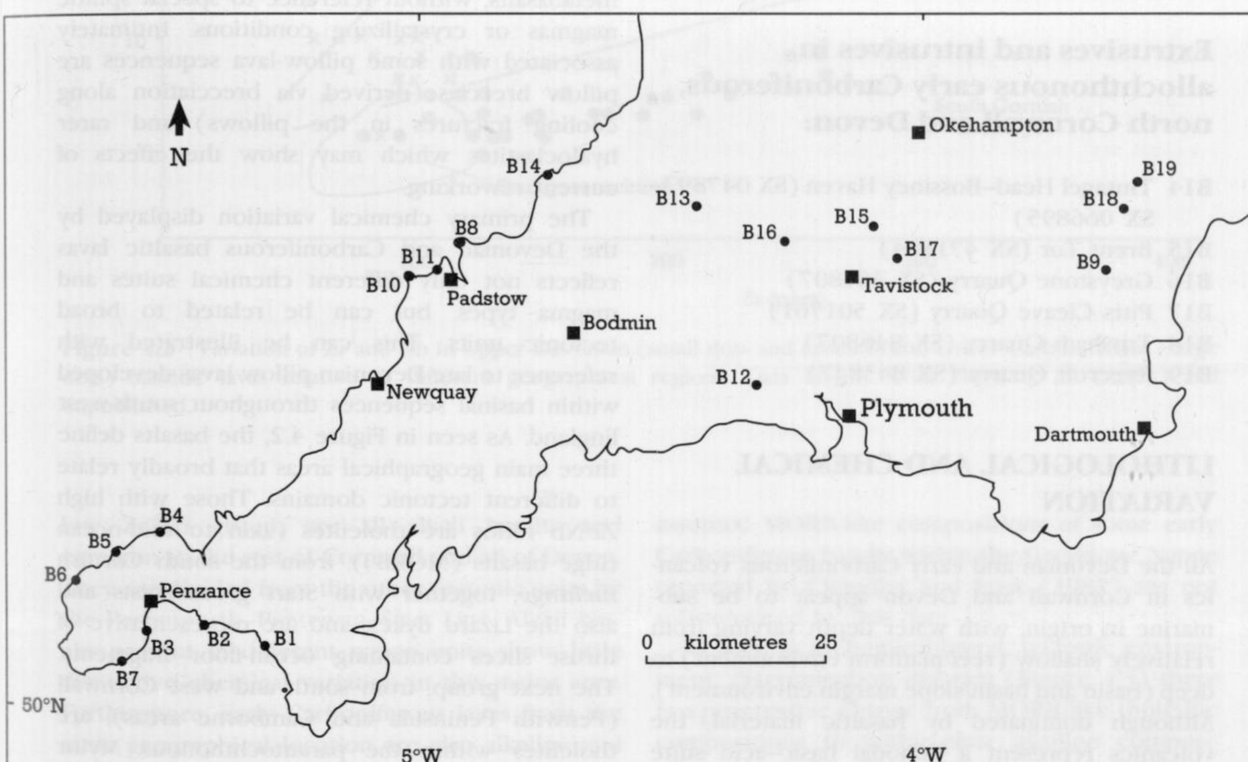


Figure 4.1 Outline map of south-west England showing the location of Group B sites.

Contact-metamorphosed extrusives and intrusives in parautochthonous late Devonian, west Cornwall:

B3 Penlee Point (SW 474269)
B4 Carrick Du–Clodgy Point (SW 507414–SW 512410)
B5 Gurnard's Head (SW 432387)
B6 Botallack Head–Porth Ledden (SW 362339–SW 355322)
B7 Tater-du (SW 440230)

Extrusives and intrusives in allochthonous late Devonian, north Cornwall and Devon:

B8 Pentire Point–Rumps Point (SW 923805–SW 935812)
B9 Chipley Quarries (SX 807712)
B10 Dinas Head–Trevose Head (SW 847761–SW 850766)
B11 Trevone Bay (SW 890762)
B12 Clicker Tor Quarry (SX 285614)
B13 Polyphant (SX 262822)

Extrusives and intrusives in allochthonous early Carboniferous, north Cornwall and Devon:

B14 Tintagel Head–Bossiney Haven (SX 047892–SX 066895)
B15 Brent Tor (SX 471804)
B16 Greystone Quarry (SX 364807)
B17 Pitts Cleave Quarry (SX 501761)
B18 Trusham Quarry (SX 846807)
B19 Ryecroft Quarry (SX 843847)

LITHOLOGICAL AND CHEMICAL VARIATION

All the Devonian and early Carboniferous volcanics in Cornwall and Devon appear to be submarine in origin, with water depth varying from relatively shallow (reef/platform environment) to deep (basin and basin/slope margin environment). Although dominated by basaltic material, the volcanics represent a bimodal basic–acid suite comprising lavas, high-level intrusives and abundant volcaniclastics, often in close stratigraphical association.

The following summarizes some of the different lithological and eruptive associations that are readily identified, together with an outline of their primary chemical variation (see also Floyd, 1983).

Basaltic pillow lavas and pillow breccias

The original petrography of these submarine lavas is commonly obscured by the secondary products of low-grade regional metamorphism (or contact metamorphism when located within the granite aureoles). Primary mafic phases are generally lacking or rare, and low-temperature albite invariably replaces original plagioclase. However, relict textures and secondary assemblages indicate that the pillow lavas were predominantly plagioclase-phyric, variably vesicular, quenched basalts subsequently metamorphosed in the prehnite–pumpellyite or lower greenschist facies. They are typical 'spilites' in terms of their mineral assemblages and were referred to as such in the early literature (for example, Dewey, 1914), whereas today we recognize them as metabasalts, without reference to special spilitic magmas or crystallizing conditions. Intimately associated with some pillow-lava sequences are pillow breccias (derived via brecciation along cooling fractures in the pillows) and rarer hyaloclastites which may show the effects of current reworking.

The primary chemical variation displayed by the Devonian and Carboniferous basaltic lavas reflects not only different chemical suites and magma types, but can be related to broad tectonic units. This can be illustrated with reference to late Devonian pillow lavas developed within basinal sequences throughout south-west England. As seen in Figure 4.2, the basalts define three main geographical areas that broadly relate to different tectonic domains. Those with high Zr/Nb ratios are tholeiites (akin to mid-ocean ridge basalts (MORB)), from the south Cornish *mélange*, together with Start greenschists and also the Lizard dykes, and are representative of thrust slices containing ocean-floor fragments. The next group, from south and west Cornwall (Penwith Peninsula and Camborne areas), are tholeiites within the parautochthonous Mylor Slate Formation; they have chemical features intermediate between enriched-type MORB and basalts found in the interior of plates. The third, a

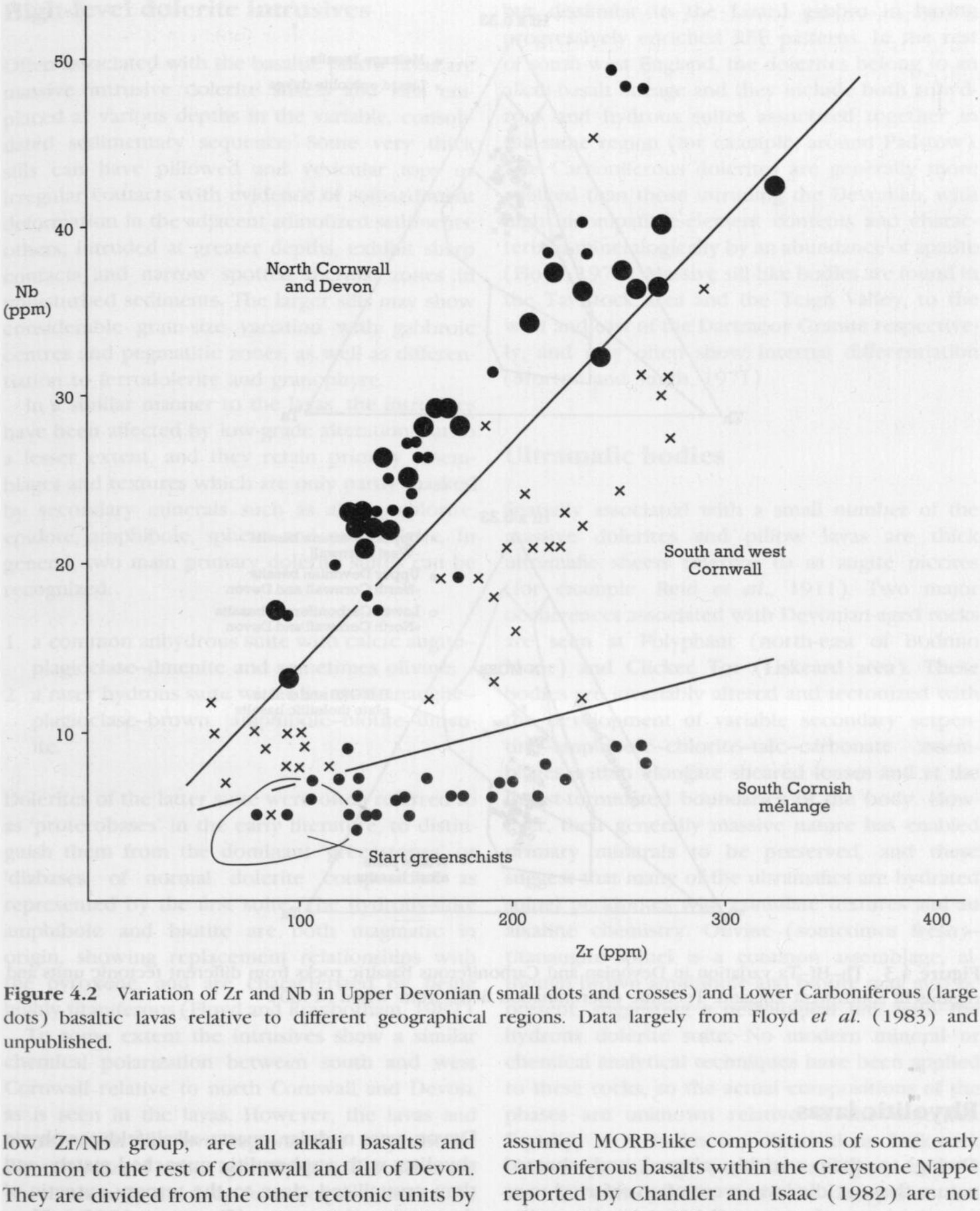


Figure 4.2 Variation of Zr and Nb in Upper Devonian (small dots and crosses) and Lower Carboniferous (large dots) basaltic lavas relative to different geographical regions. Data largely from Floyd *et al.* (1983) and unpublished.

low Zr/Nb group, are all alkali basalts and common to the rest of Cornwall and all of Devon. They are divided from the other tectonic units by the Perranporth–Pentewan–Start Line. Alkali basalts present in different nappe units show little distinctive chemical variation in this major area. Furthermore, early Carboniferous lavas from the same geographical location are also alkaline and they exhibit similar Zr/Nb ratios (Rice-Birchall and Floyd, 1988) and normalized incompatible-element patterns to the late Devonian lavas. The assumed MORB-like compositions of some early Carboniferous basalts within the Greystone Nappe reported by Chandler and Isaac (1982) are not substantiated by this data.

As seen in a chemical-based, tectonic environment, discrimination diagram (Figure 4.3) there is a progressive change from MORB-like tholeiitic compositions to within-plate alkaline compositions across south-west England that relate to major units which are now geographically juxtaposed by thrust–nappe tectonics.

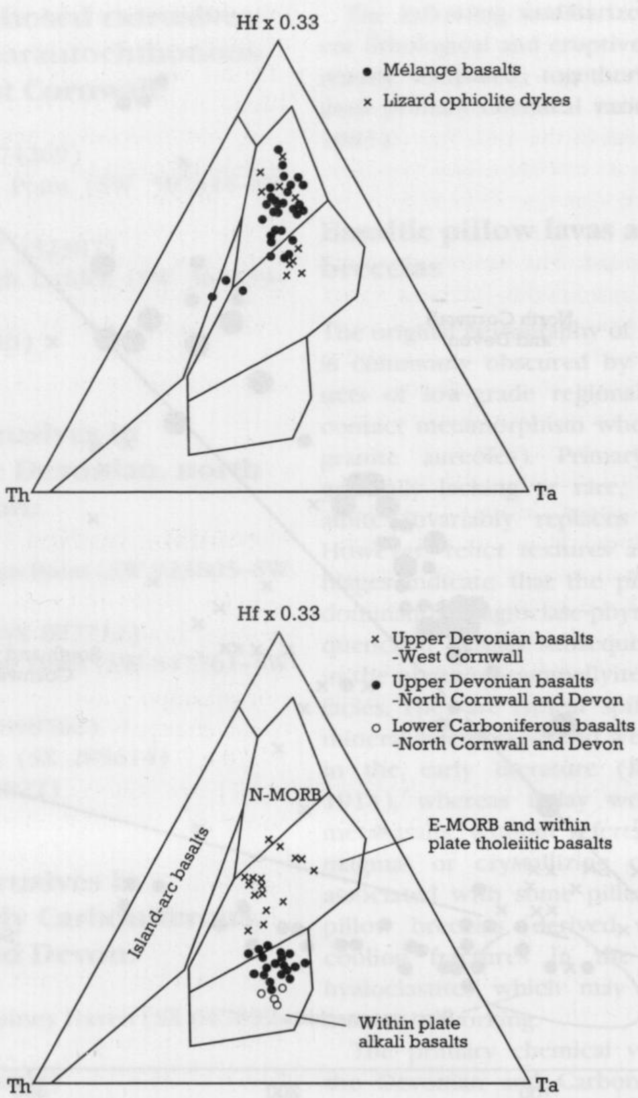


Figure 4.3 Th–Hf–Ta variation in Devonian and Carboniferous basaltic rocks from different tectonic units and regions in south-west England. Tectonic discrimination fields from Wood (1980).

Rhyolitic lavas

Owing to their variably altered and sheared nature these acidic lavas were often referred to as (quartz)-keratophyres or 'felsites' in the earlier literature (for example, Ussher, 1904). However, they retain relict textures and an observed (or inferred) primary mineralogy that clearly suggest that they were quenched rhyolitic or rhyodacitic flows.

Early acidic flows (early Devonian) in south Devon were nodular, quartz–alkali-feldspar-phyric rhyolites with a spherulitic quenched matrix, and they crystallized close to the ternary eutectic of the wet granite system (Durrance, 1985a). They are highly siliceous, with high K, Rb and Th, but chemically distinct from the Cornubian granites, granite porphyries and Permian rhyolites. Determination of their possible tectonic setting using chemical data suggests an active margin environment (Durrance, 1985a).

High-level dolerite intrusives

Often associated with the basaltic pillow lavas are massive intrusive dolerite sheets and sills emplaced at various depths in the variable, consolidated sedimentary sequence. Some very thick sills can have pillowed and vesicular tops or irregular contacts with evidence of soft-sediment deformation in the adjacent adinolized sediments; others, intruded at greater depths, exhibit sharp contacts and narrow spotted thermal zones in undisturbed sediments. The larger sills may show considerable grain-size variation with gabbroic centres and pegmatitic zones, as well as differentiation to ferrodolerite and granophyre.

In a similar manner to the lavas, the intrusives have been affected by low-grade alteration but to a lesser extent, and they retain primary assemblages and textures which are only partly masked by secondary minerals such as albite, chlorite, epidote, amphibole, sphene and pumpellyite. In general, two main primary dolerite suites can be recognized:

1. a common anhydrous suite with calcic augite–plagioclase–ilmenite and sometimes olivine;
2. a rarer hydrous suite with olivine–titanaugite–plagioclase–brown amphibole–biotite–ilmenite.

Dolerites of the latter suite were often referred to as 'proterobases' in the early literature, to distinguish them from the dominant 'greenstones' or 'diabases' of normal dolerite composition as represented by the first suite. The hydrous-suite amphibole and biotite are both magmatic in origin, showing replacement relationships with the pyroxene, and are characterized by being highly titaniferous (Floyd and Rowbotham, 1982).

To some extent the intrusives show a similar chemical polarization between south and west Cornwall relative to north Cornwall and Devon, as is seen in the lavas. However, the lavas and intrusives in the two regions also may not be directly related either spatially (the intrusives are not necessarily the deep-seated equivalents of the lavas) or genetically (via a magmatic process such as crystal fractionation) (Floyd, 1983). The dolerites/gabbros of south Cornwall are generally isolated, massive, differentiated tholeiitic bodies with olivine–pyroxene cumulates (Floyd and Al-Samman, 1980). They are relatively primitive chemically, with low Zr/Y and high Zr/Nb ratios, but dissimilar to the Lizard gabbro in having progressively enriched REE patterns. In the rest of south-west England, the dolerites belong to an alkali-basalt lineage and they include both anhydrous and hydrous suites associated together in the same region (for example, around Padstow). The Carboniferous dolerites are generally more evolved than those intruding the Devonian, with high incompatible-element contents and characterized mineralogically by an abundance of apatite (Floyd, 1976). Massive sill-like bodies are found in the Tavistock area and the Teign Valley, to the west and east of the Dartmoor Granite respectively, and may often show internal differentiation (Morton and Smith, 1971).

Ultramafic bodies

Spatially associated with a small number of the massive dolerites and pillow lavas are thick ultramafic sheets referred to as augite picrites (for example, Reid *et al.*, 1911). Two major occurrences associated with Devonian-aged rocks are seen at Polyphant (north-east of Bodmin Moor) and Clicker Tor (Liskeard area). These bodies are invariably altered and tectonized with the development of variable secondary serpentine–amphibole–chlorite–talc–carbonate assemblages within elongate sheared lenses and at the thrust-terminated boundaries of the body. However, their generally massive nature has enabled primary minerals to be preserved, and these suggest that many of the ultramafics are hydrated spinel peridotites with cumulate textures and an alkaline chemistry. Olivine (sometimes fresh)–titanaugite–spinel is a common assemblage, although brown amphibole and biotite may also be present, suggesting a petrological link with the hydrous dolerite suite. No modern mineral or chemical analytical techniques have been applied to these rocks, so the actual compositions of the phases are unknown relative to the dolerites. Equally, little is known about their bulk-rock chemistry, although (as seen in Figure 4.4), Ni and Cr contents for both the Polyphant and Clicker Tor localities fall in the stratiform cumulate field. They are chemically distinct from the spinel peridotite of the Lizard and ophiolitic cumulates in general: the latter point suggesting that the Polyphant body is unlikely to form part of an ophiolite as postulated by Chandler and Isaac (1982).

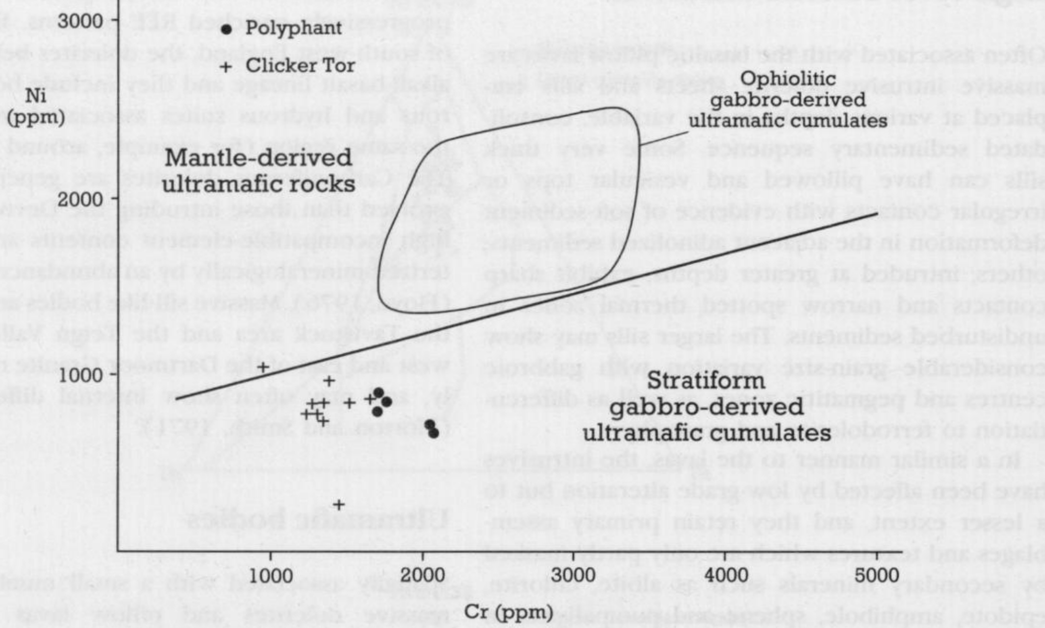


Figure 4.4 Distribution of Ni and Cr in Variscan ultramafic bodies associated with dolerites and pillow lavas relative to ophiolitic and stratiform cumulates (boundaries from Figure 3.3).

Volcaniclastic rocks

Largely due to poor outcrop and the high degree of alteration exhibited, little modern volcanological work has been attempted on the tuffaceous volcaniclastic horizons. In general both acid and basic tuffs ('keratophyric' and 'spilitic', respectively, in previous accounts) are common, with an admixture of lithic clasts, altered glass, broken crystals and pumiceous lava fragments. Coarser-grained volcaniclastics could be represented by part of the early Carboniferous Tintagel Volcanic Formation (Freshney *et al.*, 1972), which contains large tectonized fragments that might once have been a basaltic agglomerate or lava breccia. Many of the commoner laminated tuffs within the mid and late Devonian appear to have settled through the water column, although there is also evidence for current reworking and sorting (Holwill, 1966). It is generally assumed that the volcaniclastics are the explosive products of submarine volcanism which were sometimes redistributed away from the vents by slumping down volcanic slopes. There is no reason to suppose that some are not air-fall tuffs subsequently deposited through water, although most volcaniclastic accumulations are associated with submarine lavas. However, the presence of shallow-water fauna associated with middle Devonian tuffs in south Devon could imply near-surface volcanic edifices. Some tuff horizons have been interpreted as subaqueous pyroclastic flows (Burton, pers. comm., 1986) with basal zones of local, soft-sediment rip-up clasts and flow alignment of large volcanic fragments.

B1 PORTHLEVEN (SW 628254–SW 634250)

Highlights

The time relationships between sedimentation, dolerite sill intrusions, and the earliest Variscan deformation, are well displayed at this type locality of the Mylor Slate Formation.

Introduction

The section of low cliffs and beach outcrops to the south-east of Porthleven Harbour (from Little Trigg Rocks to about Eastern Tye) is often considered the type area for the laminated argillites and sandstones of the Upper Devonian Mylor 'Series' or Mylor Slate Formation (Lever-

Figure 4.5 Apparently discordant relationship between a basic intrusive body (on the right) and adjacent foliated sediments of Lower Devonian age (on the left). Porthleven, Cornwall. (Photo: P.A. Floyd.)

idge and Holder, 1985; Holder and Leveridge, 1986). The intrusive bodies which here affect the Mylor beds are typical of the smaller greenstones in west Cornwall. Little detailed work has been done on them, although they are mentioned in early descriptions of the general area (Phillips, 1876; Flett, 1903, 1946).

Description

Within the sediments at Porthleven are small, relatively thin (typically <1–2 m in thickness), high-level, intrusive sill-like bodies of basic composition. They are typical Cornish 'greenstones' or 'diabases' – regionally altered or metamorphosed doleritic intrusives featuring secondary albite, chlorite, actinolite, iron oxides and minor epidote, quartz, mica and carbonate. No chemical work is available, although they are probably tholeiitic in composition, in common with other bodies intruding Devonian strata in south and west Cornwall.

Intrusive relationships with the adjacent sediments are variable, although generally concordant contacts with the sedimentary lamination indicate that most of the bodies are sill-like in attitude. However, on the small scale, contacts may be slightly transgressive or highly irregular, with lobate junctions and cross-cutting intrusive tongues (Figure 4.5). Some contacts suggest that intrusion occurred at a high level into wet material with the development of attendant, soft-sediment deformation features, although thorough mixing between magma and sediment (peperite) was not achieved. Adjacent sediments may be locally baked and bleached at the contacts, although adinolization is rare; a *c.* 1 m pale-grey bleached zone is seen at the (upper?) contact of the largest body near the end of the beach section.

Relative to the deformation, there is evidence that some intrusives were pre-cleavage, and that they have been conformably folded with the sediments, probably during the early F_1 fold phase of the late Devonian (Taylor and Wilson, 1975). Local shearing and minor faulting affect some masses, together with later extensive net veining by massive quartz.

In thin section, the intrusive greenstones are fine-grained, non-vesicular, subophitic metadolerites, typically replaced by various green, hydrous secondary minerals. The only primary phases remaining are (rare) clinopyroxene and apatite, the former showing partial replacement by a uralitic fringe of actinolite or pseudomorphed by chlorite. The more altered varieties are dominated by albite–chlorite (up to 60–70 vol.%), with variable carbonate, quartz, muscovite, epidote, iron oxides, sphene and rare biotite. Contact zones may show chilling in the thicker sills, but are often foliated and composed of green chlorite.

Interpretation

Accompanying soft-sediment deformation implies that some of these small bodies were intruded at a very high level into a wet sediment pile. It is interesting to speculate that the small greenstones did not actually form pillows because they were intruded into a sequence of rapidly deposited distal turbidite-generated muds and sands, and the magma did not actually reach the sediment–water interface. Penecontemporaneous intrusion and sedimentation is one of the more interesting aspects of the site, together with the sills being involved in the first phase of folding in south Cornwall. They are also typical of the smaller greenstone bodies of this region: illustrating the effects of low-grade regional metamorphism and the development of a variety of secondary assemblages characterized by albite–chlorite. The grade of regional metamorphism is generally assumed to be lower greenschist (chlorite zone), as pumpellyite has not been recorded and the chemical composition of the chlorite is undetermined.

Conclusions

That the dolerite sills are only slightly younger than the rocks in which they are found, is shown by the evidence that these sediments were still soft when intrusion took place. Further, the earliest structural element in the sediments, a cleavage, can also be found in some of the sills, indicating that these at least were emplaced before the onset of the Variscan Orogeny.

B2 CUDDEN POINT–PRUSSIA COVE (SW 548275–SW 555278)

Highlights

The massive, zoned metadolerite/gabbro at this site is the best exposed of the south Cornish sills; its chemical composition is unique within that group. Low-grade regional metamorphism is typical, but an unusual, axinite-bearing, vein assemblage probably reflects the influence of the nearby Godolphin Granite.

Introduction

The site covers the rocky rib of Cudden Point headland and the adjacent coves and gullies from Arch Zawn in the west to Bessy's Cove in the east, as well as small exposures inland. The intrusive greenstone seen at Cudden Point is not only representative, but one of the best exposed of the massive sill-like basic bodies seen along the south Cornish coast. It is situated within the Porthleven Breccia Member of the Upper Devonian Mylor Slate Formation (Holder and Leveridge, 1986). Although once interpreted as one limb of a broad fold on the older Geological Survey maps, this is no longer considered to be the case, as the intrusion is terminated by an approximate east–west tectonized contact with the adjacent sediments behind the headland (Figure 4.6). Previous work has largely involved petrographic and geochemical studies (Floyd and Lees, 1972; Floyd and Fuge, 1973; Floyd, 1976; Floyd and Al-Samman, 1980), which revealed the primitive tholeiitic nature of the sill relative to the alkaline composition of many south-west England greenstones.

