Igneous Rocks of South-West England

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Chapter 3

Lizard and Start Complexes (Group A sites)

INTRODUCTION

This chapter presents some of the classic sites from the Lizard Complex of south Cornwall, illustrating various aspects of its ophiolitic character in the light of relatively recent work. It is one of the few good examples of preserved Variscan ocean crust in the Rhenohercynian zone of northern Europe; together with the adjacent *mélange*, it illustrates the development and subsequent closure of the Devonian Gramscatho Basin. The metavolcanic greenschists of the Start Complex are also included here as they have chemical characteristics that are comparable with the ophiolite and basaltic clasts in the *mélange* and thus contribute additional evidence for the local preservation of Variscan ocean crust. The localities of all the sites are shown on Figure 3.1.

LIST OF SITES

A1 Lizard Point (SW 695116–SW 706115)
A2 Kennack Sands (SW 734165)
A3 Polbarrow–The Balk (SW 717135–SW 715128)
A4 Kynance Cove (SW 684133)
A5 Coverack Cove–Dolar Point (SW 784187–SW 785181)
A6 Porthoustock Point (SW 810217)
A7 Porthallow Cove–Porthkerris Cove (SW 798232–SW 806226)
A8 Lankidden (SW 756164)
A9 Mullion Island (SW 660175)
A10 Elender Cove–Black Cove, Prawle Point (SX 769353–SX 769356)

LITHOLOGICAL AND CHEMICAL VARIATION

The following lithological units are now recognized within the Lizard Complex (Figure 3.2):

1. Partially serpentinized peridotite (Lizard Serpentinites);
2. Massive and weakly layered gabbros (Crousa and Trelan gabbros);
3. Variably metamorphosed basaltic dykes;
4. Heterogeneous acid/basic intrusive complex (Kennack Gneiss);

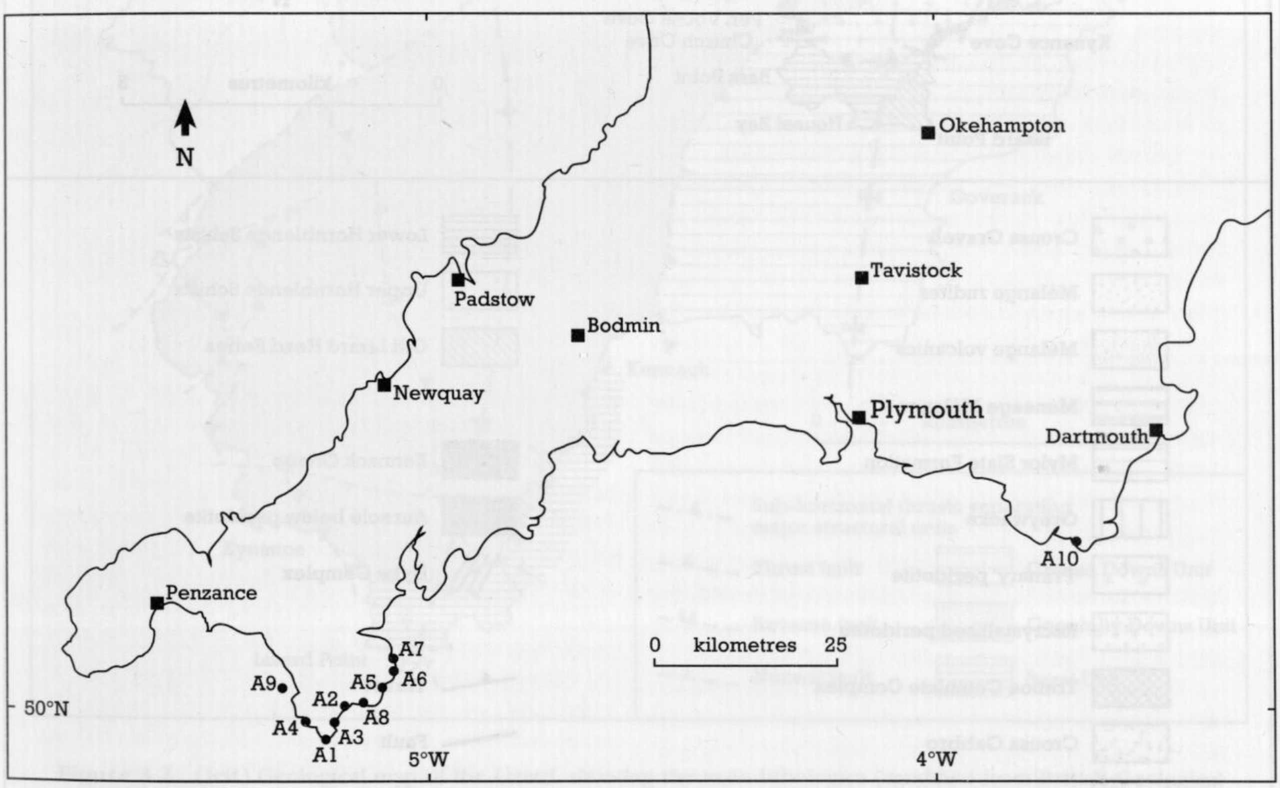
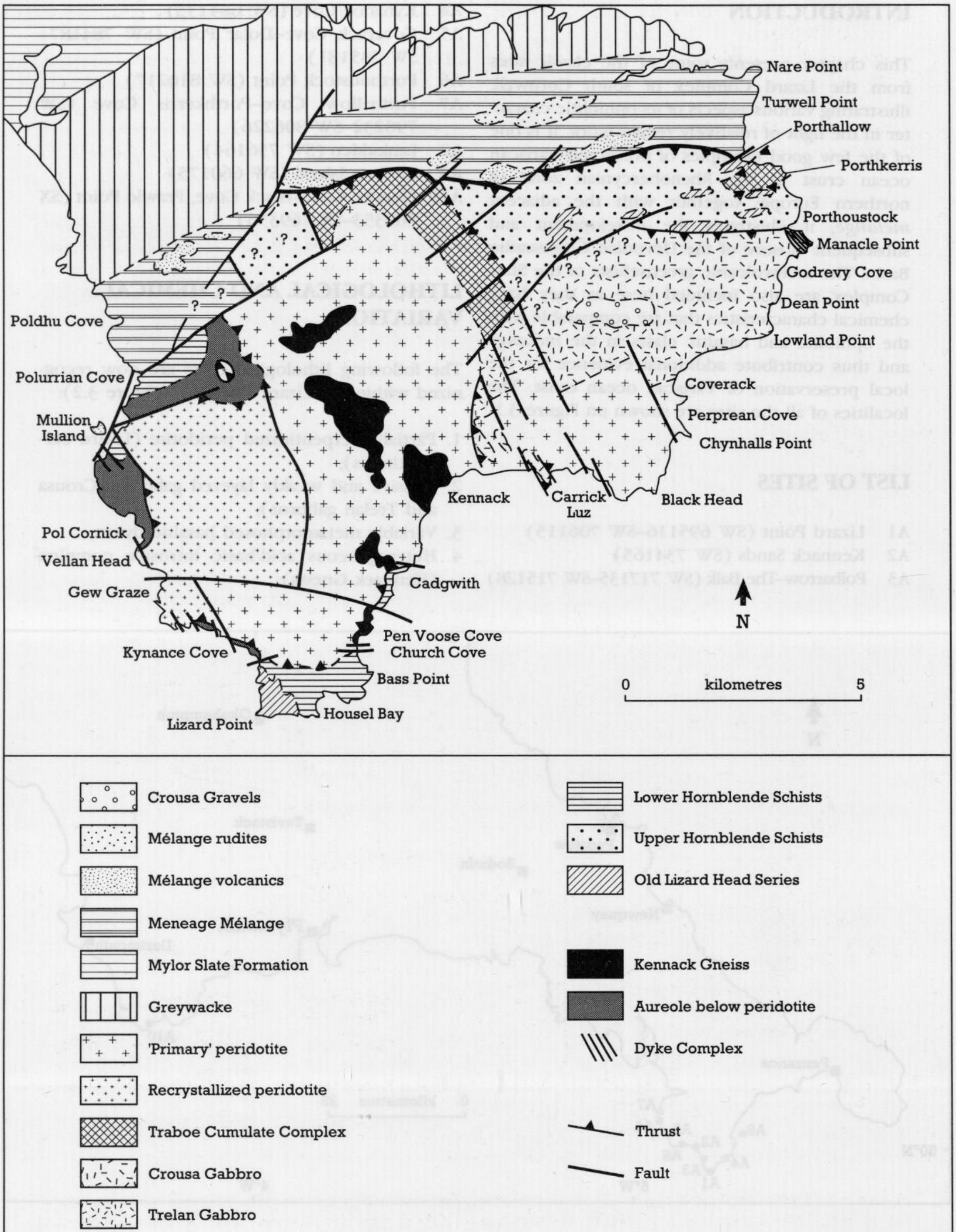