Description

This intrusive body is typical of massive greenstones, with the preservation of good relict textures and primary minerals that indicate that it was originally an internally differentiated dolerite. Dark-green olivine–clinopyroxene cumulates are present, together with gabbroic pegmatites within the central portion of the sill, and minor granophyric pods.

The lower tectonized contact is exposed in Arch Zawn and Piskies Cove adjacent to deformed and foliated Mylor phyllites and semi-

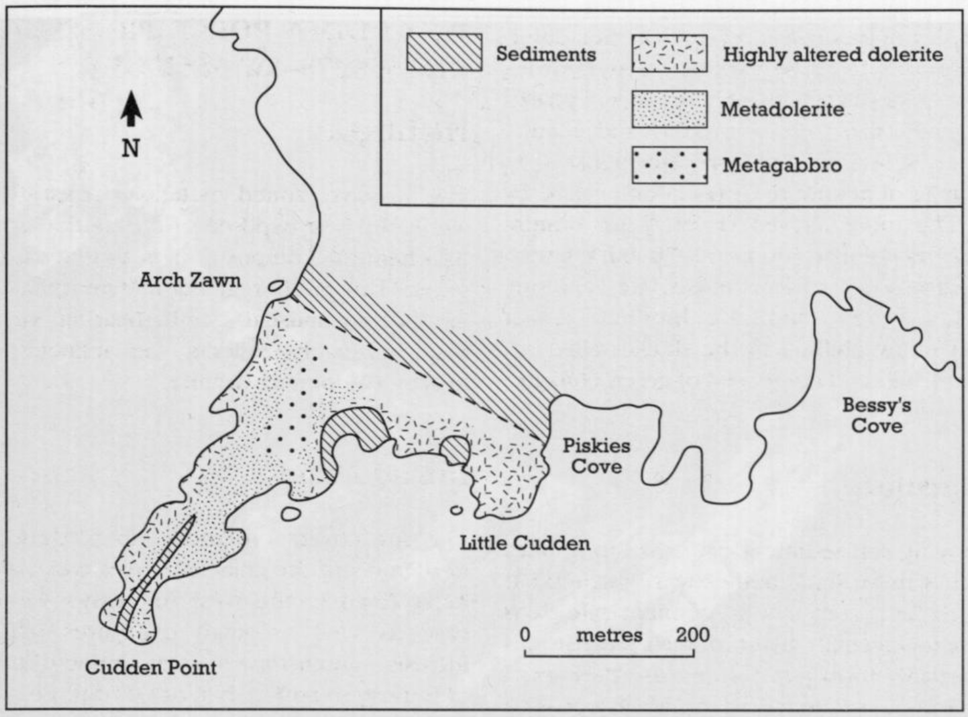


Figure 4.6 Simplified map of the Cudden Point greenstone body.

pelites. At Arch Zawn, the southward-dipping sheared contact is subparallel to the dominant axial-planar cleavage within the metasediments; a number of small shear zones within the dolerite body have a similar trend. In the east near Little Cudden, the greenstone is highly sheared, with about 30–40 m of a pale-green, albite–chlorite–actinolite schist showing an irregular, possibly folded, contact with the adjacent metasediments. At the extremity of Cudden Point proper is a pale-grey semipelitic metasediment raft with near-vertical tectonized margins, that was probably incorporated during intrusion, as the dolerite is chilled against its margin. Other interesting contact features include various mineral veins developed parallel, as well as oblique, to the main metasediment foliation, with the assemblage axinite–calcite–tremolite–chalcopyrite, and bimineralic veins of tremolite with either quartz, plagioclase or actinolite. The Ca required for these veins was probably mobilized from the dolerite during shearing. Axinite, however, is a Ca- and B-bearing mineral typical of contact metamorphism adjacent to potassic granites, and it is rare outside the visible contact aureoles of south-west England. Thermally developed chlorite spots may also be seen in the more pelitic metasediments near the contacts, although this may not have been induced by the dolerite, as spotting is often developed on a regional scale in west Cornwall, reflecting the influence of hidden granite ridges.

The foliated margins of the sill are now pale-green albite–chlorite–actinolite schists, whereas the major part of the body is a metadolerite that grades into a metagabbro. Central portions of the sill exhibit large relict plates of primary augite that are invariably fringed by fibrous actinolite (Figure 4.7). Sometimes, very thin exsolution lamellae of pigeonite may be observed within the larger clinopyroxenes. Towards the sill margins, clinopyroxene is invariably replaced, either partially or totally, by actinolite, in common with a general increase in the degree of alteration. Chlorite ovoids within the augite and matrix probably represent pseudomorphs after early olivine. Apart from the augite relicts and skeletal ilmenite, the only other primary phase is a rare, brown magmatic amphibole that is always replaced along its margins by zoned blue-green to colourless secondary actinolite. The presence of a primary hydrous phase is unique in these greenstones, and proves that the original magma contained some water and was not a typically anhydrous tholeiitic melt. Alteration domains of secondary minerals are common within the outer

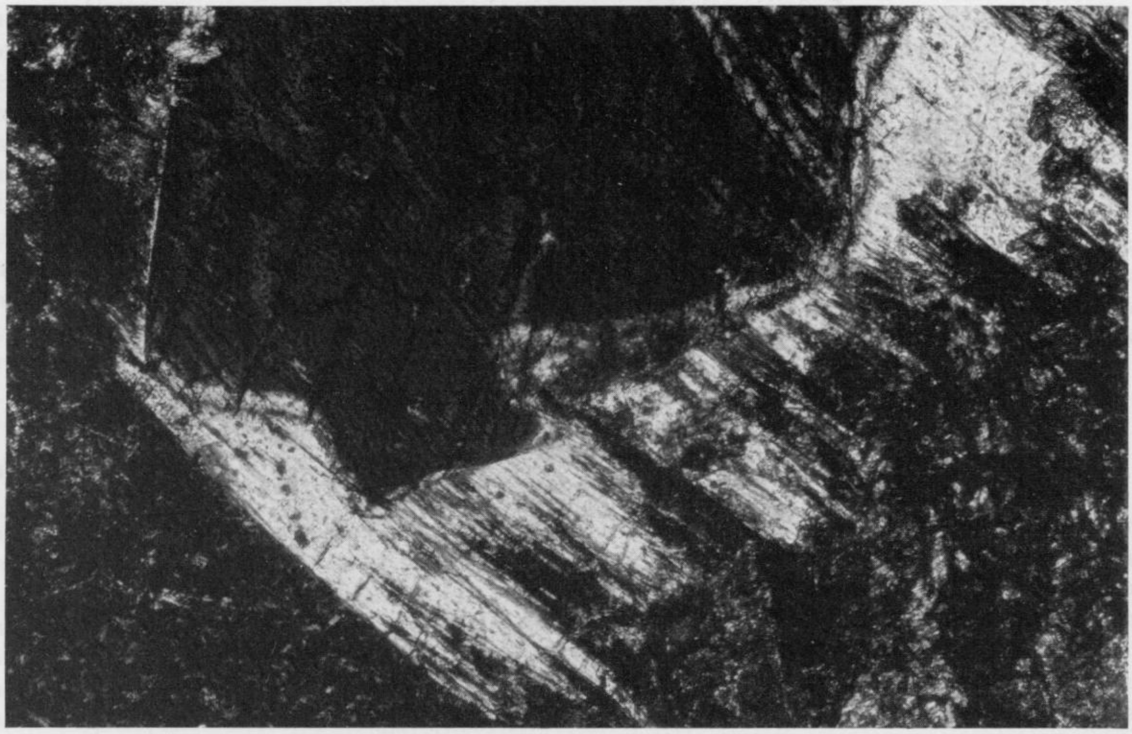


Figure 4.7 Photomicrograph of the coarser facies of the Cudden Point greenstone showing primary augite partly replaced by a fringe of actinolite (cross polars). (Photo: P.A. Floyd.)

portion of the sill and are dominated by chlorite–epidote–white mica with all original plagioclase now replaced by albite. Pumpellyite has not yet been recorded.

Interpretation

This greenstone is unique among the south Cornish intrusives in having a chemically primitive tholeiitic composition with low incompatible-element and high Mg, Ni, Cr and Sc abundances. These features suggest that the magma was probably derived by relatively high degrees of melting (*c.* 25%). Incompatible-element ratios, such as Zr/Y and Zr/Nb, can be matched with the extrusive suites which make up the south Cornwall magmatic province (Floyd, 1984; see Figure 4.2 above). The wide range of Cr (*c.* 700–50 ppm) and Ni (*c.* 600–50 ppm) values indicate that chemical variation was governed by mafic fractionation and dominated by the accumulation of olivine and clinopyroxene (Floyd and Al-Samman, 1980). One further feature of chemical interest is the strong enrichment of the marginal foliated facies in K, Rb, Cs, Li, F and Cl (Floyd and Lees, 1972; Floyd and Fuge, 1973), which, together with the presence of spotting and veins exhibiting typical aureole minerals (for example, axinite), suggest the effects of contact metasomatism. It is likely that granite-derived fluids, possibly from a hidden, shallow extension of the nearby Godolphin Granite, penetrated the sill via the channelways afforded by the sheared margins.

Conclusions

The Cudden Point Sill is typical of the massive greenstone intrusives found in south Cornwall, but it has some unique chemical and mineralogical features. It is a chemically primitive, olivine-bearing tholeiite, internally differentiated, with a textural variation governed by the differential cooling of a massive body. That the magma became hydrated on crystallization, is indicated by the presence of rare brown amphibole – until recently only recorded in the alkali dolerites of the north Cornish coast near Padstow. The degree of alteration was governed by distance from the locally sheared contact, although alteration domains are patchily developed through the

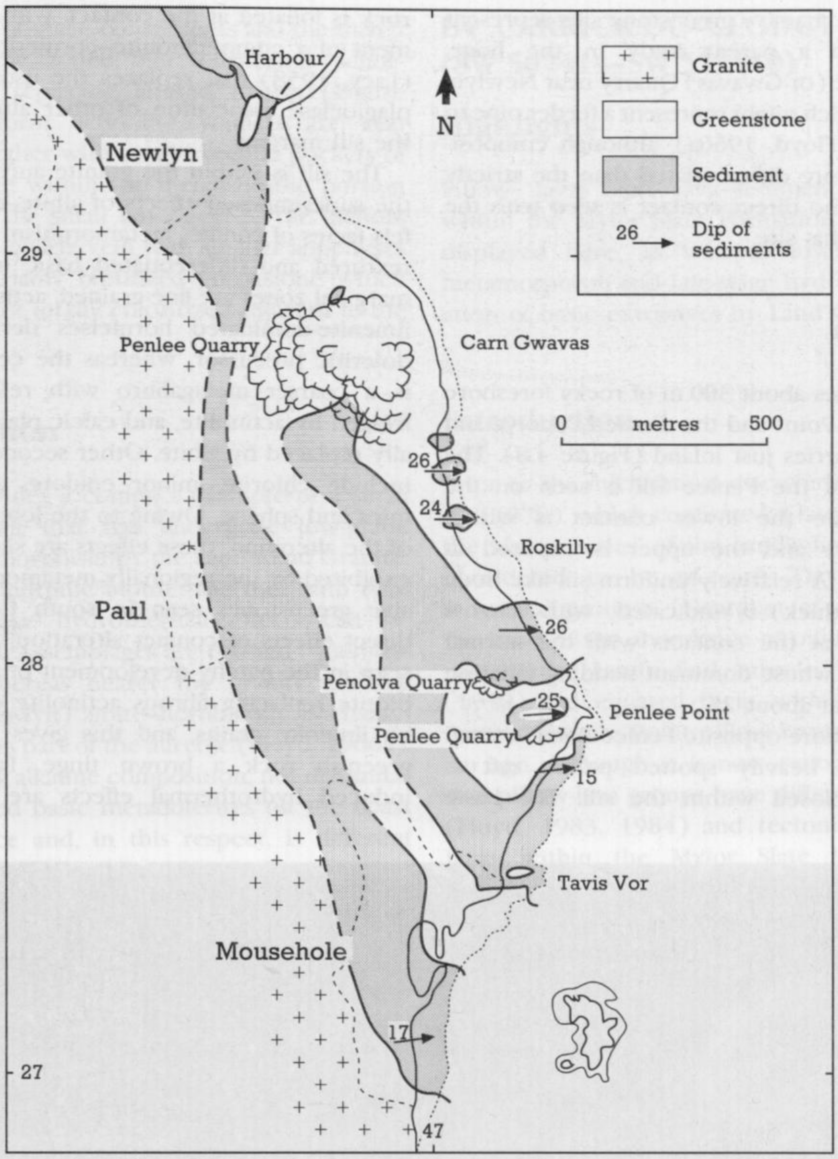


Figure 4.8 Geological map of the Mousehole–Newlyn section of the Land's End Granite aureole, showing the distribution of the dolerite sills around Penlee Point (after Floyd, 1966a).

body. The marginal facies provides evidence for alkali-element and F–B metasomatism from a nearby granite source.

B3 PENLEE POINT (SW 474269)

Highlights

At Penlee Point, spectacular contact-metamorphic and metasomatic mineral assemblages are superimposed on a dolerite sill and its sediment rafts.

Introduction

The site is located within the Land's End Granite aureole. It is topographically 600–700 m from the inferred contact, and it exhibits the effects of low-grade contact alteration. Apart from brief descriptions within the Survey Memoir (Reid and Flett, 1907), Floyd (1966a) recognized two sills in this section of the aureole, the uppermost of which (Penlee Sill) constitutes this site; the lower sill (Gwavas sill) is exposed along the foreshore to the north (Figure 4.8). It is generally assumed that both these massive greenstone sills represent offshoots from a parent body in the huge, working Penlee (or Gwavas) Quarry near Newlyn, the rocks of which might represent a feeder pipe to all local sills (Floyd, 1966a), although compositionally it is more differentiated than the strictly basic sills and no direct contact is seen with the Penlee Sill of this site.

Description

The site includes about 300 m of rocky foreshore around Penlee Point and the disused Penolva and old Penlee quarries just inland (Figure 4.8). The central mass of the Penlee Sill is seen on the foreshore, while the lower contact is within Penolva Quarry and the upper is exposed in Penlee Quarry. A relatively uniform sill-like body (about 30 m thick) is indicated, with narrow flinty adinoles at the contacts with the normal aureole pelites whose dominant bedding foliation dips eastward at about 25°.

On the foreshore opposite Penlee Point, a small biotitized and heavily spotted pelitic raft is apparently enclosed within the sill. The basic rock is foliated at the contact, with the development of a cummingtonite–cordierite assemblage (Lacy, 1958) that replaces the usual actinolite–plagioclase association of other altered parts of the sill margins.

The sill is within the granite aureole; it shows the superimposed effects of albite–epidote hornfels facies of contact metamorphism on a variably textured and differentiated basic intrusive. The marginal zones are fine-grained, actinolite–albite–ilmenite-dominated hornfelses derived from a doleritic precursor, whereas the central portion is a coarser metagabbro with relict pyroxene fringed by actinolite, and calcic plagioclase partially replaced by albite. Other secondary minerals include chlorite, minor epidote, quartz, white mica and sphene. Owing to the low-grade nature of the alteration, these effects are similar to those exhibited by the regionally metamorphosed, massive greenstones seen in south Cornwall. The direct effects of contact alteration, however, are seen in the patchy development of metamorphic biotite replacing fibrous actinolite or nucleating on ilmenite grains, and this gives the normally greenish rock a brown tinge. Later, granite-induced hydrothermal effects are the variable

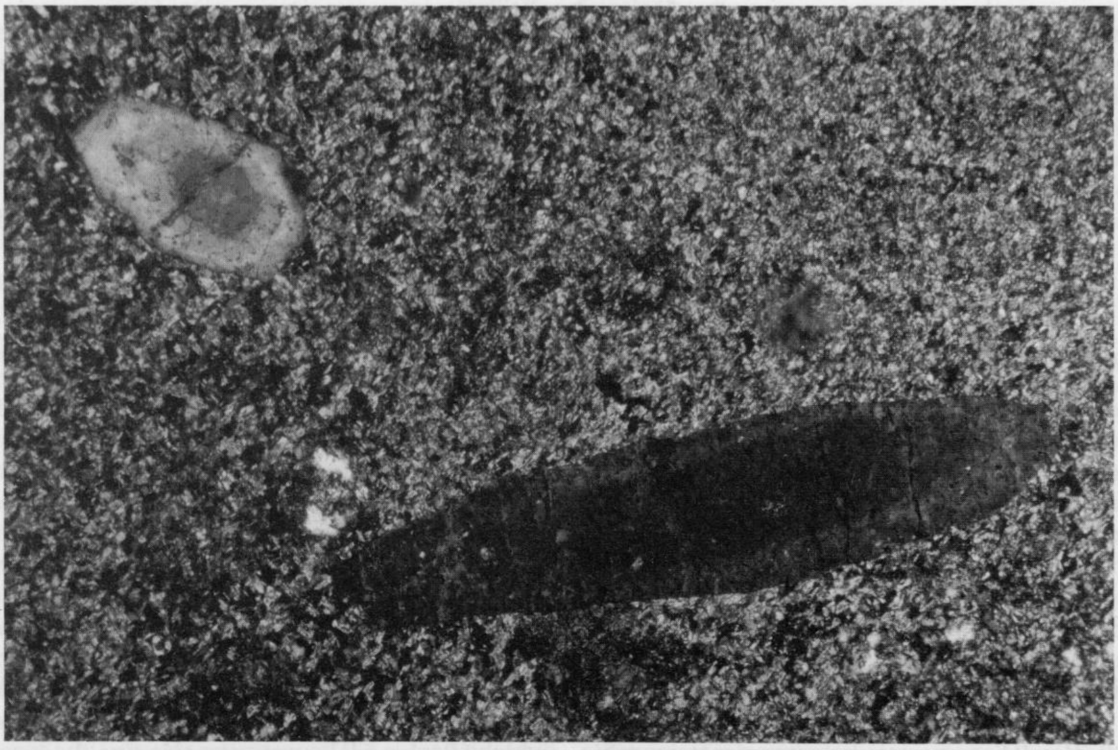


Figure 4.9 Photomicrograph showing late zoned tourmaline replacing chloritic matrix of contact metamorphosed Penlee dolerite (cross polars). (Photo: P.A. Floyd.)

chloritization of mafic constituents and the development of large, zoned, blue tourmaline (schorlite) crystals replacing altered matrix (Figure 4.9). Asbestiform actinolite veinlets are also common, together with small irregular pockets of late amphibole within the metagabbroic portion of the sill. In the small cove next to the lifeboat house, a large quartz vein with smaller apophyses intrudes a variably biotitized greenstone which has been almost totally chloritized adjacent to the vein.

Interpretation

The site provides a compact example of a small greenstone sill that has undergone low-grade contact metamorphism by the Land's End Granite. Contact-metamorphic biotite, together with relatively late-stage hydrothermal effects can be demonstrated. Assemblages are typified by albite–actinolite, whereas nearer the granite (Penlee Quarry at Newlyn) albite–hornblende is characteristic for this part of the aureole (Floyd, 1966a). It has a mildly alkaline composition, not dissimilar to the evolved basic metadolerites on the coast near Penzance and, in this respect, is different from other more massive, chemically primitive, dolerite/gabbro intrusives typical of south Cornwall generally (for example, Cudden Point, described below). Its relationship to the pipe-like (feeder?) intrusion at Penlee Quarry is not clear, but the latter has a different composition, even allowing for hydrothermal alteration effects.

An unusual feature, at Penlee Point proper, is the development of a cummingtonite–cordierite assemblage in the marginal zone of the intrusive adjacent to the enclosed pelitic raft. This probably developed from contact metamorphism of an altered and foliated Ca-poor marginal facies of the dolerite generated during initial regional deformation.

Conclusions

The alkali-dolerite sill at Penlee Point displays a coarse, gabbroic inner zone and raft of pelitic sediment. When the later Land's End Granite was emplaced nearby, spectacular low-grade metamorphic (albite–actinolite and cummingtonite–cordierite) and metasomatic (tourmaline-bearing) mineral assemblages were developed across the sill, its rafts and the enclosing country rock.

B4 CARRICK DU–CLODGY POINT (SW 507414–SW 512410)

Highlights

Pillow lavas and lava–sediment relationships within the Mylor Slate Formation are very well displayed here, as well as low-grade contact metamorphism and late-stage hydrothermal alteration of basic extrusives by Land's End Granite.

Introduction

Prior to the microfaunal discoveries of Turner *et al.* (1979), which confirmed a late Devonian age, the Mylor 'Series' of the Land's End Memoir was considered to be of early Devonian age on structural grounds (Dearman *et al.*, 1969). On the basis of the abundance of pillow lavas in this part of the Land's End aureole, however, Lacy (1958) had equated them with the well-documented Pentire Point pillow lavas of late Devonian age. Although it is now recognized that the two pillow-lava groups have different chemistries (Floyd, 1983, 1984) and tectonic settings, the lavas within the Mylor Slate Formation are, nevertheless, considered to belong to the parautochthonous Upper Devonian, and they are associated with the deep-water argillaceous facies within the Gramscatho Basin (Holder and Leveridge, 1986)

Description

This site is located along a stretch of about 1200 m of scenic coastline just to the north-west of St Ives and Porthmeor beach, in the outermost reaches of the Land's End Granite aureole. It comprises two low-lying headlands of small cliffs and gullies separated by a pebble beach, as well as a disused quarry in the pasture behind Carrick Du.

The site displays both vertical sections (Carrick Du) and northward-dipping platforms (Clodgy Point) of pillow lavas (Figure 4.10) together with some pelitic sediment and tongues of more massive lava. Many of the pillows are small, with cross-sections of only 0.2–0.6 m, although some horizons have clearly undergone a degree of tectonic flattening and shearing into phacoidal forms. Interpillow relationships show that they

Figure 4.10 View of the pillow-lava sequence at Clodgy Point, Penwith, Cornwall. (Photo: P.A. Floyd.)

are the correct 'way-up', generally concordant with the sedimentary laminations, and that they dip about 20° to the north. The elongate tube-like structure of typical pillow-lava piles is not well developed, as many appear to be either of short length or individually bun-shaped, possibly developed towards the base of a submarine slope. There is little interpillow sediment within the main pillow horizons, although some discontinuous sediment horizons contain small, irregular, lava globules representing squirts of basalt magma into wet, partially consolidated, sediment (Figure 4.11). Although the pillow matrix is fine-grained, chilled margins are rarely preserved and vesicles uncommon. Some pillows, however, exhibit small pits or 'spots' which in thin section appear to represent the weathering out of cordierite porphyroblasts, rather than true vesicles. Polygonal and transverse cooling cracks may be seen on the exposed top surfaces of some small bun-like pillows (Figure 4.12).

Apart from the pillow lavas and their sheared analogues, thin (1–3 m), high-level, sheet-like intrusives are also present which invariably show a tectonized contact with the metasediments. Hard, white massive and mylonitized adinoles, together with thin shear zones containing an admixture of brecciated and rolled adinole, pelite and greenstone fragments may be observed at sediment–greenstone contacts (Figure 4.13).

All the rocks now display a typical, low-grade, albite–epidote hornfels facies of contact-metamorphism mineralogy. The pelitic/semipelitic sediments are mainly laminated quartz–mica–chlorite and cordierite–biotite hornfelses, whereas the pillow lavas are fine-grained albite–actinolite

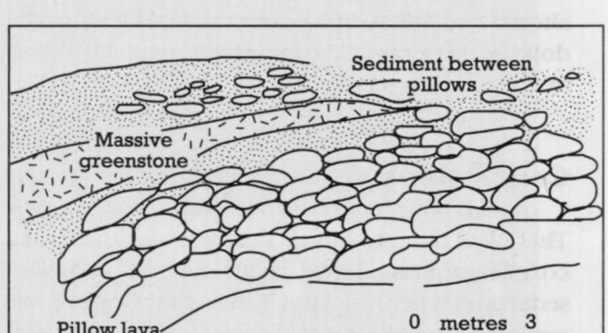


Figure 4.11 Relationship between Upper Devonian pillow lavas and interlayered pelitic sediment, Clodgy Point, Penwith Peninsula.

Figure 4.12 Polygonal cooling cracks on pillow-lava sequence at Clodgy Point, Penwith, Cornwall. (Photo: P.A. Floyd.)

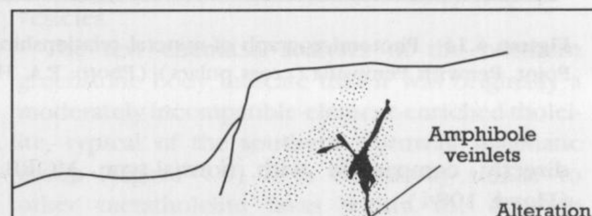


Figure 4.13 Sketch of the tectonized contact between adinolized sediments and greenstone, Clodgy Point, Penwith Peninsula.

hornfelses with no original magmatic phases left. Contact-metamorphic biotite may replace the actinolite and impart a purplish colour to the rock. The most distinctive feature of the basic rocks is the effect of granite-derived, late-stage hydrothermal fluids. This takes the form of pale, bleached patches and zones often closely associated with networks of pale-green amphibole veinlets. Mineralogically the 'bleached' matrix shows chloritization of amphibole and biotite, leucoxenization of ilmenite, and replacement of plagioclase by kaolinite. Amphibole veinlets may also exhibit radiate groups of blue-green to dark-blue zoned tourmaline, both of which may be partially replaced by late epidote, calcite and rare axinite (Figure 4.14). These mineralogical replacements suggest that the initial Na–Mg–Fe-rich fluids subsequently became more Ca-rich.

Chemically, the pillow lavas of Clodgy Point are tholeiitic basalts with subhorizontal chondrite-normalized REE patterns and, in this sense, are not

Figure 4.14 Photomicrograph of mineral relationships in late amphibole-rich hydrothermal veins, near Clodgy Point, Penwith Peninsula (cross polars). (Photo: P.A. Floyd.)

directly comparable with normal-type MORB (Floyd, 1984).

Interpretation

The importance of this site rests on the excellent examples of pillow lavas exhibited that typify the extrusives within the parautochthonous Upper Devonian of west Cornwall. They are evidence for submarine volcanism associated with the development of the deep-water facies of the Gramscatho Basin. Their limited stratigraphic occurrence and non-MORB chemistry indicates that true oceanic crust was not developed in this particular area of the Gramscatho Basin. Although they belong to the same magmatic province as other volcanics in south Cornwall, they are chemically distinct from the metabasalts of the *mélange* zone (Chapter 2) (Floyd, 1984). Moreover, their distinctive morphology and chemistry, in terms of specific incompatible-element ratios (e.g. Zr/Y), relative to other pillow-lava horizons at about the same stratigraphical level elsewhere within the aureole (e.g. Kenidjack Castle), suggest that a number of separate volcanic centres were active at this time.

The other major feature of the site is the superimposed contact-metamorphic and late-hydrothermal effects, consequent upon the emplacment of the Land's End Granite, that have completely replaced the primary mineralogy and texture.

Conclusions

The sedimentary rocks here were originally deposited as clays and silts on a sea-floor during the late Devonian Period, around 370 million years ago. Contemporaneous with sedimentation are piles of submarine lavas that formed superimposed masses of bulbous tubes (or 'pillows') as they escaped from the vent or fissure on the sea-bed. The original basalt lavas have been subsequently altered chemically and mineralogically and now bear the imprint of contact metamorphism by the Land's End Granite. However, chemical data indicate that their original eruptive environment was probably in a basin underlain by continental crust rather than oceanic crust like the Lizard ophiolite.

B5 GURNARD'S HEAD (SW 432387)

Highlights

This site is one of the few that shows a continuous gradation within a dolerite body from a massive, lower part to a pillowed top. Metasomatic effects, associated with the nearby Land's End Granite, are also well developed.

Introduction

The rocky peninsula of Gurnard's Head shows rocks in the metamorphic aureole of the Land's End Granite. Although much of the volcanic development within the Upper Devonian is recorded by classic exposures of pillow lavas; they can often be spatially associated with more-massive, intrusive, sheet-like doleritic bodies (Taylor and Wilson, 1975). Only in some cases, such as at Gurnard's Head, can these be seen to be directly related via vertical gradation from massive sheets to pillowed top.

Description

Gurnard's Head is topographically divided into two by a wide grassy hollow underlain by a metasedimentary horizon that separates the two greenstone masses to the north and south (Figure 4.15). At the site, the contrast between the type and level of emplacement of the two bodies may be seen. The southern greenstone is massive throughout, and although its contacts with the adjacent sediments are heavily sheared, it cuts the sedimentary lamination and was emplaced as a relatively late intrusive sheet. The northern greenstone rests conformably on the metasediments, below which are partially adinolized pelites and semipelites. The contact can be traced across the neck of the headland dipping at about 25° NNW; it is typically sheared and impregnated with radiating groups of hydrothermal, green amphibole. The base of the body is composed of a massive sheet-like intrusive which changes upwards to a crudely pillowed and vesiculated top. This implies emplacement at a high level, with the topmost magma batch in contact with water. The lenticularity of some of the pillows is partly a consequence of later shearing (Figure 4.16).

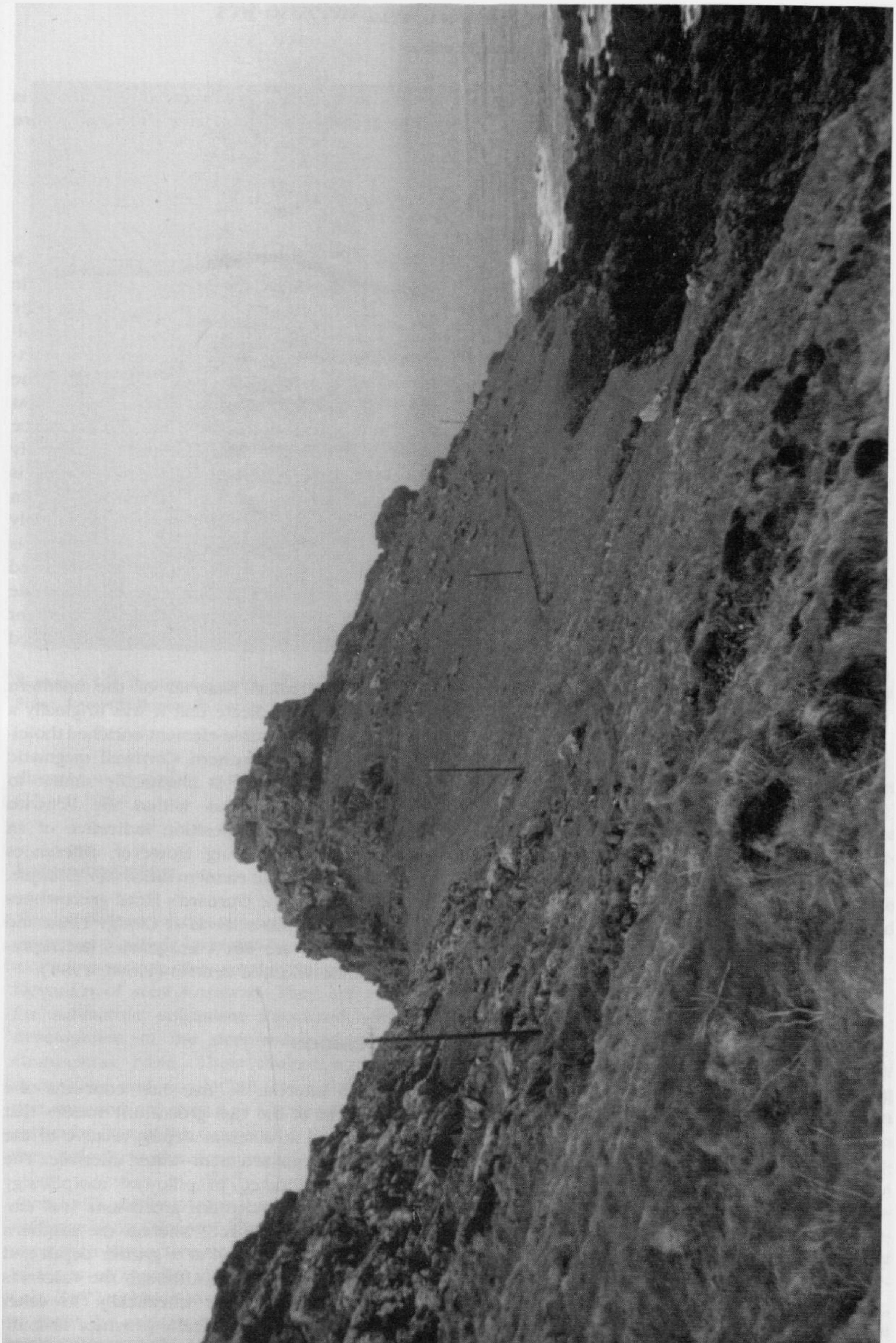
Interpretation

Both of the Gurnard's Head greenstones (which originally ranged from dolerite to basalt) lie within the Land's End Granite aureole, and they are now fine-grained ilmenite–plagioclase–actinolite hornfelses. The later replacement of contact-metamorphic amphibole by biotite implies the migration of K-bearing hydrothermal fluids across the width of the aureole from the granite source about 1000 m away. This example of externally derived fluids metasomatizing the greenstone is in contrast to the localized movement (within restricted shear zones) of Ca-rich fluids initially derived from the greenstone. This latter effect is represented by horizons within the pillowed greenstone, which contain white bands of diopside that replace the actinolite and probably represent the mobilization of Ca from original calcite-filled vesicles.

The few chemical analyses of the northern greenstone body indicate that it was originally a moderately incompatible-element-enriched tholeiite, typical of the southern Cornwall magmatic group (Figure 4.2). It is chemically similar to other metatholeiite lavas within the Penwith Peninsula with a composition indicative of an intraplate eruptive setting. However, differences in some incompatible-element ratios (for example, Zr/Y) imply that the Gurnard's Head greenstones and the nearby pillow lavas at Clodgy Point and Botallack Head are not comagmatic, but represent separate volcanic centres (Floyd, 1984).

Conclusions

The main interest in the site concerns the emplacement of the two greenstone masses that were intruded at different depths relative to the contemporaneous sediment–water interface. The change from sheeted to pillowed morphology indicates that the northern greenstone was emplaced near the interface, whereas the southern greenstone was intruded at a greater depth and within the sediment pile. Although the volcanics of this site are similar chemically to other metatholeiites in the magmatic province of south Cornwall, they probably represent a separate



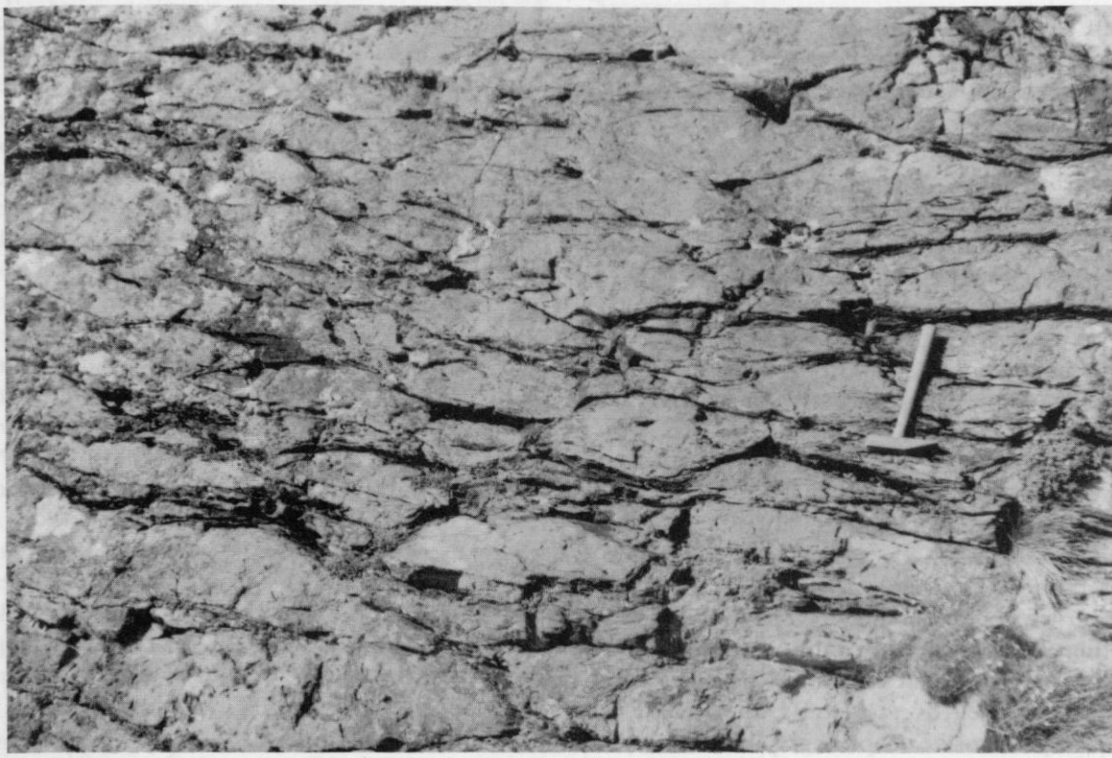


Figure 4.16 Sheared and flattened Upper Devonian pillow lavas associated with the massive greenstone body at Gurnard's Head, Cornwall. (Photo: P.A. Floyd.)

volcanic centre. This is a common situation, with many outcrops representing isolated, small volcanic edifices at about the same stratigraphical level within a deep-basinal sequence.

The other feature of interest concerns the metasomatic replacement of basic contact-metamorphic assemblages by the minor development of biotite and diopside. These minerals are representative of two different metasomatic processes seen elsewhere within the Land's End aureole: the K (for biotite) being derived 'externally' from the granite, whereas Ca (for diopside) was derived 'internally' via mobilization of greenstone constituents.

Figure 4.15 The two greenstone masses of Gurnard's Head. The intervening hollow is underlain by metasediments. Gurnard's Head, Cornwall. (Photo: P.A. Floyd.)

B6 BOTALLACK HEAD–PORTH LEDDEN (SW 362339–SW 355322)

Highlights

Within the Land's End aureole, this classic site provides the best section of basic hornfels formed by the metamorphism and metasomatism of massive dolerite sills and basaltic pillow lavas. Uniquely, these pre-Variscan basalts contain granitoid xenoliths, possibly indicating an underlying continental crust at the time of their extrusion. This site also contains industrial relicts of some of the most famous and productive tin and copper mines in the mining history of South-west England.

Introduction

Scenically and geologically, this site is one of the best coastal sections within the aureole of the Land's End Granite. Steep cliffs and deep, inset, narrow gullies (locally called 'zawns'), together with a few exposures on the grassy cliff-top platform, provide excellent examples of both metamorphic and metasomatic hornfelses derived from basaltic pillow lavas and massive greenstones.

This area represents a classic example of contact metamorphism of basic volcanic rocks by the Land's End Granite, although gross morphology, relict textures and mineralogy often enable their original composition to be deduced. In general, contact metamorphism produced both typical hornblende-bearing hornfelses, as well as more unusual hornfelsic assemblages whose origin has been often debated and for which this area is famous.

The 'normal' basic hornfelses mainly display ilmenite–plagioclase–hornblende ± biotite assemblages and have often been intensively sheared into bands and lenses. It is not always possible to determine whether they were originally extrusive or intrusive, although the degree of heterogeneity within the sequences and the sheared outline of pillow lavas indicates that the majority of the normal, as well as the exotic, hornfelses were probably extrusive. A petrographic relict of the intensive deformation prior to contact metamorphism, is seen in the granulation of primary ilmenite into parallel trains across which new contact minerals have grown. All aureole hornfelses (including the metasediments) have been metasomatized by the granite and exhibit enhanced contents of Sn, Zn, Be, B, F, Cl, U and the light-REE (Floyd, 1966b, 1967; Wilson and Floyd, 1974; Alderton and Jackson, 1978; Mitropoulos, 1982, 1984; van Marcke de Lummen, 1985).

This part of the aureole initially became known for the presence of two groups of hornfelses with unusual mineral associations:

1. Mg-rich assemblages with anthophyllite–cordierite and cummingtonite–plagioclase, and
2. Ca-rich assemblages with sphene–diopside–hornblende, diopside–garnet and garnet–epidote–calcite.

Early work suggested that the two unusual hornfelsic groups represented the metasomatically derived end products of the normal hornblende-bearing hornfelses, under the influence of hydrothermal solutions emanating from the granite (Tilley and Flett, 1930; Tilley, 1935). However, rather than an origin invoking purely Mg and Ca metasomatism, it is now considered that they were developed by the isochemical contact metamorphism of previously altered basaltic volcanics (Vallance, 1967; Chinner and Fox, 1974). Alteration would have taken place during earlier, low-grade regional metamorphism (late Devonian), with the patchy development of variably degraded assemblages ranging from chlorite-rich (isochemically producing the Mg-rich assemblages) to epidote–carbonate-rich (eventually producing the Ca-rich assemblages). During contact metamorphism, Ca-rich solutions, however, were mobilized from Ca-bearing degraded areas and together with granite-derived mineralizing fluids (containing Sn, B, etc.) also locally metasomatized the adjacent normal hornfelses (Floyd, 1965; Jackson and Alderton, 1974; Floyd, 1975; Alderton and Jackson, 1978; van Marcke de Lummen, 1985). During the redistribution of elements within the aureole volcanics on contact metamorphism, it is clear that Sn-rich fluids were also circulating so that ore deposition within the aureole is often marked by Ca-rich skarn-type alteration (Jackson, 1974). However, oxygen and hydrogen isotope studies indicate that fluids in equilibrium with the skarn minerals were not purely magmatic, but, as temperatures fell, were mixed with an increasing meteoric component (van Marcke de Lummen, 1985).

Description

The site comprises the coastal strip between Botallack Head in the north to Porth Ledden, near Cape Cornwall, in the south. An outline geological map of the area is shown in Figure 4.17. It contains a prehistoric cliff castle at the Kenidjack Castle headland and is particularly famous for its mining history that covered an active period of nearly 200 years. Botallack Mine, probably one of the oldest in the St Just mining area, commenced mining in 1721 and became one of the richest tin mines by the early nineteenth century. Between 1815 and 1905, about 20 000 tons of copper ore and 14 000 tons of tin ore were won, with workings extending 800 m beyond the cliffs under the sea at a maximum depth of about 500 m (240 fathom level, Figure 4.18) (Barton, 1965; Embrey and Symes, 1987). Two derelict engine-houses still stand perched on the cliff edge at The Crowns, just south of Botallack Head (Figure 4.19), from which the famous, diagonal Boscawen shaft descended into the mine. Inland from Kenidjack Cliff was the extensive Wheal Owles Mine that, apart from tin, was one of the

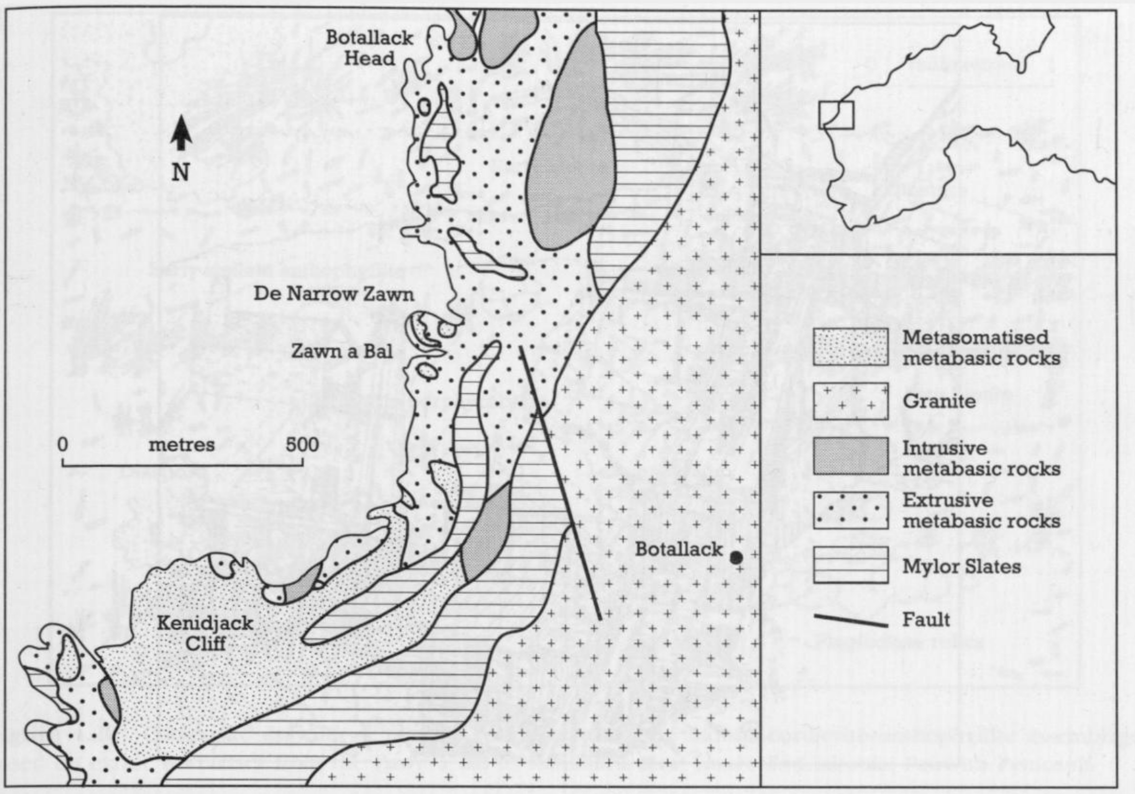


Figure 4.17 Geological map of the Botallack–Cape Cornwall section of the Land's End aureole, Penwith Peninsula (after Goode and Merriman, 1987).

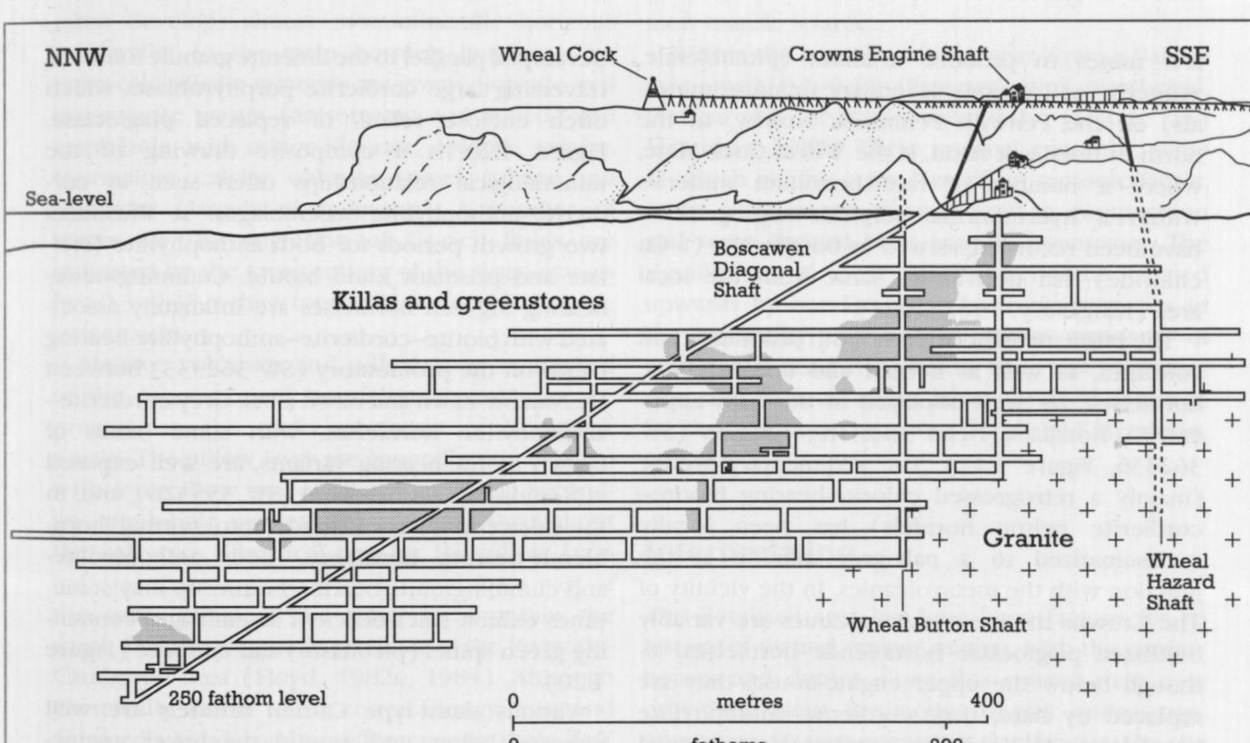


Figure 4.18 Section through the Botallack Mine, showing the sub-sea-floor workings and famous diagonal shaft, near St Just, Penwith Peninsula (after Embrey and Symes, 1987).

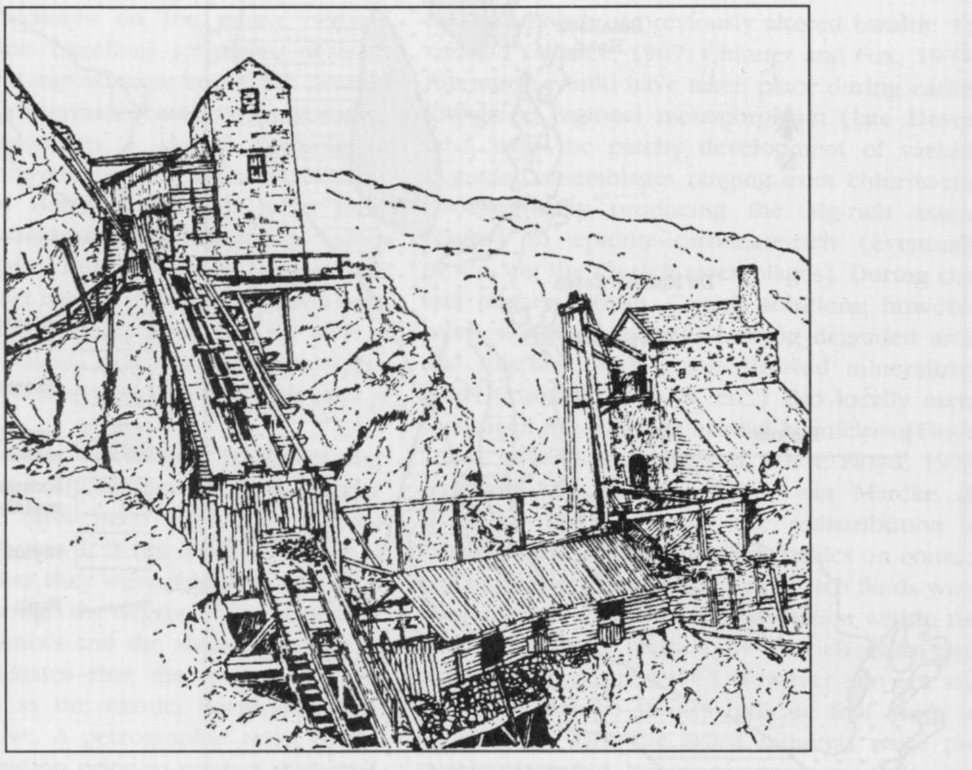


Figure 4.19 Line drawing of the cliff-edge engine-houses of the Botallack Mine and the beginning of the diagonal shaft at The Crowns, near St Just, Penwith Peninsula (reproduced from Barton, 1965).

few mines to produce uranium (pitchblende, zeunerite and various secondary uranium minerals) on the Penwith Peninsula. Nearby, to the north of Botallack Head, is the Wheal Cock Mine, where a number of rare beryllium minerals within a hydrothermal sulphide-bearing skarn have been recorded, as well as botallackite (a Cu chloride) that derives its name from the local area (Kingsbury, 1961, 1964).

The intimate association of both sediments and volcanics, as well as normal and unusual basic hornfelses, are well displayed in the cliffs adjacent to Botallack Head and The Crowns (SW 362336, Figure 4.17). The sedimentary wedge (mainly a retrogressed chlorite-bearing biotite–cordierite pelitic hornfels) has been locally metasomatized to a pale-grey adinole at the junction with the metavolcanics. In the vicinity of The Crowns the basic metavolcanics are variably biotitized plagioclase–hornblende hornfelses, although below the upper engine-house, they are replaced by hard, dark cordierite–anthophyllite hornfelses with cordierite porphyroblasts aligned along the major foliation. Thin-section examination shows stellate groups of anthophyllite needles, developed parallel to the ilmenite granule foliation, traversing large cordierite porphyroblasts which often enclose relicts of replaced plagioclase. Figure 4.20 is a composite drawing of the mineralogical relationships often seen in cordierite–anthophyllite assemblages: it illustrates two growth periods for both anthophyllite (stellate and prismatic) and biotite. Cummingtonite-bearing Mg-rich hornfelses are intimately associated with biotite–cordierite–anthophyllite-bearing bands on the promontory (SW 362333) between De Narrow Zawn and Zawn a Bal. Grey cordierite–anthophyllite hornfelses, with some bands of brown biotite-bearing variants, are well exposed at Kenidjack Cliff headland (SW 355326), and, in the adjacent quarries, grade into normal hornblende-bearing hornfelses. Both anthophyllite- and cummingtonite-bearing hornfelses may sometimes exhibit silica-deficient assemblages containing green spinel (pleonaste) and diaspore (Figure 4.20).

Various skarn-type Ca-rich hornfels are well exposed below and around the lower engine-house at The Crowns; they form pale-coloured grey, pink and green masses. The banded foliation

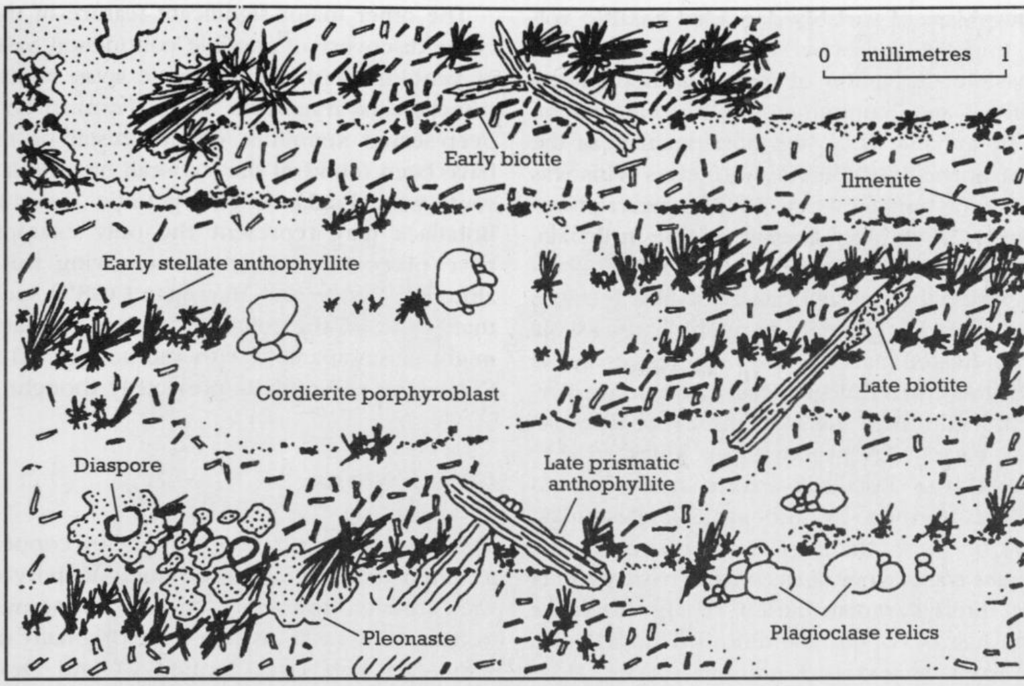


Figure 4.20 Composite drawing of mineral relationships in the biotite–cordierite–anthophyllite assemblage, based on exotic hornfelses from the Zawn a Bal to Kenidjack area, Land's End aureole, Penwith Peninsula.

of the adjacent hornblende hornfelses may be lost where the skarn replaces it, although the latter often develops almost monomineralic horizons subparallel to the main hornfels banding. The main calc-silicate minerals are green diopside, red grossularite garnet (anisotropic and zoned) and amphibole, with minor idocrase, epidote, axinite, tourmaline, calcite, chlorite, spinel, sphene and sulphides (largely chalcopyrite). A number of stages for the migration of Ca-rich fluids are indicated by the cross-cutting of the skarn masses by a 0.3–0.35 m thick tourmaline–diopside-bearing garnet vein.

Massive volcanics and pillow lavas composed of the more normal hornfelsic assemblages are present on the rocky platforms of Kenidjack Castle. The pillow lavas are generally thin (<1 m) with interpillow spaces filled with silica. Secondary amphibole veinlets are common throughout the volcanics. Chemical data for the pillow lavas indicate that they are tholeiitic and form part of the same group as the other lavas within the south Cornish magmatic province of the Penwith–Camborne area (Floyd, 1982a, 1984). Although chemically similar to the coeval Clodgy Point and Gurnard's Head basalts, differences in their Zr/Y ratios and degree of light-REE-enrichment implies that the lava occurrences are not comagmatic, but represent three separate volcanic centres generated by variable partial melting of a common mantle source.

Within the basic hornfelses near Zawn a Bal are rare, small (0.1–0.4 m diameter), pink, weathered, feldspar-rich crystalline xenoliths (Goode and Merriman, 1987). These unusual xenoliths, some of which exhibit a pre-Hercynian tectonic fabric, range from intermediate to acid in composition and were derived from granitic precursors. The significance of these granitic xenoliths, carried upwards by late Devonian basic magmas, lies in the possibility that they represent remnants of continental crust lying below the Penwith Peninsula, and as such might have provided a source for the Cornubian granites (Goode and Merriman, 1987).

Interpretation

The Botallack area has long been famous for its history of tin and copper mining, with the engine-houses and dumps along this coastal strip now providing silent testimony to past endeavours. Apart from its past economic significance, the site provides excellent examples of the different hornfelsic types produced during the contact metamorphism of variably degraded basaltic volcanics. Initially, studies by Tilley (1935) identified the possible derivation of exotic anthophyllite–cordierite- and cummingtonite-bearing assemblages by variable Fe + Mg metasomatism of the adjacent normal hornblende hornfelses. This was one of the first detailed petrographic descriptions of these rocks within a granite aureole in Britain, and Tilley (1935) compared them with occurrences within the Precambrian crystalline terranes of Scandinavia. For example, early studies by Eskola (1914) indicated that the anthophyllite–cordierite rocks of the Orijarvi region had been derived by the wholesale Mg metasomatism of siliceous 'leptites' (acidic lavas and tuffs). Tilley (1935) considered the Botallack exotic hornfelses to have been formed by the same metasomatic process, but with the important difference that the former rocks were derived from basic parents via the internal redistribution of Mg (together with the loss of Ca, etc.), and not by the addition of Mg from an external granitic source as at Orijarvi. The origin of these unusual rocks is important, not only in terms of metamorphic paragenesis and parental composition, but as economic guides because they are often associated with massive sulphide deposits in many parts of the world. Although the theory of a metasomatic origin held sway for some time, work on the regional degradation of basaltic volcanics has indicated that they could also be generated by the isochemical metamorphism of the low-grade secondary products of such rocks (Vallance, 1967; Chinner and Fox, 1974). However, as indicated by Floyd (1975), removal of Ca, etc. from the degraded assemblages is still required to produce a suitably Mg-rich precursor. In this context, Floyd (1975) linked the derivation of the skarn hornfelses to the Mg + Fe-rich hornfelses, with the former representing the repository of the released Ca. Thus, both groups of exotic hornfelses can be related to the variable degradation of basaltic volcanics and the differential migration of Ca-rich fluids. The normal hornblende hornfelses were developed isochemically from metabasalts containing relatively small proportions of secondary Ca-bearing phases. It is interesting to record, however, that Reynolds (1947), noting the intimate association of the exotic hornfelses, suggested that the Mg + Fe-rich group were derived from calcareous sediments (remnants becoming the Ca-rich group) which suffered Mg metasomatism from an advancing basic front produced by local granitization.

The other major significant feature of this site is the discovery of possible continental basement as xenoliths within the basaltic lavas. Apart from some crustal fragments within Permian lavas, no deep-seated xenoliths, either crustal or mantle, have been found in the Variscan basaltic lavas of south-west England. The granitic xenoliths at Botallack may represent the only example we have of continental crust underlying this area, although Goode and Merriman (1987) speculate that some of the foliated granites of Haig Fras might be comparable with and not related to the Cornubian batholith as previously thought.

Conclusions

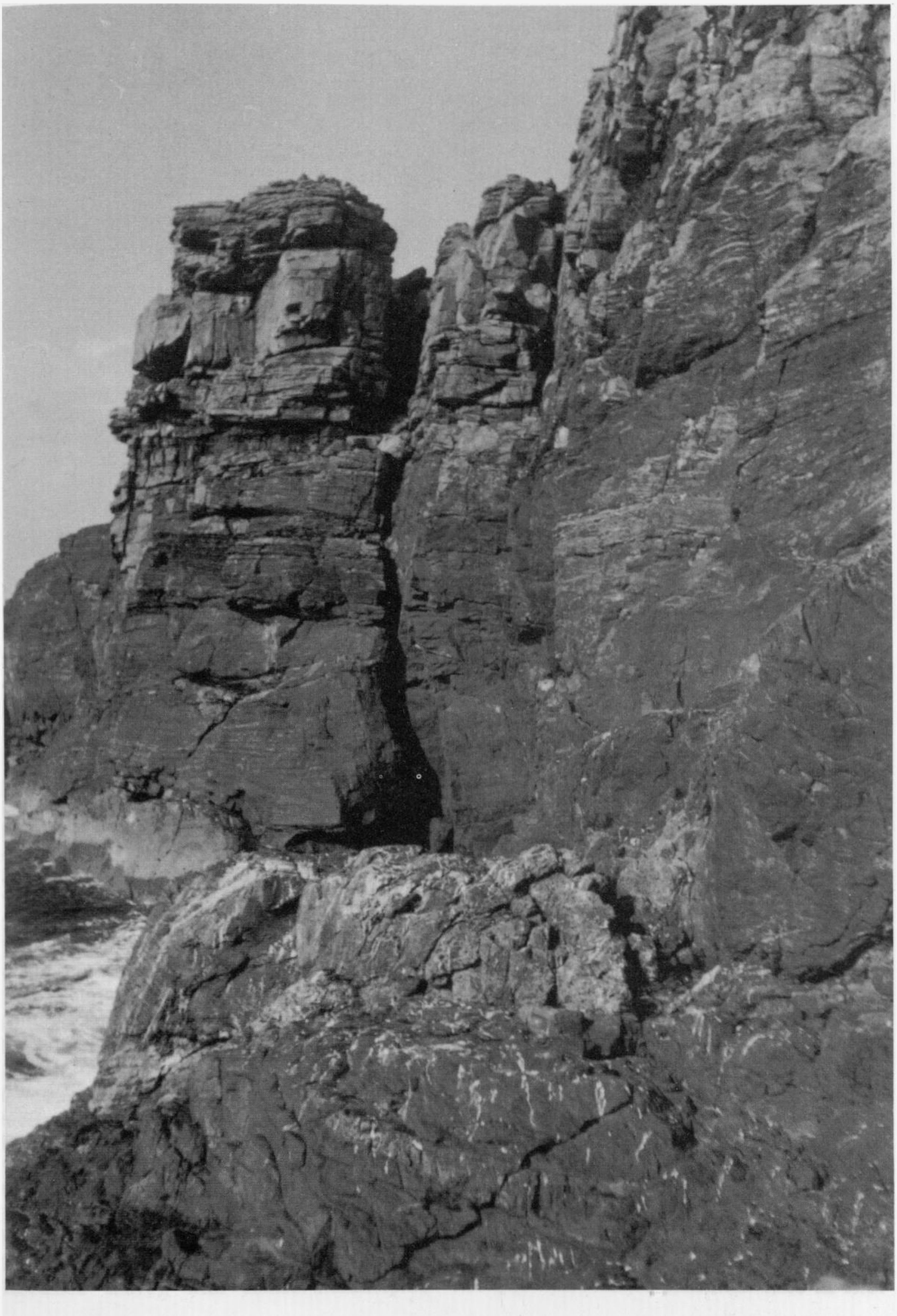
This site is world famous for its copper and uranium minerals and the mining activity which they attracted in the last century. These minerals occur within rocks, which were originally marine sediments and lavas formed in late Devonian times, around 370 million years ago. These rocks were subsequently mineralized by the action of hydrothermal solutions emanating from the Land's End Granite that caused the mobilization and redistribution of economically important elements. Prior to granite emplacement, the basaltic lavas had undergone low-grade alteration with the development of two different chemical groups – one Fe + Mg-rich, the other Ca-rich. On contact metamorphism by the granite, these two groups developed a unique set of exotic mineral assemblages for which the area is famous. Within the Devonian lavas are found inclusions of granitic rocks that are considered to represent fragments of continental crust through which the basalt magmas passed. Their presence is the only direct evidence for the existence of continental crust below the submarine basins of south-west England.

B7 TATER-DU (SW 440230)

Highlights

At this excellent contact with the Land's End Granite, the progressive change from basaltic

Figure 4.21 Massive cliff section composed of various banded, amphibole-bearing, basic hornfelses of volcanic origin. In the foreground is a small irregular raft of metasediment caught up during the emplacement of the basalts. Tater-du, Cornwall. (Photo: P.A. Floyd.)



lavas to metamorphic and metasomatic hornfelses of varied mineralogy and chemistry, is particularly well seen.

Introduction

The dark, steep cliffs and sloping rock platforms of Tater-du at the southern tip of the Penwith Peninsula (SW 440230) are a small erosional relict of aureole rocks adjacent to the Land's End Granite (Figure 4.21). The area from Tol Toft in the east to Zawn Gamper in the west, including the crags and quarry just inland, are perched on the southerly dipping contact zone of the surrounding megacrystic granite. The eastern end is represented by a faulted gully, while to the west an excellent contact between the aureole rocks and the marginal facies of the granite is exposed in the wall of Zawn Gamper. Apart from a petrographic description of the hornfelses (with some chemical data), little research has been done on this aureole segment (Floyd, 1965, 1975), although it represents a microcosm of the contact alteration of basic volcanics in the hornblende hornfels facies.

Description

Directly above the granite contact at Zawn Gamper, is a thin, variably retrogressed cordierite–biotite pelite that can be traced intermittently along the lower rock ledges below the main cliffs of Tater-du. At the granite contact it is tourmalinized and shows the development of late, randomly orientated, muscovite flakes. The rest of the site is mainly composed of massive, well-banded, dark hornblende-bearing hornfelses, with minor horizons of unusual Mg-rich and Ca-rich hornfelses. These are best developed below the main cliffs near one of the metasedimentary lenses; this has a thin, partly developed, cummingtonite-bearing adinolized contact zone with the adjacent metavolcanics.

The basic volcanics here were intensely sheared prior to contact metamorphism, so that there is little direct evidence as to their original nature. The presence of adinolized sediment implies that some of the volcanics were probably intrusive sheets, as adinole development is only seen adjacent to dolerite sills in other less-tectonized parts of the aureole. However, the majority of the Tater-du basic hornfelses exhibit small diopside-rich lenses and spots, now drawn out parallel to the foliation, which may have originally been infilled vesicles in a sequence of lavas. The mimetic growth of contact-metamorphic minerals accentuates the early shear foliation and locally this produces a banded rock composed of various, nearly monomineralic, layers – typically amphibole, biotite or diopside (Figure 4.22). Some of the more lenticular structured hornfelses show weather-resistant amphibole phacoids surrounded by deeply eroded, pale-purple, biotite rims. The hard phacoids might have originally represented the more crystalline cores of metamorphosed pillow lavas; the altered glassy rims (altered to chlorite) were subsequently replaced by biotite during contact metasomatism.

The normal basic hornfelses are mainly composed of the ilmenite–plagioclase–hornblende assemblage with variable replacement of the amphibole by biotite, representing the introduction of K from the granite. Some bands feature calciferous zones with the development of diopside and labradorite in lenses and the replacement of primary ilmenite by sphene in the matrix. This feature can be seen throughout the site, but is well displayed in the small quarry behind the lighthouse, where the calciferous lenses may represent metamorphosed vesicle infillings. The normal assemblages were largely developed by the isochemical metamorphism of basic volcanics under hornblende hornfels facies conditions.

In addition to these dominant assemblages, unusual hornfelses are well developed on the rock platforms under the main cliffs and towards Tater-du Point. Two groups may be observed: Mg-rich hornfelses and Ca-rich hornfelses. The lower portion of the cliffs consists of lenticular, variably biotitized hornblende hornfelses with large white lenses of diopside. Below and interbedded with this horizon is a conspicuous highly foliated biotite–cummingtonite hornfels with black lenses of cummingtonite-rich rock weathering less than the biotitic matrix. Traced towards Tater-du Point, these rocks become more massive, lustrous black in colour, and are represented by cordierite–anthophyllite hornfelses. This small section demonstrates the lateral gradation from normal hornfelses through to cummingtonite-bearing and finally anthophyllite-bearing types. On the same rock platforms, but below the pelitic wedges, is a small outcrop of the Ca-rich hornfels or skarn. This highly weathered mass replaces both the hornblende hornfelses below and the

Figure 4.22 Typical, banded, basic hornfels of volcanic origin, composed of dark layers of hornblende and biotite, with light-coloured, segregation lenses of diopside. Tater-du, Cornwall. (Photo: P.A. Floyd.)

adjacent pelites, such that fragments of adinole are found within the skarn deposit. The skarn is dominated by grossularite and diopside, although sphene, zoisite, clinozoisite, axinite and calcite are also present. In the contact zone with the basic hornfelses, diopside and garnet replace hornblende and plagioclase, and sphene nucleates on ilmenite.

Interpretation

The significance of this locality concerns the paragenesis and range of hornfelses produced by the contact metamorphism and metasomatism of originally basaltic volcanics. Not only have normal hornblende-bearing contact hornfelses been produced, but also two groups of unusual hornfelses that are genetically complementary and chemically linked. In particular, they demonstrate both the importance of original composition and the effects of local metasomatism on the final metamorphic assemblage. Their development is the same as similar exotic hornfelses from Botallack (discussed above), with contact-metamorphic effects acting on variably degraded basaltic volcanics, together with localized element migration under hydrothermal conditions. The lateral gradation of hornblende hornfelses into both the Mg-rich and Ca-rich hornfelses is important field evidence for the origin of the unusual hornfelses from the initial basic assemblages. However, mineralogical relationships and replacements suggest two different, but complementary, processes. The normal hornfelses represent basic volcanics that have been only slightly altered by previous regional metamorphism, whereas the Mg-rich hornfelses were developed isochemically from highly degraded, carbonate-poor but chloritic metabasics, as direct mineral replacements are rare. On the other hand, the skarn deposits show ample evidence for replacement of the normal hornfels assemblage, as well as progressive internal replacement of previous calc-silicates. After the initial assemblage of sphene–diopside–grossularite was produced under hornblende–hornfels–facies conditions, a retrogressive phase started with the replacement of garnet by clinozoisite and zoned axinite, and finally all minerals by calcite (Floyd, 1965). As at Botallack, the involvement of granite-derived fluids is indicated here by the presence of B-bearing axinite during the later phases of skarn development.

Conclusions

Tater-du shows rocks of late Devonian age (around 370 million years old) that have been so severely affected by later geological events that there is little direct evidence of their original composition, although they are believed originally to have been basalt lava flows. They have been altered to different hornfelses, the product of mineralogical and chemical alteration largely induced by contact with the emplacement of the adjacent Land's End Granite. The different types of mineral assemblages within the hornfelses indicate different phases of replacement both prior to and during granite intrusion. This is a key site for studying the complexities of chemical and mineralogical change brought about by element mobility and the reactions that occur in rocks of differing composition and origin.

B8 PENTIRE POINT–RUMPS POINT (SW 923805–SW935812)

Highlights

This classic British site for the study of pillow lavas, is one of the best exposed in Cornwall. The alkali-basalt lavas are only weakly metamorphosed and a massive metadolerite (greenstone) is also well exposed.

Introduction

This scenic section of the north Cornish coast includes the steep 80–100 m high cliffs around Pentire Point and also the rocky crags of the The Rumps Peninsula. The latter has a prehistoric cliff castle and is joined to Pentire Point proper by a neck of land showing the now subdued remains of an ancient earthwork.

During the late Devonian, the main expression of magmatism associated with basin development was the production of localized pillow-lava sequences. The north Cornish coast from Pentire Point westwards to Port Isaac shows many isolated examples of pillow lavas, although the best-exposed sequences are found along the Pentire cliff section. These rocks were some of the first lavas of submarine origin to be recognized in Britain (Whitley, 1849). The Pentire Point pillow lavas were described in detail by Reid and Dewey (1908) and Dewey and Flett (1911) and provided evidence for early ideas as to their mode of formation (Reid *et al.*, 1910; Dewey, 1914). To early workers like Dewey (1914), pillow lavas were individual spheroids, each representing a 'thick-walled bubble of lava' and, together with their highly vesicular nature, he suggested that each lava droplet welled up independently to form a buoyant, gas-filled, floating pillow. Another interesting feature of the initial work on the Pentire pillows was the notion that 'vapours' or 'juices' trapped within the lava reacted with the hot, partially crystallized rock to produce the alteration assemblages we recognize today as the effects of post-consolidation metamorphism (Vallance, 1965).

Description

The steep east–west orientated cliffs of Pentire Point and the rock platforms below, show the underside of the pillow lava sequence in longitudinal section. Here the lavas can be seen to be elongate tubes drapped over each other, with the pillow interspaces filled with chert or sometimes calcareous argillite.

On the other hand, cross-sections (seen on joint faces at right angles to the cliffs) are characteristically ovoid in shape with each pillow moulded over the ones below, providing evidence for 'way-up' and a southwards-younging direction. The total cliff section is composed of three main pillow-lava domes, separated by argillite that laps on to the sides of the domes as well as eventually enveloping them completely (Figure 4.23).

Stratigraphically, the pillow lavas are Frasnian in age and they form the basal part of a sequence of Upper Devonian slates that are slightly overturned and which young southwards, away from the coast. They comprise the Pentire Pillow Lava Group (Gauss and House, 1972), which is about 450 m thick and includes various pillow-lava horizons and subordinate tuffaceous sediments and agglomerates in the local area. The Upper Devonian here is allochthonous, the pillow lavas forming part of the Port Isaac Nappe (Selwood and Thomas, 1986a). They are chemically distinc-

Figure 4.23 View of Pentire Point cliffs showing Upper Devonian pillow-lava mounds. (Photo: P.A. Floyd.)

Figure 4.24 Pillow-lava breccia formed by fragmentation on cooling soon after submarine extrusion. Pentire Point, Cornwall. (Photo: P.A. Floyd.)

tive, relative to the west Cornish tholeiitic lavas of similar age in the Penwith Peninsula, in being alkali basalts with intraplate chemical features (Floyd, 1982a, 1983).

The pillows are generally 0.3–0.6 m in diameter, rarely over 1 m, and are highly vesicular. Some show a series of vesicular zones separated by massive lava and a central vacuole. The vesicles are now filled with chlorite at the margins and carbonate and/or silica in the interior which appears to have replaced earlier chlorite or smectite. Originally glassy margins are no longer seen, either having spalled off during extrusion or been completely replaced by secondary chlorite. Small, black, wispy fragments of laminated argillite may be seen within some pillows, and these represent partly consolidated sediment entrapped during extrusion. Although relatively uncommon, pillow breccias (Figure 4.24) are present, situated near the margins of the lava domes. These demonstrate the partial fragmentation of the lavas along both radial and concentric cooling joints within the pillows (Figure 4.25). The breccias have suffered minimum downslope movement, as individual fragments can often be fitted together jigsaw fashion.

Although now metabasalts, the pillow lavas still display features that can be used to infer their primary characteristics. The lavas are plagioclase-phyric, with lath-shaped microphenocrysts and skeletal microliths, now converted to secondary albite. The microliths may be curved and sometimes show tuning-fork terminations indicative of rapid quenching. The matrix is largely composed of chlorite, carbonate and oxidized materials which probably replaced original glass. No primary mafic minerals remain. Stable-element chemical data demonstrate that the Pentire lavas form a single differentiated suite of basalts which were not comagmatic with the intrusive dolerite at The Rumps. One interesting chemical feature concerns the location of stable elements in the altered pillow basalts. A study by Williams and Floyd (1981) showed that elements like Ti, Zr and Nb are relocated on alteration into stable secondary phases like rutile and zirconolite. On the other hand, U migrated throughout the matrix, eventually concentrating around vesicle margins and sometimes, within the infilling calcite, giving it a cloudy appearance.

The pillow-lava sequence is underlain by the Middle Devonian Trevose Slate Formation which

Figure 4.25 *In situ* autobrecciation of a lava pillow. Pentire Point, Cornwall. (Photo: P.A. Floyd.)

has been intruded by a massive greenstone sill at The Rumps. Separated from Pentire by a small fault, this body is typical of differentiated dolerite-gabbro intrusives often associated with lavas, although in this case there is no evidence for high-level emplacement or chemical association with the lava sequences. The body exhibits a sharp concordant junction with the sediments which are bleached and indurated, but not adinolized. One feature of interest shown by the greenstone is the effect of intense shearing that has granulated and foliated the body into highly oxidized chloritic schist zones.

Interpretation

The interest of this site is that it not only represents one of the classic pillow-lava locations in Britain, but is typical of the major episode of extrusive late Devonian activity within the Variscan fold belt, such as that exhibited in the Harz Mountains and Lahn-Dill in Germany. It was here that some of the early ideas concerning pillow-lava development were formulated and enabled the correlation with similar, but more extensive, volcanism of similar age within the Rhenohercynian Zone of Germany to be made. In tectonic terms, the volcanic activity represents the onset of basinal development, with magma penetrating marginal fractures that mark the site of the change from platform to slope. They are also typical of Variscan spilites, characterized almost entirely by secondary assemblages, which were at one time considered to have been produced by late primary magmatic (deuteric) processes. We now recognize these lavas as low-grade metamorphosed basalts.

This site is significant in the magmatic history of Variscan south-west England, as the lavas are plagioclase-phyric alkali basalts with enriched incompatible-element patterns, forming a province quite distinct from temporally analogous pillow lavas in south Cornwall. They exhibit chemical features typical of intraplate volcanics that are also characteristic of many lavas within the Variscan fold belt of Northern Europe.

Conclusions

This is a key site for the study of Upper Devonian submarine lavas and has been studied since the middle of the nineteenth century, when it was realized that the peculiar pillow-shaped masses of lava, normally up to a metre across, were the product of eruption of basalt lava into sea-water. Rapid chilling by the sea-water produced glassy margins which often spalled off or completely fragmented the pillow into small angular blocks. Similar pillow lavas may be seen forming today where submarine volcanism occurs, producing rounded or sausage-shaped extrusions on the sea-bed, venting bubbles of gas. At Pentire Head, the lavas and subordinate fragmented volcanic rocks make up a 450-m-thick pile locally. The lavas were originally basalts, although they have been altered subsequently under conditions of low-grade metamorphism during the Variscan Orogeny. Pillow lavas are characteristic of a major phase of volcanic activity in the Devonian and Carboniferous seas of Variscan Europe; this is one of the classic sites where they were first studied and attempts made to explain their form, chemistry and origins.

B9 CHIPLEY QUARRIES (SX 807712)

Highlights

This is a classic site for the study of pillow lavas. Unusually, these vesicular, shallow-water, pillowed alkali basalts can be dated precisely here from their association with fossiliferous sediments.

Introduction

This site includes the two small disused quarries on the wooded hillside adjacent to the Chipley–Bickington road. The site is situated in a classic late Devonian region which is now recognized as allochthonous and as forming part of the southerly derived Chudleigh Nappe (Selwood and Thomas, 1986a).

Some of the earliest descriptions of the volcanic rocks of this region of south Devon were made by Champernowne (1889). The detailed petrography of the Chipley pillow lavas was initially described by Flett (*in* Ussher, 1913), and he included a single major-element analysis. The lava sequence here is situated within the grey Gurrington Slate Formation which has yielded ostracods (*hemis-*

phaerica–dichotoma biozone) indicative of a Famennian age (Middleton, 1960). Although part of the major late Devonian extrusive activity in south-west England this contrasts with the Frasnian age of similar pillow lavas at Pentire Point (discussed above). Geochemical work indicates that the Chipley lavas are also intraplate alkali basalts, although they can be distinguished from the Pentire sequence by different incompatible-element ratios and light-REE-enrichment patterns (Floyd, 1982a, 1983). Both occurrences, however, are characteristic of the 'spilite suite' which has counterparts within the Rhenohercynian zone of northern and central Europe, and whose origin and composition have long been debated (for instance, Juteau and Rocci, 1974; Wedepohl *et al*., 1983).

Description

The Chipley pillow lavas (Figure 4.26) are similar in many respects to those at Pentire Point and are excellent examples of extrusive submarine activity. Both of the quarries in the site exhibit a *c*. 30 m sequence of tectonically flattened, but well-formed, closely fitting lava tubes with negligible interpillow sediment. Good ovoid cross-sections are visible, displaying the highly vesicular (up to 50% volume) nature of the lavas (Figure 4.27). Vesicles are smaller at the margins than towards the core, although central vacuoles are uncommon. The high degree of vesicularity of the pillows suggests extrusion into relatively shallow water (<500 m depth). However, the basalts were originally alkaline and, as such magmas often contain a relatively high volatile content, the degree of vesiculation may not always be a reliable guide to the depth at which extrusion occurred.

The pillow lavas were originally plagioclase-phyric alkali basalts, but are now completely degraded to low-grade metamorphic assemblages with no primary minerals remaining. Both phenocrystic and matrix plagioclase are now converted to secondary albite, set in a matrix composed of variable chlorite, quartz, carbonate, epidote, prehnite, sphene, magnetite and leucoxene – a typical spilite assemblage. Plagioclase microlites may be skeletal or form long, curved crystals, sometimes with tuning-fork terminations; features which are indicative of rapid quenching in a submarine environment. Much of the fine-grained chloritic matrix probably represented original glass. Vesicles are infilled with chlorite or more rarely prehnite, both of which may be replaced by quartz or carbonate.

Interpretation

Owing to the low-grade, altered nature of the lavas, it is only possible to determine their original magma type by using incompatible elements that are stable during secondary alteration. These indicate that the lavas are alkali

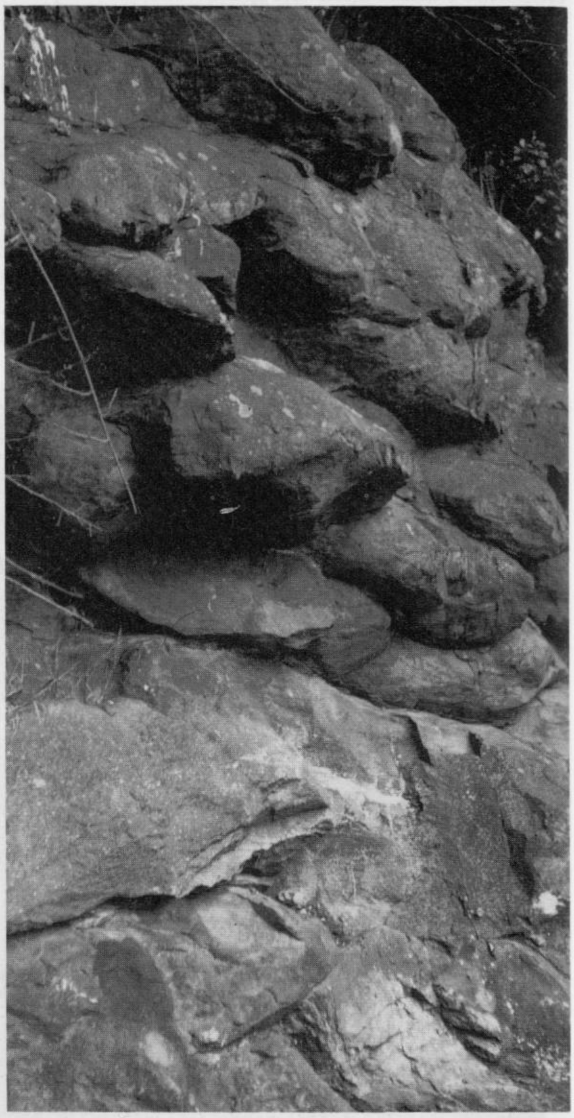


Figure 4.26 Upper Devonian pillow lavas of alkali-basalt composition. Chipley Quarries, Devon. (Photo: P.A. Floyd.)

basalts with an overall composition similar to other extrusives and intrusives within the north Cornwall and Devon magmatic province (Floyd, 1982a; Rice-Birchall and Floyd, 1988).

Late Devonian basaltic activity was often associated with the development, especially the deepening of basins, although there were environmental differences between north Cornwall (with the Pentire lavas) and south Devon (with the Chipley lavas) during this period. For example, the latter area saw the extensive development of carbonate-dominated facies, with thin, condensed sequences of Upper Devonian, pelagic, nodular carbonates and mudstones developed on submarine rises (House, 1963, 1975). These grade into adjacent, deeper-water, basinal argillites which contain the local pillow lavas encompassed by this site. Their development near a submarine rise is different from broadly similar lavas at Pentire Point in Cornwall, which developed on the northern margin of a deepening fault-controlled trough (Selwood and Thomas, 1986b). Chemically, the pillow lavas are also characteristic of the north Cornwall and Devon magmatic province of alkali volcanics (Chapter 2).

Conclusions

This locality has been studied since the late nineteenth century when it was realized that the peculiar pillow-shaped masses were the result of the eruption of basalt lava into sea-water. At Chipley the pillow lavas are shot through with voids (vesicles) which were originally the site of gas bubbles. As a result of the sudden release of pressure and rapid chilling on the extrusion of individual pillow flows, gas was forced out of solution in the volatile-rich lava, leaving the solidified rock full of voids. The Chipley basaltic lavas have been altered and their original mineralogy replaced by secondary minerals (cf. Pentire Point), although textures still preserve evidence of rapid chilling. Laterally the lavas may be traced out into the sedimentary rocks which were deposited as mud on the deep sea-bed. Volcanic activity occurred here at the very end of the Devonian period around 360 million years ago. Chipley differs from the pillow-lava site at Pentire Head (of about the same age) in terms of the chemical composition of the basalts and its eruptive setting.

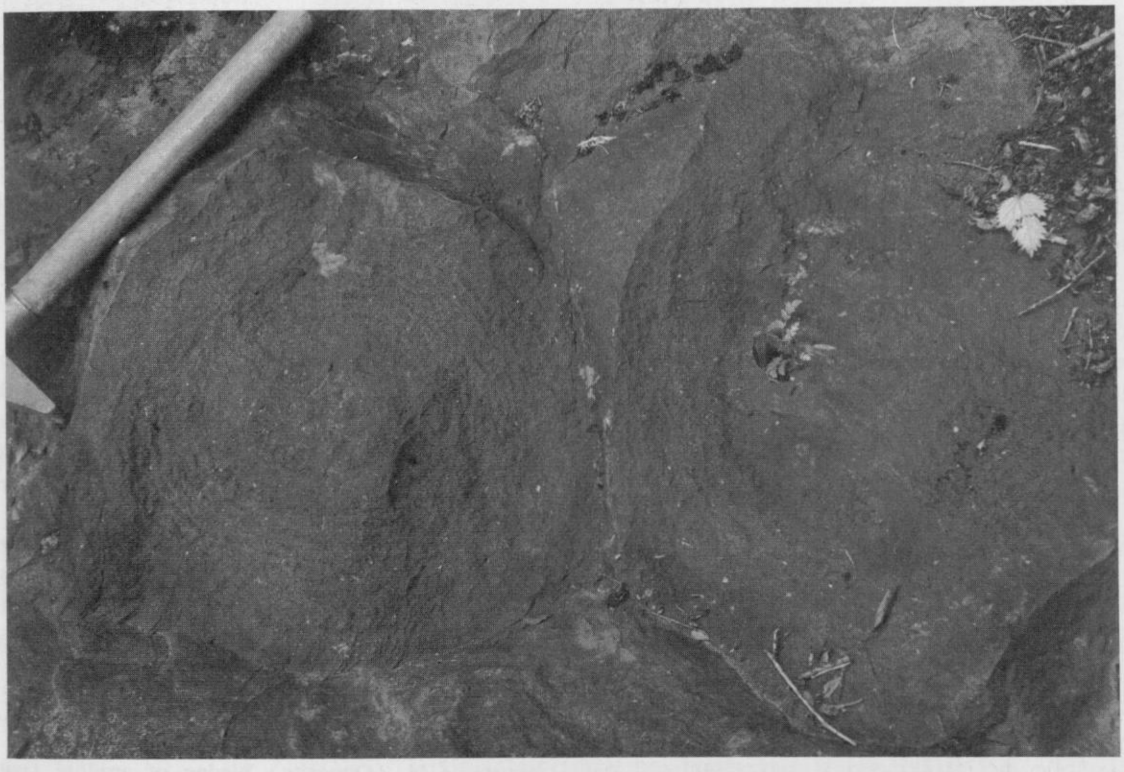


Figure 4.27 Cross-section through two pillows showing the high degree of vesicularity and its concentric disposition. Chipley Quarries, Devon. (Photo: P.A. Floyd.)

B10 DINAS HEAD–TREVOSE HEAD (SW 847761–SW 850766)

Highlights

This site is the best in south-west England and a classic in Britain for the study of the progressive development of adinole at the contact between a dolerite intrusion and its enclosing sediments.

Introduction

This scenic coastal site includes the rocky, terraced cliffs of Dinas Head from Mackerel Cove to Stinking Cove, and the rock platforms around Trevose Head lighthouse (Figure 4.28). The old quarry at the back of Stinking Cove is also included.

Apart from the massive intrusive greenstone which was described by Reid *et al.* (1910) and later by Agrell (1939), interest in this site has centred on the contact effects of the body on the adjacent sediments. One of the characteristic features of some large, sill-like intrusions, is the development of a narrow contact aureole of intensely Na + Si-metasomatized sediments called spilosites and adinoles. Fox (1895) initially noted the development of these adinoles as metasomatized sediments, whereas their particular pseudospherulitic texture was commented on by McMahon and Hutchings (1895). The Dinas Head adinoles were also mentioned by Dewey (1915) who demonstrated the importance of sediment composition in the production of adinoles, with Fe^{3+}-poor, grey and black argillites being readily altered to adinoles. A more extensive survey of adinolization in the area (Agrell, 1939, 1941) showed that the abnormally large metasomatic zone at Dinas Head was a function of the intimate penetration of the sediments by many sill-like offshoots from the top of the intrusive mass.

Description

The sedimentary rocks here are laminated Upper Devonian black and blue-grey argillites; they form part of the Port Isaac Nappe (Selwood and Thomas, 1986a). The sediments occupy the rib of Dinas Head, although as sea-level is approached, they become progressively metasomatized and penetrated by tongues of greenstone (metadolerite). The sedimentary rocks/greenstone junction is often irregular with random ramifications and entrapment of sedimentary wedges. The first effects seen of contact metamorphism are the development of chloritic and incipient cordierite spotting, as well as the growth of andalusite prisms (Agrell, 1939). Partially metasomatized argillites (spilosites) retain the original slaty cleavage, but show the development of quartz–chlorite and porphyroblastic albite 'spots', together with tourmaline and leucoxene. Completely metasomatized argillites (adinoles) consist largely of quartz–albite assemblages with variable carbonate content. Original spots and andalusite are now pseudomorphed by quartz–chlorite or carbonate–chlorite. The progressive metasomatic changes are well displayed in a section from the top of Dinas Head down to sea-level towards the intrusive. However, spilosites and adinoles may often be interbedded, reflecting changes in the original composition of the sediments rather than distance from the intrusive contact. A number of different textural types have been recognized in the metasomatized sediments by Agrell (1939).

The majority of the greenstone is a fine- to medium-grained, subophitic alkali metadolerite with occasional relicts of primary clinopyroxene set in an altered low-grade matrix. The pyroxene may be partially replaced by a fringe of uralitic actinolite or completely pseudomorphed by actinolite and chlorite. Plagioclase is now albite, but may also be replaced by sericite, epidote, prehnite and carbonate. Chlorite, albite and carbonate are common secondary minerals throughout the finer-grained marginal facies. Skeletal ilmenite may be leucoxenized or rimmed by replacive sphene granules. Apatite needles are relatively rare.

The general shape of the greenstone mass appears sheet-like, but its junction with the sediments is very irregular on the medium scale (several metres) and a number of separate large tongues penetrate the sediments to the north and south of Dinas Head. In the quarry, which is topographically above the Dinas Head part of the greenstone, the very high-level nature of the upper surface can be demonstrated. Much of the greenstone here is very fine grained and contains

Figure 4.28 (Opposite) Wedge of argillite (pale-coloured cliffs) resting on dark intrusive dolerite near sea-level. Trevose Head, Cornwall. (Photo: P.A. Floyd.)

flattened and aligned chlorite-filled ovoid vesicles. Small wedge-shaped rafts of laminated and adinolized sediments are also present within the greenstone, which shows irregular cuspate margins indicative of intrusion into water-bearing, partly consolidated, sediment. Fallen blocks lying on the quarry floor exhibit pillow structure with small, surface-aligned vesicles in the rim zone and larger, circular vesicles in the pillow core. The top of the quarry also exhibits a number of thrusts that separate the fine-grained marginal facies of the greenstone from black, unaltered (non-adinolized) laminated sediments. The thrusts trace an irregular surface over the resistant greenstone, below which may be heavily quartz veined and sometimes foliated at the junction.

Interpretation

Agrell (1939) considered the Na + Si-rich metasomatizing fluids were derived from the basic igneous rock, driving all other constituents out of the adjacent sediments and precipitating albite and quartz. However, one feature not mentioned is that there is evidence for soft-sediment deformation at the margins of the body, suggesting that intrusion was into only partly consolidated sediments. These would still have retained sea-water in sediment pore spaces, which could have become an active metasomatizing fluid on heating by the intrusion. In this model, the metasomatizing agents are obtained from the sediments and not the basic intrusion. In general terms, therefore, extensive adinolization appears only to be developed adjacent to high-level massive bodies where there is evidence for intrusion into partly consolidated wet sediments. In other cases, where the intrusion took place at a deeper level and the sediments are relatively 'dry', only isochemical thermal effects are observed adjacent to massive bodies.

One of the main features illustrated by this greenstone is its irregular nature and evidence for high-level intrusion into partly consolidated sediments. The large size of the body and the degree of lateral penetration into wet sediments are probably the main reasons for the extensively developed contact zone of adjacent metasomatized sediments. The development of the adinoles and spilosites is of considerable significance as they represent one of the few classic British occurrences of such metasomatized rocks and certainly the best example in the Variscan of south-west England. However, it has been generally assumed that the metasomatic fluids were derived from the igneous body itself, whereas a more likely mechanism is that they were mobilized by the heat of the intrusion from within the wet, partly consolidated, sediments. In this context the nature of the contacts with the sediments and the general shape of the body is considered important.

Conclusions

Here is seen a large irregular, high-level intrusive 'greenstone' body (originally a dolerite) that was emplaced into and altered the still wet and unconsolidated enclosing sediments. The hot magma not only deformed the sediments but caused localized chemical changes in their bulk composition (metasomatism). Some of the less-altered or metasomatized sedimentary rocks still retain their original sedimentary laminations (termed spilosites), whereas others have nothing remaining of their original texture or minerals (termed adinoles) and are totally replaced by new phases. This is an important site at which to study the effects of thermal and chemical change caused by basic intrusions on adjacent fine-grained sediments.

B11 TREVONE BAY (SW 890762)

Highlights

This locality provides the best exposure of one of a suite of unusual, hydrous, potassic metadolerites found in north Cornwall. The pumpellyite facies of regional metamorphism is also well seen.

Introduction

The intrusive body constituting the interest of this site is located in the small cliffs and rock platforms along the east side of Porthmissan beach towards Roundhole Point.

The majority of the massive intrusive greenstones of the Variscan were originally subophitic dolerites with a primary anhydrous mineralogy. Both tholeiitic and alkaline types are present, with the latter restricted to north Cornwall and Devon. However, apparently confined to the Upper Devonian are another set of greenstones that are mineralogically and chemically distinct and referred to as 'proterobases' or 'minverites' (after the type locality at St Minver, north of Wadebridge) in the early literature (Reid *et al.*, 1911; Dewey, 1914). This suite is characterized by having a primary hydrous assemblage and an overall alkaline composition and features (in fresh samples) high levels of large-ion-lithophile elements, such as K, Rb, Ba and the light-REE (Dewey, 1914; Floyd and Rowbotham, 1982). Relative to the commoner greenstone type of anhydrous sodic metadolerites, these rocks can be classified as hydrous potassic metadolerites.

The site illustrates an example of this greenstone type; it is situated within the grey, Upper Devonian slates of the Port Isaac Nappe. The presence of secondary prehnite and aluminous pumpellyite, along with other alteration minerals, in the greenstone indicate that the area reached the pumpellyite facies of regional metamorphism during the Variscan Orogeny (Floyd and Rowbotham, 1982).

Description

The sill-like basic body here is very variable in texture and grain size, grading from fine-grained, granular dolerite to subophitic gabbro containing large, lustrous black clinopyroxenes, that often weather out on joint surfaces. The central portion of the body may have irregular pegmatitic zones, these were initially composed of large clinopyroxene prisms (5–10 mm long), but are now invariably replaced by green chlorite. Although altered to varying degrees, petrographic relationships between the main primary phases are easily discernible, and these illustrate a crystallization history under falling temperature and increasingly hydrous conditions. Minor original olivine (now occurring as chloritized ovoids) is totally enclosed in large plates of titaniferous clinopyroxene (salite) that have been selectively replaced, in a magmatic reaction relationship, by brown kaersutite (Figure 4.29). The amphibole may also be fringed with titaniferous, dark-brown biotite of magmatic origin. Microprobe analyses of the

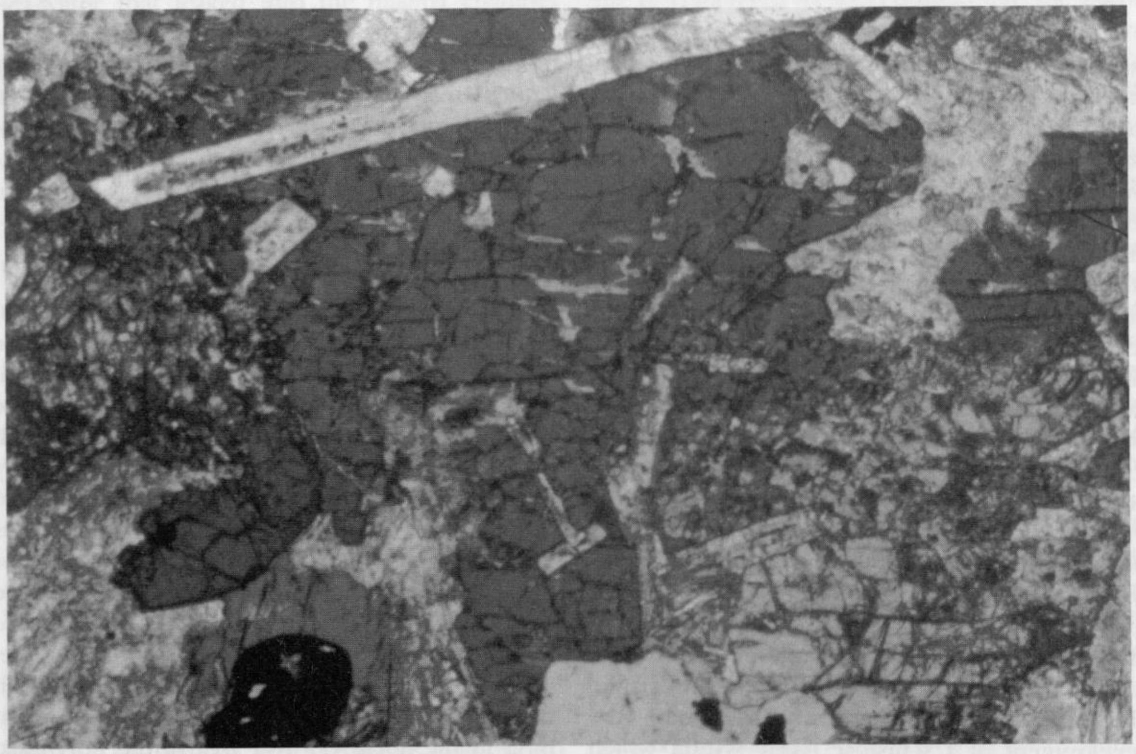


Figure 4.29 Photomicrograph of a hydrous dolerite showing large irregular crystal of dark, primary, kaersutitic amphibole replacing colourless clinopyroxene (bottom right); long needle-like apatite crystal traverses the amphibole unaltered (top). Trevone Bay, Cornwall. (Photo: P.A. Floyd.)

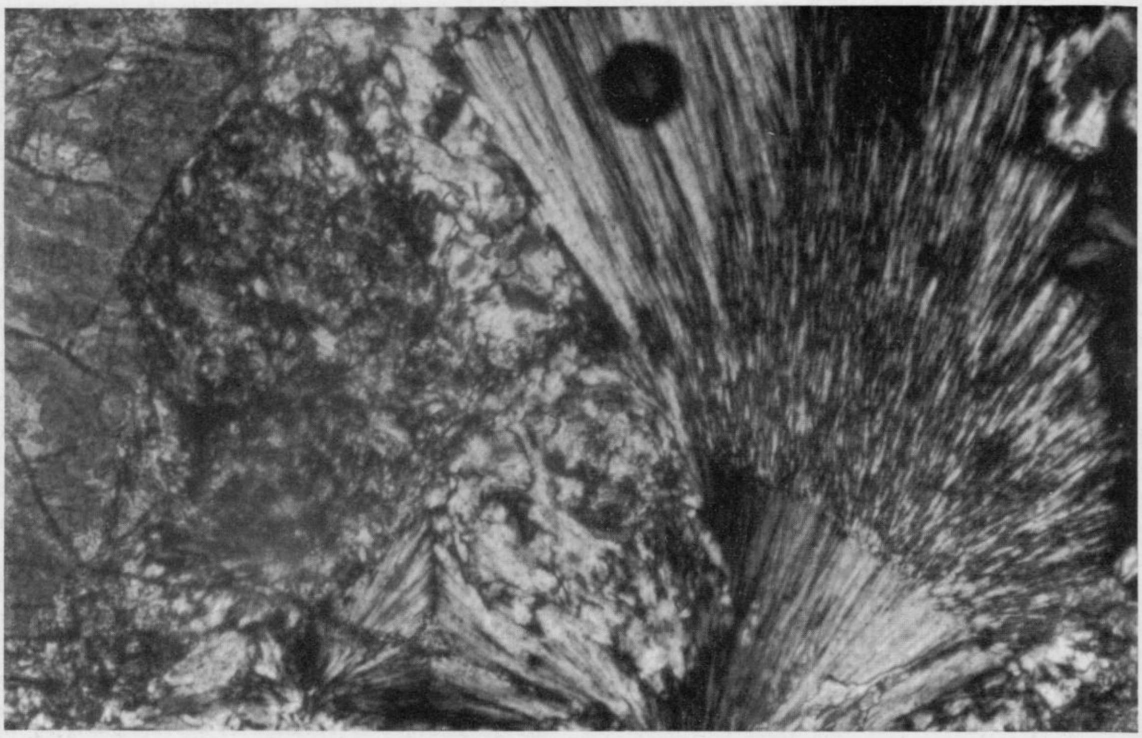


Figure 4.30 Photomicrograph of a hydrous dolerite showing the fan-like growth of secondary Al-rich pumpellyite that replaced the original plagioclase. Trevone Bay, Cornwall. (Photo: P.A. Floyd.)

primary amphibole by Floyd and Rowbotham (1982) showed that it was a kaersutite, rather than 'barkevikite' or brown hornblende as reported in the earlier literature (for example, Dewey, 1914). Mineralogically, the rock is characterized by the titaniferous nature of the major mafic phases, as well as the abundance of large, cored apatite crystals. Apart from the primary mineralogy, the metadolerite also exhibits a secondary assemblage typical of the pumpellyite facies of regional metamorphism (Floyd and Rowbotham, 1982). Together with the characteristic prehnite and colourless pumpellyite (Figure 4.30), albite, chlorite, actinolite, sphene, muscovite and epidote are also present.

Although the greenstone has a sill-like intrusive form, the upper fine-grained contact at Roundhole Point appears to be pillowed, with minor adinolization of the adjacent sediment. However, the contact zone is complex and both greenstone and sediments have been sheared and brecciated. The greenstone is often tectonized, with the development of a schistose fabric within which are resistant phacoids of coarser metadolerite, whereas the sediments show rolled adinole and rusty, pyritous sandstone phacoids set in a grey fine-grained matrix. However, where an actual contact is visible it is very irregular and often cuspate, suggesting intrusion into wet sediment.

Interpretation

This site illustrates one of the more unusual intrusive greenstone types found within the Variscan of south-west England. It is mineralogically and chemically distinct from the more normal alkaline sodic dolerite of north Cornwall and Devon, being characterized by a primary hydrous assemblage (amphibole and biotite) and enrichment in the large-ion-lithophile elements (K, Rb, Ba, light-REE). In particular, the major mafic minerals are highly titaniferous, the ore phase is ilmenite and abundant cored apatites are features typical of this potassic dolerite suite. These intrusives appear to be emplaced only in Upper Devonian strata and are particularly common in the north Cornish area of the Port Isaac Nappe. It is speculated here that some of the water available for the primary crystallization may have been sea-water that penetrated the original magma chamber which fed these high-level intrusions.

The other main feature of this site is the presence of a secondary assemblage which indicates the area underwent relatively low-grade pumpellyite-facies metamorphism during the Variscan. The secondary alteration of basic rocks can be used to determine metamorphic facies and in this respect shows that the grade here was lower than the greenschist facies of the Tintagel area just to the north-east (Primmer, 1982), although similar to south Cornwall.

Conclusions

At Trevone Bay, a massive greenstone (altered dolerite) intrusion can be seen, which still preserves evidence of the original mineral assemblage that crystallized from the magma. In addition to the usual olivine–pyroxene–plagioclase, this assemblage is distinct from other intrusive dolerites in containing primary hydrous phases (amphibole and biotite) and abundant apatite. These features indicate that the melt contained abundant water possibly derived from sea-water that leaked into the magma chamber situated at a high level in the crust. The other primary characteristic is the enrichment in many trace elements (K, Rb, Sr, Nb, Zr and P) that indicates that these rocks were derived from a distinct mantle source relative to other greenstones.

B12 CLICKER TOR QUARRY (SX 285614)

Highlights

The ultramafic rocks of this site are unique in the Variscan of south-west England in that they contain fresh olivine. They differ greatly from the ultramafic rocks of the Lizard Complex.

Introduction

The site consists of the walls of the disused and flooded elongate quarry at Lower Clicker, just south of Menheniot. The distinctive, blue-green rock has been extensively quarried for road metal since the early nineteenth century.

The Clicker Tor ultramafic body (Figure 4.31) occurs within the Middle Devonian (largely Givetian) Milepost Slate Formation (Burton and Tanner, 1986) and is closely associated with basic intrusives, as well as pillowed lavas and volcaniclastics (Ussher, 1907). Little recent work has been done on this body, which is referred to in the early Geological Survey literature as an augite picrite (e.g. Reid *et al.*, 1911), although texturally it resembles an ultramafic cumulate. Chemical analyses have been given by Parker (1970).

Description

The mapped form of ultramafic body here and its close association with gabbros (north quarry wall) suggests that it was originally intrusive or part of an intrusion, although the actual contacts with the adjacent sediments are no longer visible. The general lack of internal and marginal shearing could imply that the ultramafic rock unit was not thrust into place as a cold slab, but formed by crystal accumulation from a larger intrusive basic body after emplacement. There has been some minor internal movement, however, as seen by the development of slickensiding and the polishing of joint surfaces coated with asbestiform amphibole.

The brittle, dark-blue rock was originally composed of subrounded cumulate olivine, interstitial clinopyroxene and numerous magnetite granules (Figure 4.32). Plagioclase appears to be absent, although small, highly altered, lath-shaped areas subophitically enclosed by the pyroxene suggest its former presence in very minor amounts. A rare feature for a Variscan ultramafic rocks is the preservation of a little fresh olivine. Much of the rock has been altered or serpentinized, with olivine replaced and veined by serpentine minerals, a colourless amphibole (tremolite?) and chlorite, as well as being peppered with magnetite. A strongly pleochroic fibrous stilpnomelane is associated with or replaces the pyroxene. The overall primary composition and texture of the Clicker Tor mass suggest that it was a cumulate phase produced by the mafic fractionation of a large basic body prior to partial serpentinization.

Interpretation

The importance of this site concerns the presence of a relatively rare ultramafic unit probably

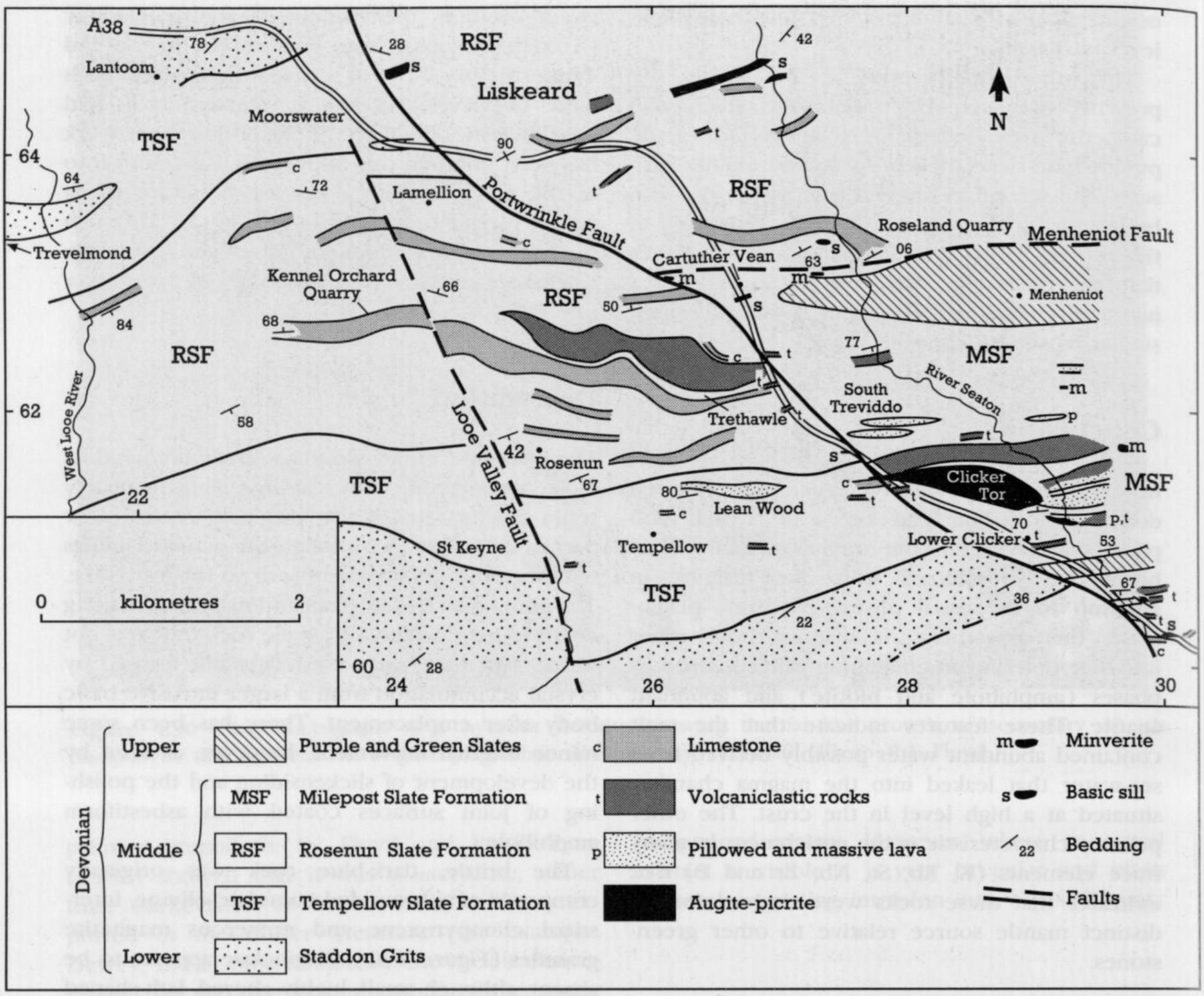


Figure 4.31 Geological map of the area to the south of Liskeard showing the location of the Clicker Tor ultramafic body (after Burton and Tanner, 1986).

derived from associated basic intrusives by mafic fractionation. Texturally, it is an olivine-rich cumulate and it has a similar chemical composition to the ultramafic cumulates of major, fractionated, stratiform basic massifs. It is probably unique for Variscan ultramafic rocks in retaining fresh olivine after partial serpentinization. It is chemically and mineralogically distinct from the ophiolitic Lizard peridotite and in no way resembles a fragmented or tectonized portion of ultramafic rocks commonly associated with ophiolites which are often high Cr–Ni harzburgites. It is also mineralogically different to the Polyphant Complex ultramafics in that it does not contain any primary hydrous phases as sometimes seen at Polyphant (as discussed below). This feature indicates that the cumulates were derived from a fractionating, anhydrous basic body different from those that crystallized primary hydrous phases.

The presence of primary olivine, a single pyroxene and possibly plagioclase indicate that the rock is probably a picritic cumulate rather than a peridotite or pyroxenite. Chemical analyses by Parker (1970), who was principally interested in the chemical and mineralogical effects due to weathering, showed that the fresh rock had high, but variable, MgO (23–28 wt. % range) and TiO_2 contents, but low Ni values (<1000 ppm) that are generally typical of stratiform-related ultramafic cumulates.

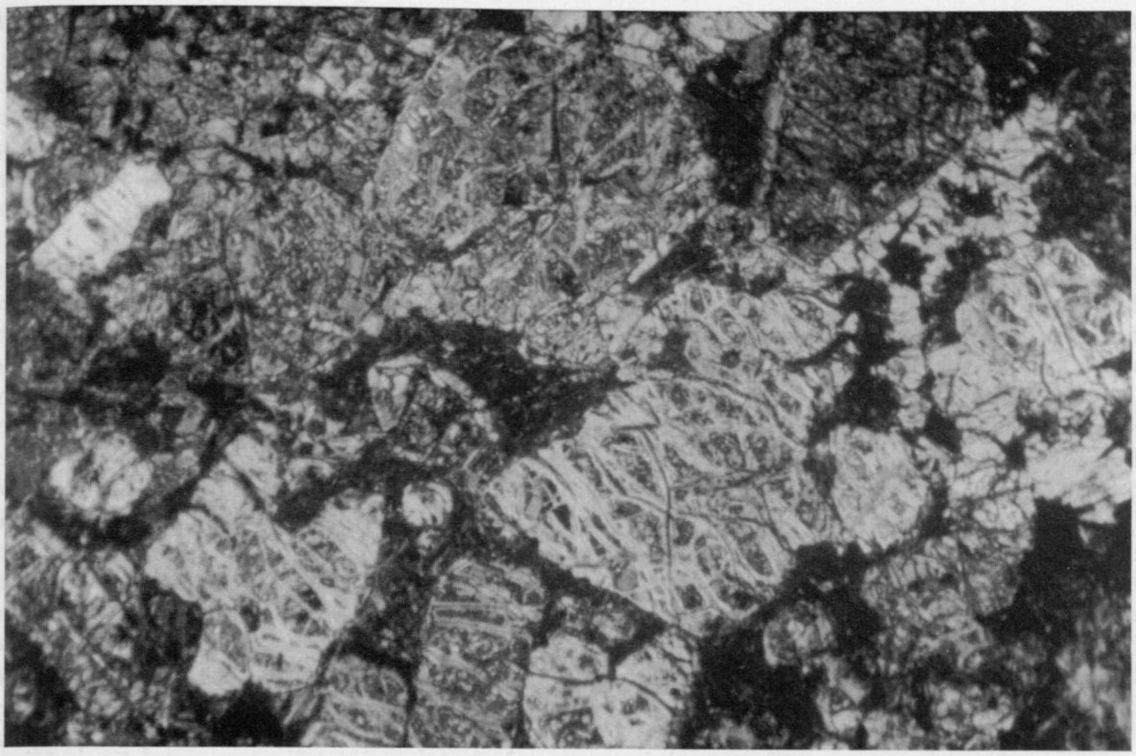


Figure 4.32 Photomicrograph of partly altered olivine crystals (with veins) and intercumulus pyroxene in the ultramafic body at Clicker Tor, Cornwall. (Photo: P.A. Floyd.)

Conclusions

Here a body of ultramafic rock associated with dolerite intrusives is emplaced into Middle Devonian (380-million-year-old) sediments and lavas. The rock is thought to have been formed within a large magma chamber as an accumulation of crystals (cumulate) which settled out during the early phases of cooling of the magma that subsequently crystallized as the adjacent dolerites. It is unique among Variscan ultramafics in showing some fresh olivine, which in similar rocks (Lizard peridotite) is invariably replaced by serpentine minerals. However, much of the body had been altered by the process of serpentinization whereby primary Mg–Fe silicates are variably replaced by serpentine together with amphibole and chlorite. The chemistry of the Clicker Tor body is distinct from that of the ultramafics at Polyphant in this area and in the Lizard Complex.

B13 POLYPHANT (SX 262822)

Highlights

This is the type locality for the assemblage of mineralogically distinctive ultramafic and mafic rocks known as the Polyphant Complex. This complex continues to play a central role in interpretations of Variscan plate tectonics in this region.

Introduction

This site, just to the north-west of Polyphant village, includes the old Polyphant Quarry and the adjacent hillside outcrops to the south of the River Inny. The quarry was the type locality for the famous 'Polyphant stone', a highly altered talcose rock that has been used for ornamental carvings since the eleventh century.

The locality is representative of part of the Polyphant Complex which is composed of an association of ultramafics, gabbros and dolerites intruded into Upper Devonian slates of the Tredorn Nappe (Stewart, 1981).

Geological mapping of the Polyphant Complex shows it is a fault-bounded, NW–SE-extending, ultramafic body with a maximum exposure width of 0.5 km (Stewart, 1981). The actual form of the body is difficult to determine geophysically because it is within the steep gravity gradient of the Bodmin Moor Granite. However, interpretations by Chandler *et al.* (1984) indicate that it is, in fact, a thin slice, about 32 m thick, and not the exposed part of a major, deep-rooted intrusion.

The mineralogy and alteration of the Polyphant ultramafic body was described by Dewey (*in* Reid *et al.*, 1911) who noted the presence of brown amphibole, and also the close association of 'proterobases' (potassic alkaline metadolerites) containing a similar hydrated primary mineralogy. In the early literature these ultramafic rocks were called picrites, although in recent times they have been referred to as peridotites and, according to Chandler and Isaac (1982), they are dominated by lherzolitic compositions.

Unlike some of the other minor ultramafic–mafic associations (see Clicker Tor) the Polyphant Complex as a whole has assumed importance in the study of the tectonic development of central south-west England. According to a pre-thrusting reconstruction for this region and the tectonic model of Isaac *et al.* (1982), the complex was immediately below the Greystone Nappe assemblage which contains Lower Carboniferous lavas and intrusive dolerites with a MORB-type chemistry (Chandler and Isaac, 1982). The apparently close geological and temporal association of Upper Devonian ultramafics and Lower Carboniferous oceanic basalts leads to the suggestion that they were part of a dismembered ophiolite which originally represented a small, short-lived ocean or marginal basin (Chandler and Isaac, 1982; Isaac, 1985). However, according to Selwood and Thomas (1986b) the facies reconstruction does not imply the presence of an ocean basin, and the interpretation of the basic rocks as MORB by Chandler and Isaac (1982), based on chemical features such as Ti–Y–Zr distributions, is open to question (Floyd, unpublished data).

Description

Although most of the ultramafic rocks in the site are serpentinized to some degree, two main lithologies can be conveniently recognized and depend on the relative degree of the secondary alteration. On fresh faces in the old quarry, a variably foliated and highly altered, blue-grey metaperidotite composed of a serpentine–chlorite–talc–carbonate assemblage can be seen. Zones rich in granular magnetite have been oxidized to brown limonite (Figure 4.33). This extreme alteration has apparently developed only at the margins of the ultramafic body due to extensive shearing as it was thrust into place. Less-altered rocks, on the slopes just south of the River Inny, show a primary assemblage of abundant olivine (invariably replaced by serpentine and tremolite) enclosed within purplish clinopyoxene or brown amphibole; the latter of which often exhibits a reaction relationship with the pyroxene (Figure 4.34). Other primary minerals include deep-red biotite, apatite and magnetite; no plagioclase appears to be present. Both the primary amphibole and biotite may be replaced by secondary tremolite and chlorite. Some of these rocks were layered cumulates, composed of mainly olivine and clinopyroxene with intercumulus hydrous fluids that subsequently crystallized amphibole and biotite. A fine banding can also be seen on some weathered surfaces. The Polyphant ultramafic rocks are mainly cumulates associated with basic intrusives that are unlikely to have formed part of a dismembered ophiolitic complex.

Interpretation

Apart from representing an example of the alteration of Variscan ultramafic rocks, the most interesting mineralogical feature at this site is the presence of primary hydrous phases. In this respect they resemble the so-called 'proterobases', or hydrous potassic suite of greenstones, in containing magmatic amphibole and biotite. The significance of the presence of similar hydrous phases could imply that the hydrous ultramafic Polyphant rocks represent the olivine + pyroxene-rich cumulates of a differentiated hydrous greenstone body. Although there are little supportive chemical data available, the Ni and Cr contents (unpublished data, Floyd, 1988) are comparable with cumulates genetically associated with layered or stratiform mafic–ultramafic bodies (Figure 4.4). The mineralogical and chemical evidence mentioned above is important in the light of some studies which interpret these rocks as part of a dismembered ophiolite complex (Chandler

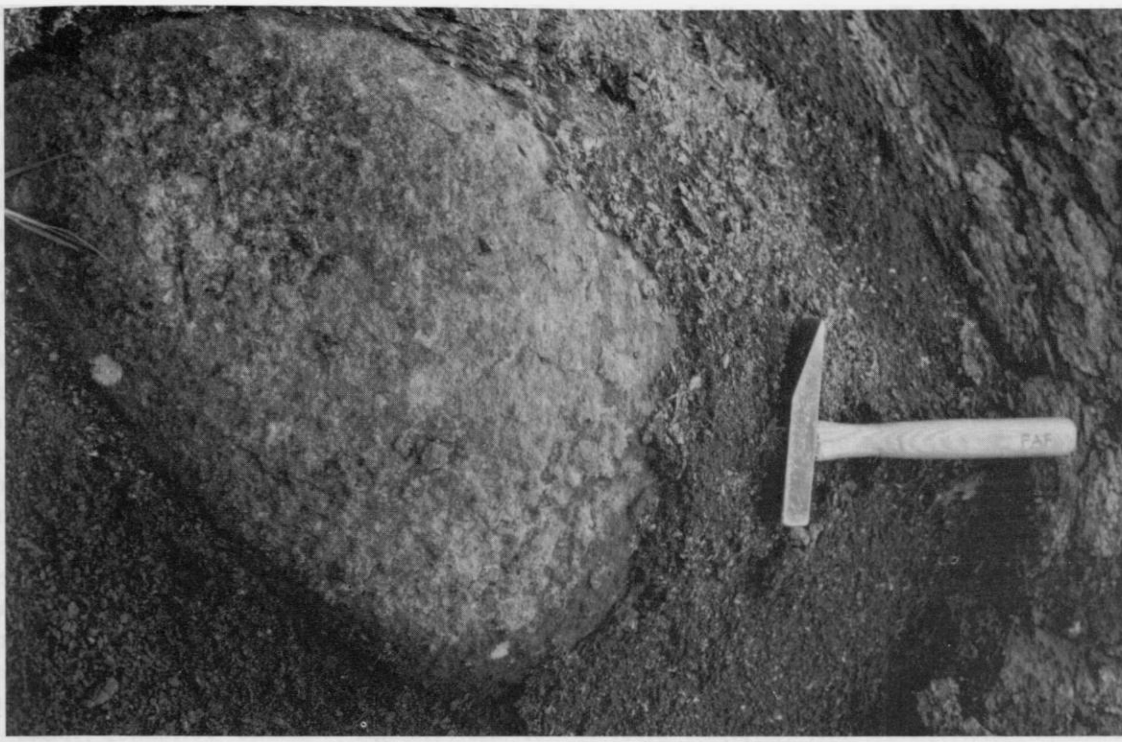


Figure 4.33 Weathering of the Polyphant ultramafic body (hydrous picrite) showing a core boulder of serpentinite within a highly oxidized, degraded matrix. Polyphant, Cornwall. (Photo: P.A. Floyd.)

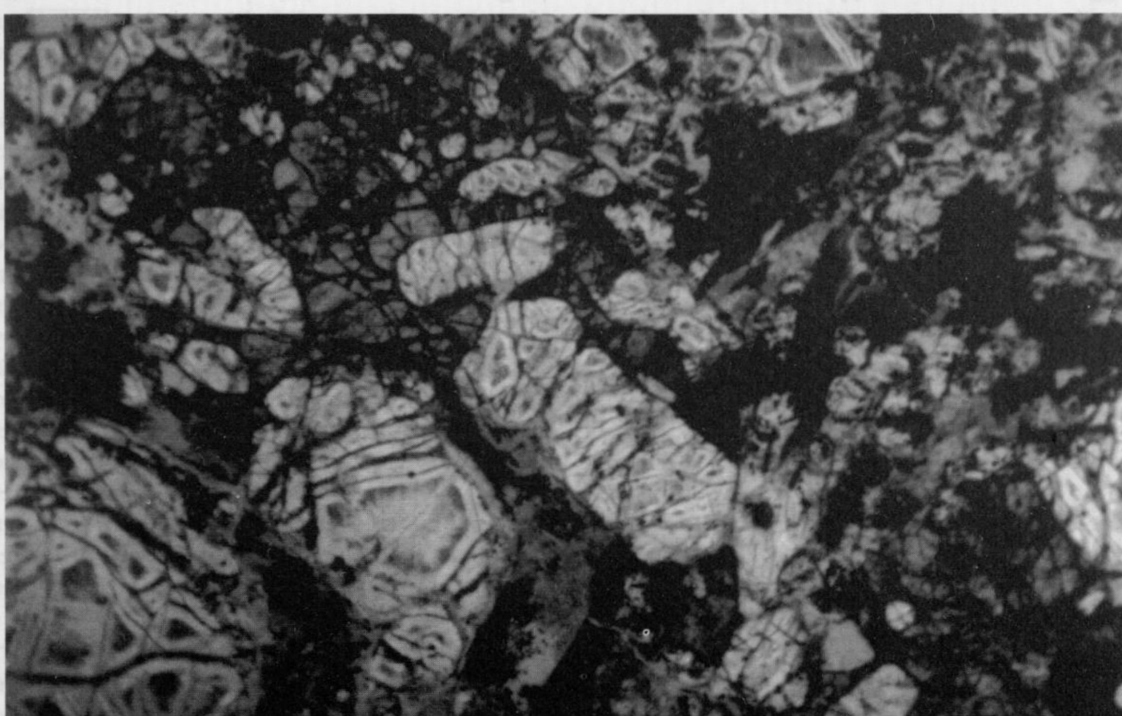


Figure 4.34 Photomicrograph of the Polyphant hydrous picrite, showing serpentinized olivine crystals, pyroxene and dark kaersutitic amphibole (top left). Polyphant, Cornwall. (Photo: P.A. Floyd.)

and Isaac, 1982). This seems unlikely on the available data and derives also from the misinterpretation of associated Lower Carboniferous lavas and intrusives as MORB – rather than intraplate alkali basalts.

Conclusions

This locality exposes an 0.5-km-wide igneous sheet which, subsequent to its emplacement, has been fragmented and sliced by low-angled thrusts. The mass has been transported on one of these thrusts into its present position and thus detached from its original roots. The rock is ultramafic in composition, a variably serpentinized peridotite, containing primary olivine, clinopyroxene, amphibole, biotite, apatite and magnetite. The presence of water-bearing primary minerals (amphibole and biotite) distinguishes it from other south-west England peridotites such as in the Lizard Complex. Associated with the peridotite are gabbros and dolerites intruded into late Devonian slates. Below the Polyphant sheet is another thrust slice containing early Carboniferous volcanic rocks and intrusions, with a chemistry possibly akin to oceanic basalts. It was suggested that the Polyphant ultramafic rocks together with the Carboniferous basalt and sediments, represented a segment of ancient oceanic crust (ophiolite), now dismembered by thrusting. However, further work on the Carboniferous volcanics and sediments has led to their interpretation as oceanic crust being questioned.

B14 TINTAGEL HEAD–BOSSINEY HAVEN (SX 047892–SX 066895)

Highlights

This is the type locality for the Tintagel Volcanic Formation, a late sequence of alkali basalt, basinal volcanics of early Carboniferous age. It is also important because the metamorphic grade is higher than elsewhere in this region.

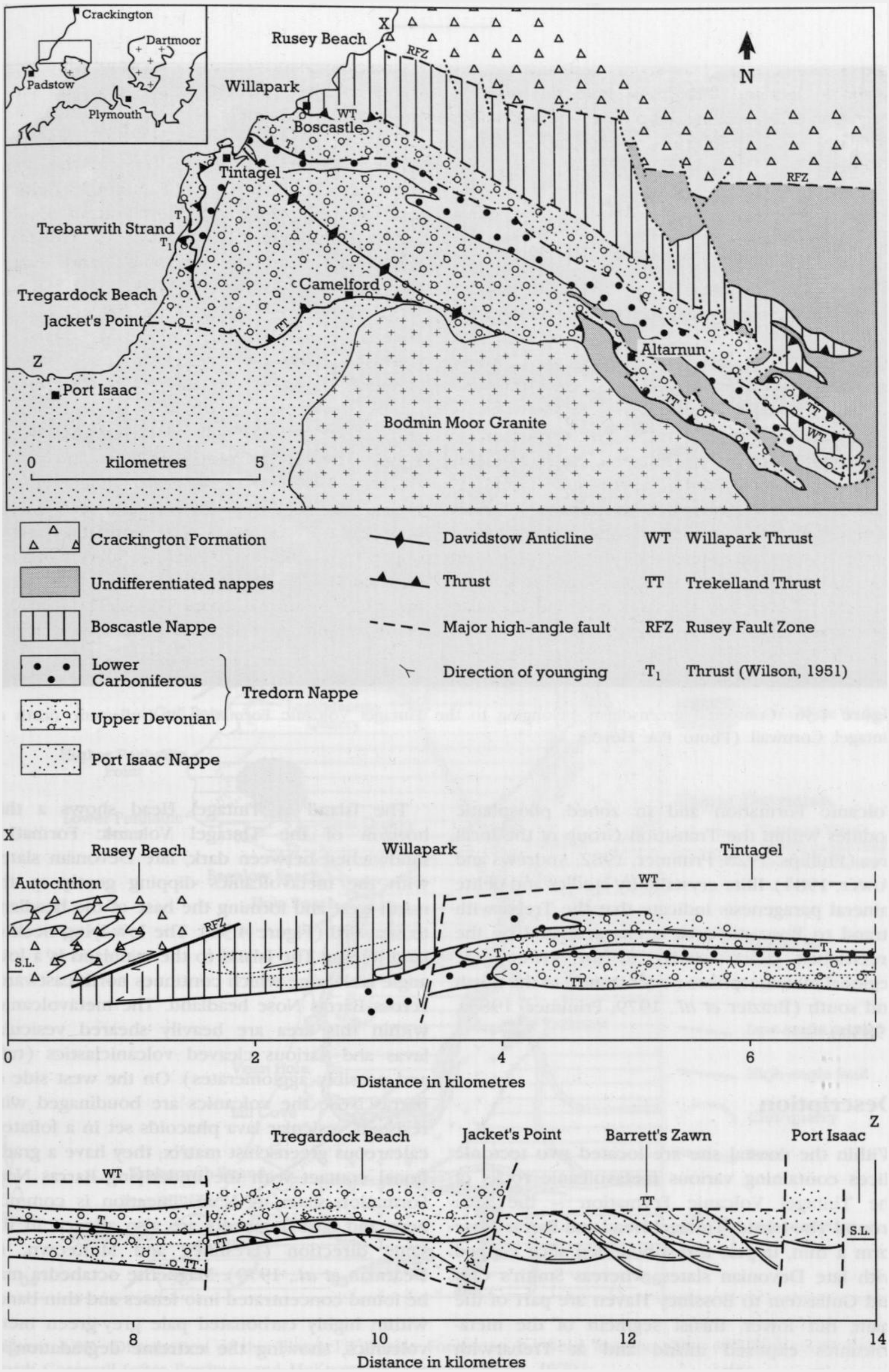
Introduction

This scenic coastal section of north Cornwall extends from The Island at Tintagel Head via the headlands of Barras Nose and Willapark to the deep, narrow inlet of Bossiney Haven. It is historically famous for the folklore of King Arthur that is attached to ancient Tintagel Castle and its prehistoric earthworks.

The site includes examples of the early Carboniferous Tintagel Volcanic Formation that occur within the Tredorn Nappe (Figure 4.35; Selwood and Thomas, 1986a) and whose volcanic equivalents can be traced southwards to Trebarwith Strand and inland to Lewannick, north-east of Bodmin Moor (Selwood, 1961, 1971; Stewart, 1981). Exposures typical of the Tintagel Volcanic Formation just inland and along the north Cornish coast show a series of variably foliated metabasic lavas and volcaniclastics (Dearman *et al.*, 1970; Freshney *et al.*, 1972) whose original nature is often difficult to determine (Figure 4.36). The local Tredorn Nappe stratigraphy (Stewart, 1981) comprises a Dinantian sequence with the Tintagel Volcanic Formation sandwiched between a lower Barras Nose Formation and an upper Trambley Cove Formation, all of which are overlain by Upper Devonian slates transported into place on the Willapark Thrust. The main part of the Tintagel Volcanic Formation forms a north–south band running inland from Tintagel to Treknow and cropping out on the coast at Trebarwith Strand (Figure 4.37). This forms a single structural unit, whereas due to further thrusting and normal faulting, it is repeated on the coast around Tintagel Head to form a separate overriding slice (Freshney *et al.*, 1972).

Recent work on the Tintagel Volcanic Formation and associated metasediments has been concerned with the grade of metamorphism and their geochemical composition and petrogenesis. Early work described the occurrence and preponderance of low-grade phyllosilicates in both pelites and volcanics, as well as chloritoid-bearing phyllites and Mn-garnet-bearing slates (Tilley, 1925; Phillips, 1928). Freshney *et al.* (1972) recognized the low-grade and polyphase nature of the metamorphism and, in particular, considered late biotite porphyroblasts within the Tintagel Volcanic Formation to be the effect of superimposed contact metamorphism. Mn-rich garnets have been found in the low-grade Delabole Slates, in graphitic slates associated with the Tintagel

Figure 4.35 (Opposite) Map and section of north Cornwall, showing the distribution and relationship of the major nappes (after Selwood and Thomas, 1986a). The Tintagel Volcanic Formation occurs in the Tredorn Nappe.



Crackington
Dartmoor
Padstow
Plymouth
Rusey Beach
X
RFZ
N
Willapark
WT
Boscastle
T1
Tintagel
Trebarwith Strand
Camelford
Tregardock Beach
Jacket's Point
TT
Altarnun
Z
Port Isaac
Bodmin Moor Granite
0
kilometres
5
Crackington Formation
Undifferentiated nappes
Boscastle Nappe
Lower Carboniferous
Upper Devonian
Tredorn Nappe
Port Isaac Nappe
Davidstow Anticline
Thrust
Major high-angle fault
Direction of younging
WT Willapark Thrust
TT Trekelland Thrust
RFZ Rusey Fault Zone
T1 Thrust (Wilson, 1951)
Autochthon
S.L.
0
2
4
6
Distance in kilometres
8
10
12
14
Barrett's Zawn
Distance in kilometres

Figure 4.36 Contorted greenschists belonging to the Tintagel Volcanic Formation at Gullastem, north of Tintagel, Cornwall. (Photo: P.A. Floyd.)

Volcanic Formation and in zoned phosphatic nodules within the Transition Group of the local area (Phillips, 1928; Primmer, 1982; Andrews and Power, 1984). Illite crystallinity studies and pelite mineral paragenesis indicate that the Trebarwith Strand to Boscastle area is characterized by the greenschist facies relative to the lower-grade regional metamorphism ('anchizone') to the north and south (Brazier *et al.*, 1979; Primmer, 1983a, 1983b).

Description

Within the coastal site are located two tectonic slices containing various metavolcanic rocks of the Tintagel Volcanic Formation – the area around The Island, Tintagel Head and Barras Nose form a thin, upper, thrust-bounded slice capped with late Devonian slates, whereas Smith's Cliff and Gullastem to Bossiney Haven are part of the main, but lower, thrust segment of the metavolcanics exposed inland and at Trebarwith Strand (Figure 4.37).

The Island at Tintagel Head shows a thin horizon of the Tintagel Volcanic Formation sandwiched between dark, late Devonian slates, with the metavolcanics dipping gently to the north-west and forming the base of the headland to seaward (Figure 4.38). The low-lying neck of land joining The Island to the mainland is a low-angle fault zone which continues north-eastwards across Barras Nose headland. The metavolcanics within this area are heavily sheared vesicular lavas and various cleaved volcaniclastics (tuffs and possibly agglomerates). On the west side of Barras Nose the volcanics are boudinaged with resistant vesicular lava phacoids set in a foliated, calcareous greenschist matrix; they have a gradational contact with the underlying Barras Nose Formation slates. A NNW lineation is common here and lava fragments are also aligned in the same direction (Freshney and McKeown, *in* Dearman *et al.*, 1970). Magnetite octahedra may be found concentrated into lenses and thin bands within highly carbonated pale grey-green metavolcanics, showing the extreme degradation of the original volcanics.

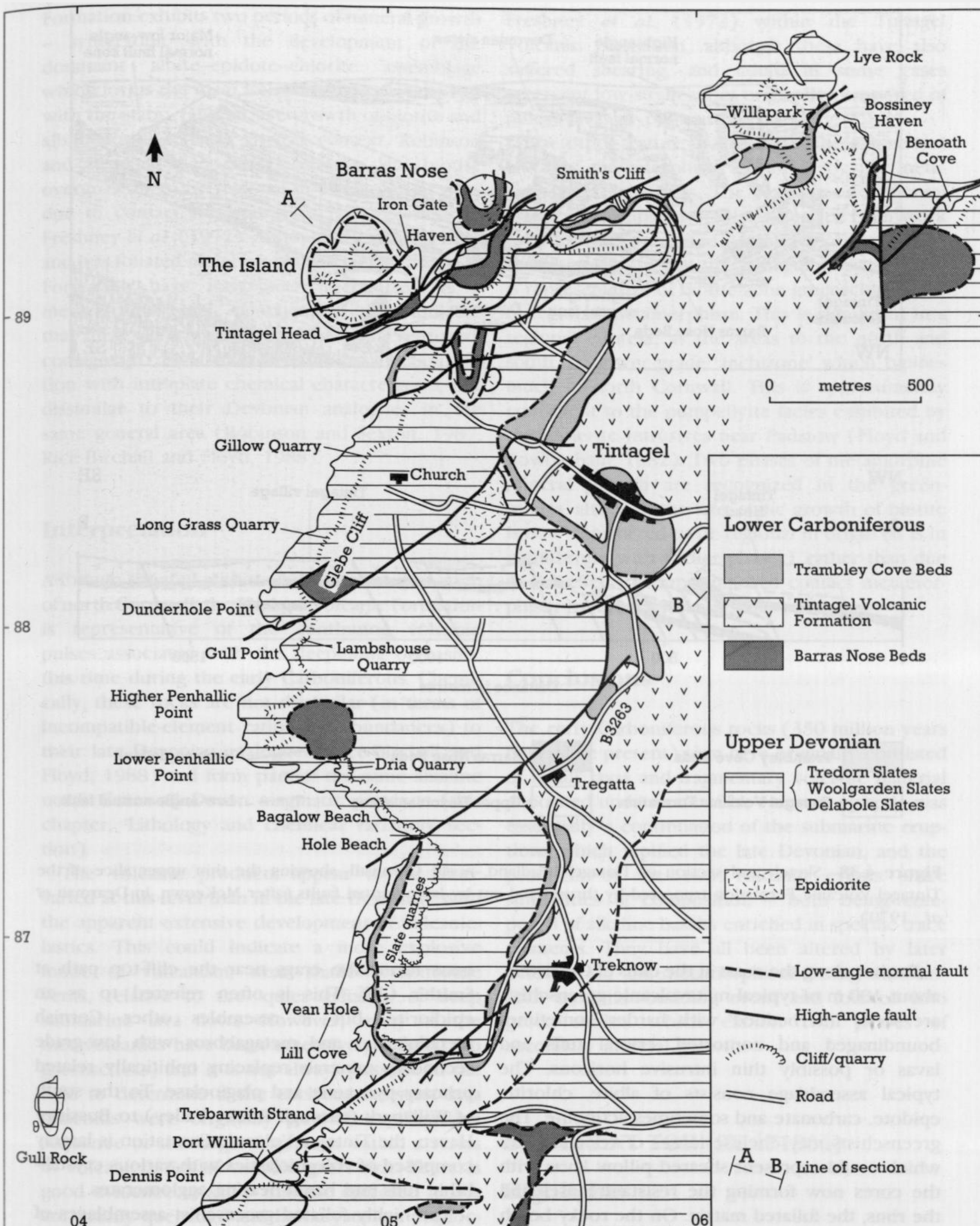


Figure 4.37 Distribution of the Tintagel Volcanic Formation between Bossiney Bay and Trebarwith Strand, north Cornwall (after Freshney and McKeown, *in* Dearman *et al.*, 1970).

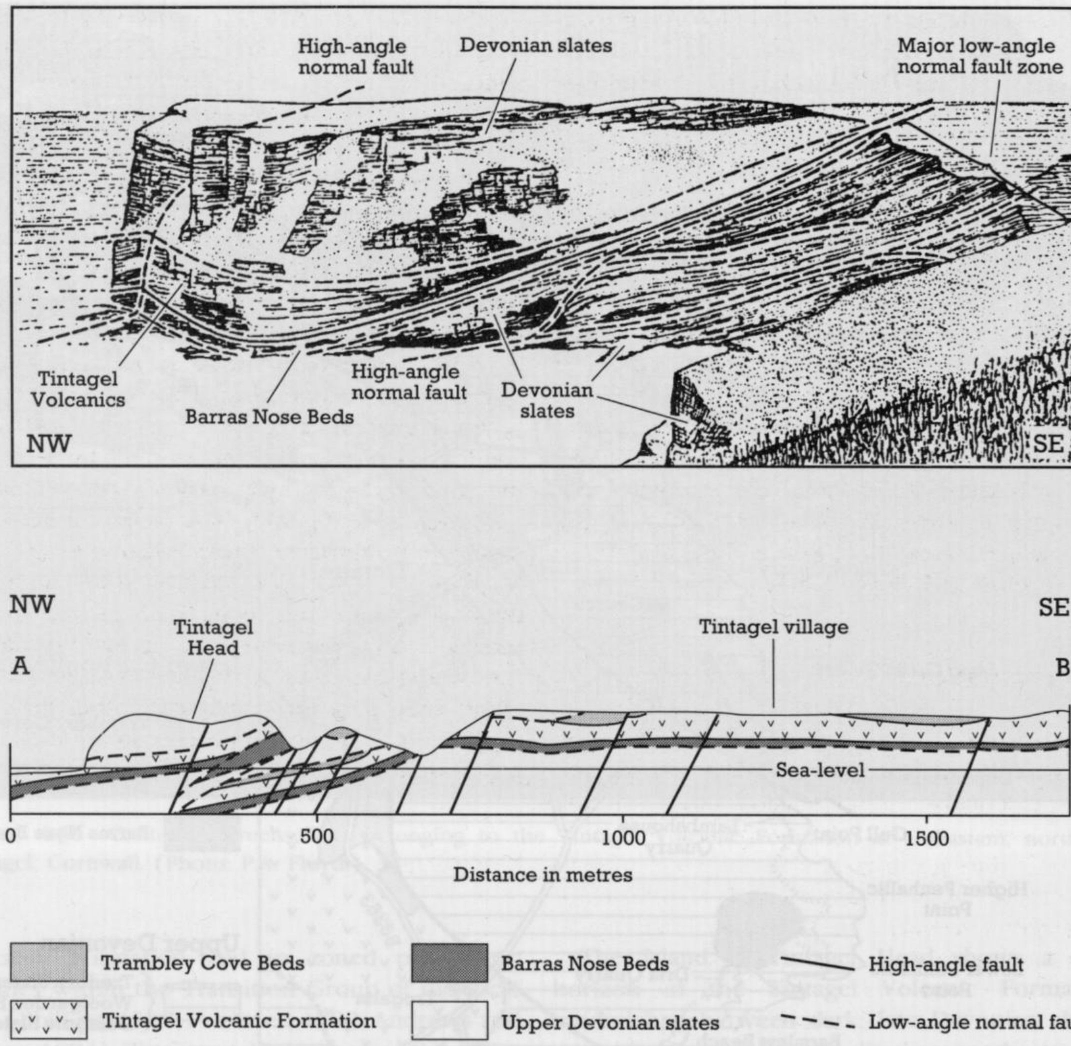


Figure 4.38 Sketch and section of Tintagel headland, north Cornwall, showing the thin upper slice of the Tintagel Volcanic Formation truncated by thrusts and cut by later normal faults (after McKeown, in Dearman *et al.*, 1970).

Farther along the coast at the cliffs of Gullastem, about 100 m of typical metavolcanic greenschists are seen, 'interbedded' with harder, sometimes boundinaged and contorted, crystal tuffs and lavas or possibly thin intrusive horizons. The typical assemblage consists of albite, chlorite, epidote, carbonate and sometimes actinolite. The greenschists may enclose lenses of vesicular lava which could represent sheared pillow lavas with the cores now forming the resistant lenses and the rims, the foliated matrix. On the rocky beach below the cliffs, are many blocks of massive and variably sheared gabbro traversed by greenschist zones. Although these blocks have been derived from an unknown locality, a sheet-like intrusive mass forms the crags near the cliff-top path at Smith's Cliff. This is often referred to as an epidiorite, but it resembles other Cornish metadolerites and metagabbros with low-grade secondary minerals replacing ophitically related primary pyroxene and plagioclase. To the south of Willapark (through Rocky Valley) to Bossiney Haven, the Tintagel Volcanic Formation is largely composed of volcaniclastics with various crystal–lithic tuffs and basalt-bearing agglomerates.

The highly foliated greenschist assemblages of the Tintagel Volcanic Formation also indicate greenschist facies (biotite zone) developed under high PO_2 equilibrium conditions (Robinson and Read, 1981; Primmer, 1982). The Tintagel Volcanic

Formation exhibits two periods of mineral growth – syntectonic with the development of the dominant albite–epidote–chlorite assemblage which forms the main foliation, and post-tectonic with the static, random overgrowth of biotite and albite porphyroblasts. In this context, Robinson and Read (1981) considered the late biotite overgrowths to be regional in origin, rather than due to contact metamorphism as suggested by Freshney *et al.* (1972). Although the greenschists and less-foliated members of the Tintagel Volcanic Formation have long been recognized as a metavolcanic suite, geochemical data indicate that they were originally a single, differentiated, comagmatic association of alkali-basalt composition with intraplate chemical characteristics, not dissimilar to their Devonian analogues in the same general area (Robinson and Sexton, 1987; Rice-Birchall and Floyd, 1988).

Interpretation

Although situated within a highly tectonized zone of north Cornwall, the Tintagel Volcanic Formation is representative of the continuing volcanic pulses associated with the deepening of basins, this time during the early Carboniferous. Chemically, these rocks are not dissimilar (in terms of incompatible-element ratios and abundances) to their late Devonian analogues (Rice-Birchall and Floyd, 1988) and form part of the same alkaline north Cornwall–Devon magmatic province (this chapter, 'Lithology and chemical variation' section).

The volcanic products appear to be more varied at this level than in the late Devonian, with the apparent extensive development of volcaniclastics. This could indicate a more explosive mode of volcanism, near shallow submarine vents, relative to the 'quiet' effusion of deep submarine lava flows. However, many of the metavolcanics have been extensively foliated (to greenschists) and it is not always possible in the field to determine if the enclosed resistant lava phacoids were originally part of a pillow-lava sequence or the larger fragments within a series of volcaniclastics of variable grain size. There is good evidence to show that the enclosed lenses are mainly quenched and holocrystalline plagioclase-phyric basalt and that the bulk chemical composition of the greenschists is that of an alkali basalt (Rice-Birchall and Floyd, 1988). Relatively homogeneous agglomerates are mentioned by Freshney *et al.* (1972) within the Tintagel Volcanic Formation, although these have also suffered shearing, and could in some cases represent low-strain zones originally composed of pillow lavas or pillow breccias.

The other feature of this site is the nature and grade of metamorphism exhibited by the metavolcanic greenschists. The textures and mineral assemblages support evidence derived from work done on the associated sediments of the region and demonstrate that the Tintagel–Boscastle area is representative of biotite-zone greenschist facies of regional metamorphism. This is significant in a regional context, as the areas to the north and south are lower grade 'anchizone' which typifies much of north Cornwall. This is approximately equivalent to the pumpellyite facies exhibited by metadolerite intrusives near Padstow (Floyd and Rowbotham, 1982). Two phases of metamorphic mineral growth are recognized in the greenschists, although the late, static growth of biotite is now considered to be regional in origin (it is in equilibrium with earlier phases), rather than due to the effects of superimposed contact metamorphism by the Variscan granites.

Conclusions

The early Carboniferous rocks (350 million years before the present) seen here originally consisted of basalt lavas and fragmentary volcanic material deposited under water. The volcanic episode was essentially a continuation of the submarine eruptions which typified the late Devonian, and the products of the two volcanic events share similarities of composition – both being composed of alkaline basalts enriched in specific trace elements. They have all been altered by later deformation and metamorphism during the Variscan mountain-building event and foliated into green schists which exhibit two phases of secondary mineral growth.

B15 BRENT TOR (SX 471804)

Highlights

This locality shows a unique example of an early Carboniferous basaltic pillow lava and hyaloclastite seamount, or mound, with a reworked volcaniclastic apron.

Figure 4.39 The conical knoll of Brent Tor is composed of Lower Carboniferous basaltic pillow lavas and hyaloclastites which formed a near-emergent seamount with a reworked volcaniclastic apron. Brent Tor, Devon. (Photo: P.A. Floyd.)

Introduction

This site covers the conical knoll of Brent Tor capped by its historic chapel (Figure 4.39). It is composed of early Carboniferous volcanics within the flysch-dominated Blackdown tectonic unit (Isaac, 1981) or Heathfield Nappe (Isaac *et al.*, 1982) and forms an isolated klippen occupying the high ground above the Greystone Nappe below. In the scheme of Selwood and Thomas (1986a) it is part of the Blackdown Nappe. The Brent Tor volcanics are generally recognized as being early Carboniferous as they rest on cherts and slates assigned to this age. However, Selwood (1974) suggested that the volcanics and associated radiolarian-bearing black slates might be late Devonian, because the sediments are lithologically similar to strata of this age north of Tavistock. The problem is compounded by the structural complexity; much of the area is composed of thin thrust slices of both Upper Devonian and Lower Carboniferous strata.

The detailed petrography of the volcanic rocks of the region to the west of Dartmoor has been described by Reid *et al.* (1911), as well as the mineralogical effects of contact metamorphism by the granite. The rocks of Brent Tor, which are outside the granite aureole, have long been recognized as the products of a volcanic eruption and, together with other magmatic rocks in the immediate vicinity, were annotated and examined in thin-section by Rutley (1878). This work was one of the first to figure hand-painted thin-section drawings of magmatic rocks from south-west England by the Geological Survey. Little modern work has been done on this interesting volcanic edifice, although a few of our unpublished chemical analyses indicate that the lavas are alkali basalts, in common with many of the extrusives and intrusives found to the west of Dartmoor.

Description

The Brent Tor volcanics are mainly composed of coarsely bedded volcaniclastics that have a southerly dip. Near the base of the section are variably foliated, platy, light and dark-grey fine tuffs upon which rest a series of basaltic hyaloclastites and pillow-lava breccias that comprise the main outcrop. The grain size of the hyaloclastites and the distribution of pillow fragments varies considerably. The crags directly below the chapel near the main path are composed of small, elongate, dark basaltic fragments set in a greyish-green, speckled tuffaceous matrix. Occasionally, larger (0.1–0.2 m), often highly vesicular, broken fragments of pillow lava with curved surfaces and chilled margins may be present. Near the chapel and towards the top of the volcanic sequence are numerous small, red (highly oxidized), scoriaceous lava fragments set in a hyaloclastite matrix. There is also some suggestion of autobrecciation of a reddened lava flow.

On the slopes to the south of the chapel are hyaloclastites containing closely packed, large fragments (up to 0.25 m long) of dark, non-vesicular basalt interbedded with foliated tuffs containing broken, vesicular pillows. The smaller, dark, non-vesicular fragments that make up the majority of the hyaloclastite matrix are irregular in shape and were probably glassy. Further downslope from the chapel, but high in the volcanic sequence are found graded hyaloclastites and pillow breccias which represent the reworking and slumping of debris down the sides of the volcanic mound. The reworked volcanic debris probably travelled some distance away as, 4 km to the south in a small quarry near Kilworthy, is a lithic–crystal tuff with rounded, oxidized fragments of Brent Tor-type lava.

All the lava fragments are highly altered and oxidized basaltic material. In thin section some contain replaced microlitic and quenched skeletal plagioclase in an oxidized, magnetite-rich glassy matrix. Small, disrupted, often filamentous, originally glassy scoria may be bounded by internal vesicle walls and exhibit curving lines reminiscent of perlitic cracking. The finer hyaloclastite matrix appears to have been generally glassy, although much is now replaced by secondary hematite, prehnite, carbonate, sericite and sphene.

Interpretation

The importance of this early Carboniferous volcanic site is that it represents an excellent example of a hyaloclastite–pillow breccia mound and, relative to other volcanic localities (dominated by pillow lavas and minor volcaniclastic sheets), it is unique in this respect. The general shape and limited extent of the hyaloclastite deposit suggests a localized submarine eruption which built a high-level mound of largely unsorted, basaltic, glassy fragments and pillow breccias. The highly reddened or oxidized character of the lavas is unusual for Cornish volcanics and might indicate that the mound was built to a high level prior to penetration by oxygenated sea-water. The upper portion of the mound was reworked by current action and unconsolidated volcanic debris slumped downslope to form an apron. Thus, this volcanic structure is different from both late Devonian and early Carboniferous volcanic forms, which invariably exhibit pillow lavas, shallow sills or thin volcaniclastic sheets. The structure exposed probably represents the top part of a small seamount-type edifice on the floor of the basin, whereas pillow lavas in the area are typically small, domal bodies developed in a much deeper-water environment. Although its form is different from other volcanic products, it is chemically compatible in having an enriched alkali-basalt composition similar to both late Devonian and early Carboniferous volcanics in the same area.

Conclusions

This locality shows unique evidence for the presence of an early Carboniferous (around 350-million-year-old) volcanic seamount. Basaltic lavas and fragmentary volcanic material were erupted at a localized centre and built a small submarine volcano up to quite shallow depths. The rocks provide evidence consistent with eruption in a submarine setting: pillow lavas (see Chipley and Pentire Head above), glassy fragments formed by the rapid chilling of the lava by sea-water and irregular clinker-like clasts (scoria) full of voids produced by the evacuation of gases on cooling, together with cemented ashes (tuffs). The fact that they are now seen to be reddened is the result of exposure of the top of the seamount to the oxygenated upper levels of the sea and indicate its growth well above the contemporaneous sea-floor.

B16 GREYSTONE QUARRY (SX 364807)

Highlights

Early Carboniferous, high-level dolerites were here intruded into unconsolidated, fossiliferous sediments penecontemporaneously with early deformation. The presence of a series of thrust units, including exposure of the tectonically important Greystone thrust, is also regionally important.

Introduction

The site includes the working quarry cut into the valley side and situated on the west bank of the River Tamar.

Recent structural interpretations of central south-west England, between Bodmin Moor and Dartmoor, have demonstrated the importance of 'thin-skinned' thrust–nappe tectonics involving late Devonian and early Carboniferous rocks (Isaac *et al*., 1982). Within the quarry site a number of thrust surfaces have been identified (Turner, 1982), of which the tectonically highest and youngest is the regionally significant Greystone Thrust. This thrust carries late Devonian green slates over an early Carboniferous allochthonous sequence of basinal cherts and argillites within the Greystone Nappe (Isaac *et al*., 1982). The early Carboniferous succession is also characterized by thick doleritic intrusions and spatially associated basic lavas. Faunal dating of the enclosing sediments (Stewart, 1981) indicates a period of volcanism that lasted from latest Tournaisian to mid-Viséan times (Chandler and Isaac, 1982).

Description

The quarry site is largely composed of a number of doleritic intrusions and early Carboniferous basinal argillites and cherts. At the highest level (varying from about 50 m to 100 m OD) is the undulating Greystone Thrust surface, on top of which the late Devonian green slates are exposed around the western side of the quarry. A geological map and cross-sections of the quarry (Turner, 1982) are shown in Figure 4.40, and these illustrate a number of sub-Greystone thrusts (T2–T5) with highly undulating surfaces within dolerites and along chert horizons. The generally competent nature of the dolerites produced thrust ramping, both parallel and perpendicular to the direction of movement (Turner, 1982).

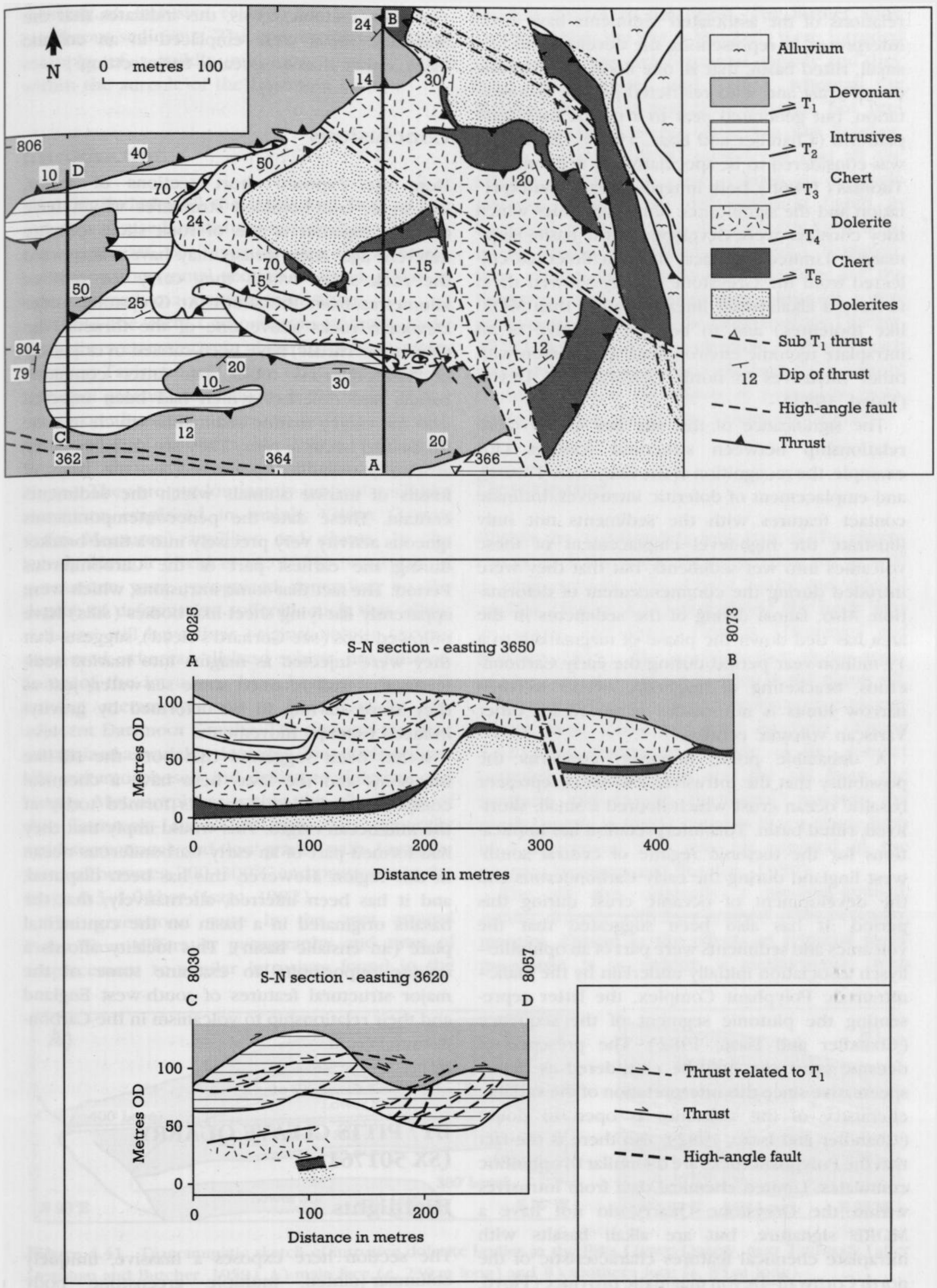
Although some of the massive dolerites appear to have an intrusive sill-like relationship with the sediments, the development of pillowy tops implies intrusion at a high-level into wet sediments. Also, detailed examination of contact relationships and enclosed sedimentary xenoliths shows that the intrusives cut deformed, early compaction and burial fabrics in the sediments. This implies that although the sediments were wet and only partly consolidated, the volcanics were intruded contemporaneously with the start of gravity-induced deformation (Isaac *et al*., 1982; Chandler and Isaac, 1982).

The dominant intrusives are mildly altered, subophitic-textured metadolerites with variable secondary assemblages of chlorite, white mica, albite and carbonate. The larger sills, however, have suffered most alteration in the marginal zone in contact with the sediments and can be extensively carbonated. Material derived from cores in the volcanics show greater variability with vesicular (infilled with chlorite and calcite) and plagioclase-phyric (now albitized or replaced by carbonate or rarely epidote) flows and minor intrusives with flow banding. The ubiquitous and typically low-grade assemblages and apparent lack of actinolite is possibly indicative of the pumpellyite facies of regional metamorphism (pumpellyite was tentatively identified by Chandler and Isaac (1982) from the Launceston area to the north); this is supported by the clay mineralogy (illite–chlorite) of the local sediments (Grainger and Witte, 1981).

Interpretation

The environmental importance of the intrusions (as seen in the site) lies in their association with the lavas, both of which are said to have stable-element compositions akin to ocean-floor basalts (Chandler and Isaac, 1982). The particular chemical signature for the volcanics and the facies

Figure 4.40 Map and cross-sections of Greystone Quarry, showing the development of undulating thrust surfaces cutting dolerite and the transportation of Upper Devonian sediments over Lower Carboniferous volcanics by the major Greystone Thrust (after Turner, 1982).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Chert
T_3
Dolerite
T_4
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T_5
Dolerites
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High-angle fault
Thrust
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C
8057
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Metres OD
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100
200
Distance in metres
Thrust related to T_1
Thrust
High-angle fault

relations of the associated sediments have been interpreted as representing the development of a small, rifted basin, that is, one floored by basaltic ocean crust and with restricted pelagic sedimentation, but generated near to a neritic carbonate platform (Chandler and Isaac, 1982). This model was considered to be speculative by Selwood and Thomas (1986b), both in terms of facies interpretation and the significance of the volcanics which they consider were developed at the basin- slope margin. Limited chemical data on dolerites collected from the Greystone Quarry showed them to have a alkali-basalt lineage (rather than MOR-like tholeiites) and to be representative of an intraplate tectonic environment, in common with other intrusives in north Cornwall and Devon (Floyd, 1983).

The significance of this site lies in the close relationship between structural features (for example, the recognition of the Greystone Thrust), and emplacement of doleritic intrusives. Intimate contact features with the sediments not only illustrate the high-level emplacement of these volcanics into wet sediments, but that they were intruded during the commencement of deformation. Also, faunal dating of the sediments in the area has tied down the phase of magmatism to a 19-million-year period during the early Carboniferous; bracketing of magmatic events to such narrow limits is not readily achieved for other Variscan volcanic centres.

A debatable point, however, concerns the possibility that the intrusives and lavas represent basaltic ocean crust which floored a small, short-lived, rifted basin. This interpretation has implications for the tectonic regime of central south-west England during the early Carboniferous and the development of oceanic crust during this period. It has also been suggested that the volcanics and sediments were part of an ophiolite–flysch association initially underlain by the mafic–ultramafic Polyphant Complex, the latter representing the plutonic segment of the sequence (Chandler and Isaac, 1982). The presence of oceanic crust can only be considered as highly speculative since this interpretation of the variable chemistry of the volcanics is open to doubt (Chandler and Isaac, 1982); also there is the fact that the Polyphant rocks are dissimilar to ophiolitic cumulates. Limited chemical data from intrusives within the Greystone Quarry do not have a MORB signature, but are alkali basalts with intraplate chemical features characteristic of the north Cornwall–Devon magmatic province (Floyd, 1984). In tectonic terms, this indicates that the magmatic rocks were emplaced in an ensialic basin, rather than an oceanic-basin setting.

Conclusions

Here are exposed short sections of major, low-angle, fault-bounded structures which have brought together a pile of rock slices of very different age. Such thrusts may have transported the rock slices which they carry for tens of kilometres from the south. At Greystone, older Devonian rocks above one of the thrusts (the Greystone Thrust) have been carried over younger, Carboniferous rocks. The latter contained basalts and dolerites which had been injected into the clayey marine sediments, which in time lithified to become rock. They are dated as being around 350 million years old, on the basis of fossils of marine animals which the sediments contain. These date the penecontemporaneous igneous activity very precisely into a time bracket during the earliest part of the Carboniferous Period. The fact that some intrusions, which were apparently flat-lying sheet-like bodies (sills) have pillowed tops (see Gurnard's Head), suggests that they were injected as magma into marine sediments that still retained some sea-water, just as they were starting to be deformed by gravity-induced (slump) movements.

It has been suggested that both the sill-like intrusions and the lavas here have a chemical composition similar to basalts formed today at the mid-ocean ridges. This would imply that they had formed part of an early Carboniferous ocean in this region. However, this has been disputed, and it has been inferred, alternatively, that the basalts originated in a basin on the continental plate (an ensialic basin). This locality affords a unique opportunity to examine some of the major structural features of south-west England and their relationship to volcanism in the Carboniferous Period.

B17 PITTS CLEAVE QUARRY (SX 501761)

Highlights

The section here exposes a massive, uniquely columnar-jointed, multiple greenstone body showing an intrusive relationship to early Carboniferous sediments. The greenstone is a typical example of a mildly metamorphosed dolerite within the aureole of the Dartmoor Granite.

Introduction

The site includes all the levels and faces of the old, now disused, roadstone quarry about 3 km to the north-east of Tavistock. In all, a nearly continuous horizontal section of about 400 m is here exposed in a massive greenstone.

Within the early Carboniferous country rocks along the western margin of the Dartmoor Granite between Tavistock and Peter Tavy, many massive intrusive greenstones ranging in thickness from a few to one hundred metres can be found. As with many of the volcanics in central south-west England they are confined to the Greystone Nappe. They are predominantly lenticular sill-like intrusions emplaced in mainly Viséan (Lower Culm Measures) argillites and cherts. In the Survey Memoir (Reid *et al.*, 1911) two types of greenstone were recognized depending on the degree of deformation suffered, such that 'albite diabases' still have their original ophitic texture preserved, whereas 'diabase schists' are foliated. Some of the intrusions have been subsequently contact metamorphosed to hornfelses by the adjacent Dartmoor Granite. The diabases are now recognized as variably degraded, low-grade regionally metamorphosed and deformed dolerites and basalts. Metamorphism within the allochthon of the Tavistock–Launceston area was generally syndeformational and low-grade, with temperatures of between 200–300°C and pressures in the range 0.3–1.0 kbar (Isaac, 1982).

The greenstone suite in the area around Peter Tavy differs in petrography and time of emplacement to similar intrusives found in the Meldon district to the north. The former suite (within which the site is situated) were intruded prior to the main deformational episode and they have been sheared and folded, whereas the Meldon group are post-deformational, but pre-granite in emplacement (Dearman and Butcher, 1959). Butcher (1958) considered that all the various greenstones were related via a single process of magmatic differentiation (such as fractional crystallization, although this view is no longer tenable on chemical grounds). However, little recent chemical work is available for the Petertavy suite of greenstones, although a few analyses from the Pitts Cleave greenstone (Parker, 1970) show it to be a moderately evolved Ti-rich alkali dolerite. The particularly high K_2O content probably reflects the effects of potassium metasomatism from the nearby Dartmoor Granite.

Description

Within the N–S-trending long face of the quarry can be seen the lenticular form of the sill, as well as large elongate rafts of hard, baked and spotted argillite (Figure 4.41) that divide the body into an upper and lower portion (Dearman and Butcher, 1959). The southern face shows spectacular curved columnar jointing in the upper sill, a feature rarely seen in the massive greenstones where most joints are more irregular (Figure 4.42). The change in attitude of the contact between the sediments and the sill from the southern end (nearly horizontal) towards the north (nearly vertical) suggests that a single limb of a recumbent fold may be exposed in the quarry (Dearman and Butcher, 1959).

The sill was originally a medium-grained, ophitic dolerite with finer-grained, often vesicular, margins. Owing to the effects of regional metamorphism it is strictly a metadolerite, with

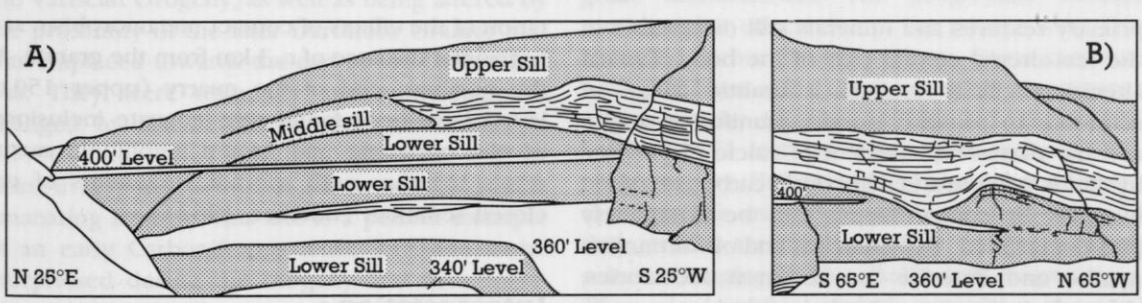

Figure 4.41 Diagrammatic sketch of intrusive dolerite bodies in the Pitts Cleave Quarry, near Tavistock (after Dearman and Butcher, 1959). A) main face (*c.* 230 m long) and B) southern face (*c.* 85 m long).

Figure 4.42 Well-developed columnar jointing in dolerite. Pitts Cleave Quarry, Tavistock, Devon. (Photo: P.A. Floyd.)

primary textures and minerals still discernible in the less-altered central part of the body. Typical alteration effects include a uralitic fringe of actinolite to primary, purple, titaniferous augite and the partial replacement of calcic plagioclase by albite, epidote and sometimes carbonate. Mafic minerals in contact zones can be completely pseudomorphed by chlorite and/or actinolite. Apatite and ilmenite are common accessories, although the latter may be skeletal and leucoxenized. The development of minor biotite after secondary chlorite is probably the only manifestation of the effects of contact metamorphism at a horizontal distance of *c.* 3 km from the granite. At the northern end of the quarry (upper 150 m level) have been found rare 'cognate inclusions' of clinopyroxene and brown amphibole megacrysts together with sporadic fragments of enclosed sediment (Butcher, 1982).

Interpretation

This site typifies a deep-level emplacement of major greenstone bodies into the early Carboniferous of the Greystone Nappe of central south-west England. Relative to the chemically similar alkali dolerite sills intruded at high levels into late Devonian strata in north Cornwall, many of the bodies in this area were apparently emplaced at a greater depth and into consolidated sediments. Together with extrusive lavas and volcaniclastics, these sills represent one of the major effects of volcanism associated with basinal sedimentation. In the example here, intrusion appears to have been relatively deep in the sedimentary pile, with the massive dolerite sill enclosing rafts of consolidated argillites that were subsequently baked and thermally spotted. The site is unique among south-west England greenstones in exhibiting curved columnar jointing that may be related to a curved or undulating upper cooling surface.

Apart from typical secondary assemblages produced by regional metamorphism, the metadolerite also shows the initial effects of contact metamorphism by the Dartmoor Granite, with the development of biotite after regional chlorite.

Conclusions

The massive 'greenstone' intrusions seen here have been profoundly affected by later geological events. They were originally dolerite sheets that intruded muddy sediments at a deep level beneath a Carboniferous sea, around 340 million years ago. The sediments were consolidated and lithified before they were intruded and substantial fragments ('rafts') were disrupted and incorporated into the body of the penetrating magma. Sediments in direct contact with the hot magma were thermally baked and underwent localized recrystallization which produced a spotted texture. The dolerites were subsequently involved in the Variscan Orogeny, as well as being altered by the proximity of the later Dartmoor Granite that was emplaced towards the end of the Carboniferous. They were texturally and mineralogically changed by the development of new minerals (biotite, amphibole) superimposed on the original fabric in response to the hot granite body and fluids emanating from it. This site is a perfect example of an early Carboniferous mafic intrusion metamorphosed during the orogeny and then metasomatized by the Dartmoor Granite.

B18 TRUSHAM QUARRY (SX 846807)

Highlights

At this locality, a metamorphosed dolerite is seen within an unthrust unit of early Carboniferous sediments. The chemistry and mineralogy of the dolerite is distinctive, together with the effects of local attendant hydrothermal alteration.

Introduction

This site includes the old water-filled quarry (originally known as Crockham Quarry) and the southern faces of the adjacent working quarry, 1.5 km due east of Hennock.

To the east of Dartmoor, the Teign Valley sedimentary succession ranges in age from the late Devonian through to the late Carboniferous, with the stratigraphically lower units falling within the metamorphic aureole of the granite. The early Carboniferous, in particular, is characterized by the presence of numerous massive greenstone sills (within one of which the site is located), together with relatively minor basaltic lavas and various volcaniclastics. The rocks in this area are autochthonous basinal successions (Selwood and Thomas, 1986b), comprising black argillites, well-bedded cherts, dark limestones and intercalated volcanics (the Foundation Unit of Waters, 1970).

The petrography of the dominant greenstone intrusives in the Teign Valley has been described by Flett (*in* Ussher, 1913), who referred to them as ophitic diabases with local quartz-bearing and highly feldspathic variants. Rare olivine is preserved only as serpentine pseudomorphs within pyroxene, whereas plagioclase is invariably altered to albite, together with variable prehnite, sericite, chlorite and calcite. As with other south-west England greenstones, the intrusives are now low-grade metadolerites. The progressive contact metamorphic effects due to the granite were also recorded within the greenstones. Some chemical work has been done on the massive greenstones in this area by Chesher (1969) and Morton and Smith (1971), and two major-oxide analyses were presented by Ussher (1913). In general terms, the dolerites are incompatible-element-rich, and they exhibit variable, but often well-fractionated suites belonging to the alkali-basalt magma type. They also exhibit typical intraplate chemical features that are characteristic for this magmatic province of south-west England (Floyd, 1983).

Description

The Trusham Quarry site is situated within a massive metadolerite body that intrudes the basal early Carboniferous Combe Formation (Chesher, 1968). It is just outside the aureole of the Dartmoor Granite. The sill-like intrusive nature of the 65–70-m-thick dolerite can be seen, with both the upper and lower contacts exposed. The body dips at about 45°–50° to the south-east. The site, however, only includes the upper contact, which can be seen at the base of the southern wall of the old, water-filled, Crockham Quarry, but can then be projected into the working quarry and is exposed in the quarry face at the upper levels. Although the contact is undulating, it is generally concordant with the sedimentary bedding. The local sediments are cleaved, blue-black argillites and buff siltstones with occasional thick sandstone units. The argillaceous sediments adjacent to the sill have been thermally metamorphosed with the development of randomly orientated, pale spots, a few millimetres in diameter, and small chiastolite prisms. The Na-metasomatism (adinolization) of the contact sediments, often a common phenomenon of high-level sills intruded into wet sediments, has not apparently taken place.

The greenstone is a mildly metamorphosed alkali dolerite characterized by primary purple titanaugite, ilmenite and abundant large apatite crystals. Original plagioclase has invariably been replaced by secondary albite and minor chlorite (penninite) and epidote. Green granular pumpellyite was tentatively identified in some plagioclase laths. Subhedral prisms of pyroxene may also be partially replaced by chlorite, which gives the rock its greenish tinge. The dolerite is medium grained with a granular to intersertal texture, occasionally plagioclase-phyric and with pegmatitic patches developed towards the top contact. The proportion of mafic to felsic minerals may vary considerably, although a ratio of 40:60 is relatively common. At the contact with the sediments is a *c.* 2 m thick, chilled margin of green, chloritized basalt which is sometimes vesicular. Adjacent to oxidized joints and calcite veins, the normal green colour of the metadolerite is replaced by a pink coloration which is seen mainly in the plagioclase laths. This is due to the development of hematite produced by the oxidation of Fe in plagioclase by late hydrothermal solutions that passed through fractures in the rock.

During later tectonism, the intrusive mass suffered some internal deformation with the development of thrusts that enclose hydrothermally argillized sediment and a highly oxidized wedge of dolerite with foliated margins. Vertical shears cut, and thus post-date, the shallow thrusts.

Chemical data on the Crockham metadolerite (Chesher, 1969) show that it has an alkaline composition and is characterized by very high incompatible element contents, especially Ti, P, Y, K, Rb and Ba.

Interpretation

The dolerite of this site is an example of an early Carboniferous intrusive within the autochthon of south-west England, whereas many of the other basic bodies are restricted to the allochthon, especially within the Greystone Nappe. One of its main features is that both contacts are exposed, and it shows the local thermal effects of contact metamorphism by such intrusives. Unlike many other Variscan dolerites, the adjacent sediments are not adinolized, but have developed spots and andalusite within the baked argillites. The lack of features indicative of intrusion into wet sediments suggests that the sill was intruded at some depth below the water–sediment interface and that the sediments were relatively dry and consolidated. It is probably this feature of the sediments that restricted the development of adinoles, whose extensive development appears to be related to intrusion at a high level into waterlogged sediments, such as is seen adjacent to the Dinas Head greenstone (above – B10).

In other respects the dolerite here is not typical of intrusives within the early Carboniferous; it has a granular–intersertal texture rather than ophitic, is often highly felspathic and is relatively well fractionated and chemically evolved. Like many of the early Carboniferous intrusives of the Teign Valley it is characterized by large and abundant apatite crystals that reflect the generally high P content of these basic magmas. However, overall it still exhibits chemical features typical of the early Carboniferous alkali dolerites of north Cornwall and Devon. One further feature is the nature of late hydrothermal alteration within the dolerite that caused a fracture-related pink coloration of the plagioclase. Whether these fluids were related to the granite is unknown, as no contact-metamorphic effects are seen in the immediate vicinity.

Conclusions

At Trusham Quarry can be seen a 60–70 m thick (metamorphosed) dolerite sheet intruded into muddy sediments during the early Carboniferous. Unlike other large bodies of similar age and composition, the Trusham intrusion is here in its original setting, and has not suffered lateral transport on the back of major thrusts sometimes many kilometres from their original setting (see Greystone Quarry above). Part of the interest of this intrusion is that, on emplacement, it thermally baked the adjacent sediments, with the development of a new phase, andalusite (an anhydrous aluminium silicate). The original mineralogy of the dolerite has been partly replaced by new minerals in response to low-grade regional metamorphism and localized hydrothermal fluids during the Variscan deformation episode. Chemically, the intrusion is incompatible-element-rich and, like many north Cornwall and Devon intrusions, belongs to the alkali-basalt magma series.

B19 RYECROFT QUARRY (SX 843847)

Highlights

Ryecroft Quarry shows an intrusion which is representative of the massive alkaline greenstone sills intruded into autochthonous early Carboniferous successions. It illustrates internal lithological variation and cryptic mineral variation due to fractional crystallization.

Introduction

This site is situated in the disused and now heavily overgrown quarry set in the hillside of Ryecroft Copse opposite Ashton Mill weir and 0.6 km north-west of Lower Ashton. The quarry face has an horizontal extent of about 500 m.

The geological setting for the massive greenstone of this site is the same as for Trusham Quarry, about 4 km due south. It is characteristic of the larger intrusives found in the autochthonous basinal sediments of the early Carboniferous (Selwood and Thomas, 1986b) and the tectonic Foundation Unit of Waters (1970). In common with the other greenstones of the area, which were described by Flett (*in* Ussher, 1913) as diabases, it is now a low-grade metadolerite. The only detailed chemical work on the Ryecroft sill is that of Chesher (1969) and Morton and Smith (1971). Morton and Smith (1971) analysed various primary and secondary mineral phases; they also record that contact metasomatism is common at the contacts of the local sills, with the production of adinoles (up to 1 m wide) composed of quartz–albite–calcite assemblages and chlorite–sericite replacing andalusite.

Description

The Ryecroft Quarry greenstone is one of the thickest doleritic intrusives in this part of the early Carboniferous, varying from about 130 m to 150 m thick. It is generally sill-like in its attitude and, in the quarry, dips to the south-east, although over its full extent it has been gently folded. The lower contact is not exposed and only the uppermost one-third of the sill is readily seen in the quarry site.

The bulk of the exposed sill is a slightly metamorphosed dolerite with a melanocratic, cumulate lower portion that grades upwards through normal dolerite to quartz-bearing variants and minor, leucocratic syenitic segregations (Morton and Smith, 1971). This internal lithological variation is characteristic of large intrusive basic bodies that have undergone crystal fractionation with the production of late, acidic liquids. The primary assemblage of the dolerite was olivine, titanaugite, plagioclase, apatite, ilmenite and possibly K-feldspar, with quartz, albite and K-feldspar characterizing the late segregations. Large, sometimes cored, apatites are a characteristic feature. Common secondary minerals include chlorite (generally 20–30 modal percent), calcite, albite, prehnite and white mica. Biotite (0.5–3 modal percent), commonly nucleated on ilmenite, also appears to be secondary and may be partially replaced by chlorite. Low-temperature hydrothermal alteration is also indicated by the variable pinking of the plagioclase.

The vertical lithological differentiation exhibited by the sill is mirrored by minor cryptic variation in both primary and secondary phases (Morton and Smith, 1971). The clinopyroxenes are salitic augites with high contents of Ti, Na and Al which are characteristic of alkali basalts, and show a change in Mg/Fe ratio up through the sill

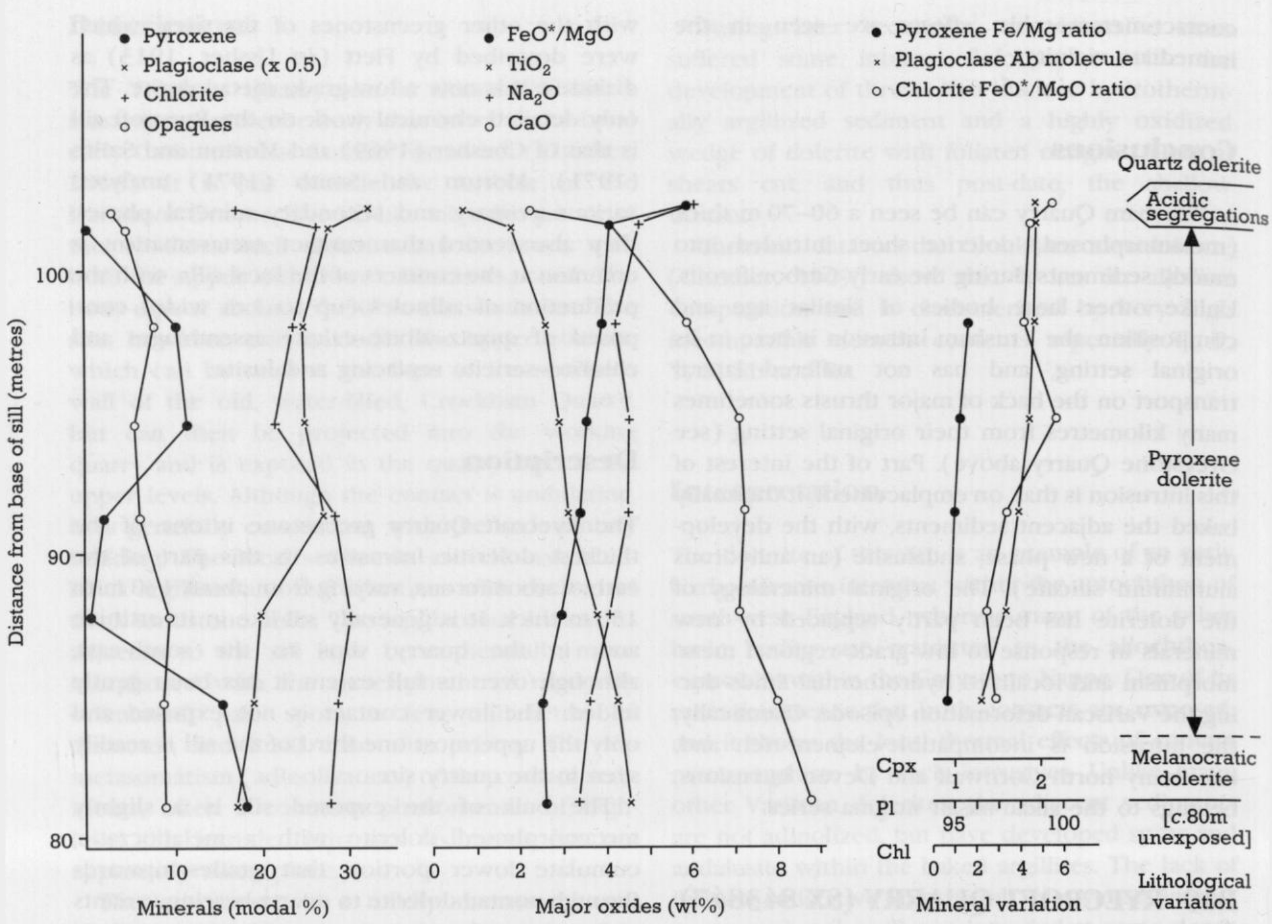

Figure 4.43 Modal and chemical variation in the upper part of the Ryecroft dolerite sill, Teign Valley, east Devon (data from Morton and Smith, 1971).

from 0.99 (near the base) to 0.84 (20 m from top). Most of the plagioclase is now almost pure albite, although the least differentiated lithologies still retain some An and Or components in their plagioclase. The chlorite exhibits a range of compositions from brunsvigite to pycnochlorite, which reflects the compositional variation of the primary host and position in the sill. The modal and chemical mineralogical variation is (shown in Figure 4.43) is characteristic of differentiated sills.

Chemically the Ryecroft sill is an alkali dolerite (Chesher, 1969; Morton and Smith, 1971), again characterized by high incompatible element abundances typical of the sodic alkali greenstone suite of north Cornwall and Devon. Major- and trace-element chemical variation mirrors the vertical lithological variation and modelling (Floyd, 1983) indicates that the sill evolved via a combination of *in situ* olivine, clinopyroxene and ilmenite fractionation.

Interpretation

The value of this site is that it is representative of some of the very thick alkaline dolerites intrusive into the early Carboniferous autochthonous succession of the Teign Valley. It has a relatively well-preserved primary texture and mineralogy, as well as exhibiting vertical lithological variation due to internal fractional crystallization during cooling. Unlike similar intrusives in north Cornwall, it generally shows a granular (rather than ophitic) texture indicating contemporaneous growth of plagioclase and clinopyroxene. It is also one of the few basic intrusive bodies in south-west England from which both primary and secondary mineral phases have been analysed. This work illustrated the control of both cryptic variation in primary minerals and the nature of the host phase in influencing the composition of secondary minerals. Thus, the composition of chlorite was seen to vary according to the degree of magmatic fractionation undergone by the replaced host phase. In general terms, this body is well evolved chemically with high incompatible-element abundances, but is characteristic of, and similar to, the Upper Devonian sodic alkali dolerites of north Cornwall and Devon that define that particular chemical province of south-west England (Chapter 3). All the secondary minerals suggest very low-grade regional metamorphic conditions (greenschist or lower) during the late Carboniferous, with the growth of biotite probably representing contact K-metasomatism by the Dartmoor Granite at a later stage. The site, however, is about 650 m outside the mapped aureole of the granite, and this indicates the distance travelled by migratory solutions beyond the extent of mineralogical reconstitution of the country rocks.

Conclusions

Here a massive, 130–150 m thick, concordant doleritic intrusion (a sill) has metasomatized the adjacent marine sediments into which it was injected. This process occurred some 340 million years ago during the early Carboniferous Period. The sill is remarkable for the evidence it presents for the operation of the fractional crystallization process during consolidation. This is now represented by progressive changes in mineral assemblages and compositions from the bottom to the top of the sill, with the most-evolved portion (near the top) being the most silica rich. The same mineral from different positions within the sill also shows chemical variation from the earliest to the latest formed. The preservation here of original and later superimposed metamorphic mineral phases, has made this site the subject of much mineralogical and chemical study.