Figure 3.1 Outline map of south-west England, showing the location of Group A sites.



Nare Point
Turwell Point
Porthallow
Porthkerris
Porthoustock
Manacle Point
Godrevy Cove
Dean Point
Lowland Point
Coverack
Perprean Cove
Chynhalls Point
Black Head
Carrick Luz
Kennack
Cadgwith
Pen Voose Cove
Church Cove
Bass Point
Housel Bay
Lizard Point
Kynance Cove
Gew Graze
Vellan Head
Pol Cornick
Mullion Island
Polurrian Cove
Poldhu Cove
N
0 kilometres 5
Crousa Gravels
Mélange rudites
Mélange volcanics
Meneage Mélange
Mylor Slate Formation
Greywacke
'Primary' peridotite
Recrystallized peridotite
Traboe Cumulate Complex
Crousa Gabbro
Trelan Gabbro
Lower Hornblende Schists
Upper Hornblende Schists
Old Lizard Head Series
Kennack Gneiss
Aureole below peridotite
Dyke Complex
Thrust
Fault

5. Traboe Cumulate Complex (Traboe Hornblende Schists);
6. Metabasalt amphibolites (Landewednack Hornblende Schists);
7. Pelitic, semipelitic and hornblendic metasediments (Old Lizard Head 'Series');
8. Intermediate orthogneiss (Man of War Gneiss).

The structure of the Lizard Complex has been a controversial issue for many years. The tremendous difference between the high-grade metamorphic rocks of the Lizard and the Devonian rocks to the north was recognized by the earliest workers (De la Beche, 1830). This gave rise to theories that it was either an upfaulted block of basement or part of a large thrust sheet, possibly associated with rocks of the Start Complex in south Devon (discussed in Flett, 1946). All workers had accepted that the peridotite was essentially a diapir-like intrusion until the work of Sanders (1955) who suggested that it was a thin sheet-like body. Green (1964a, 1964b, 1964c) carried out a very detailed study of the peridotite and concluded that it had formed as a diapiric intrusion of hot mantle, with a well-developed metamorphic aureole.

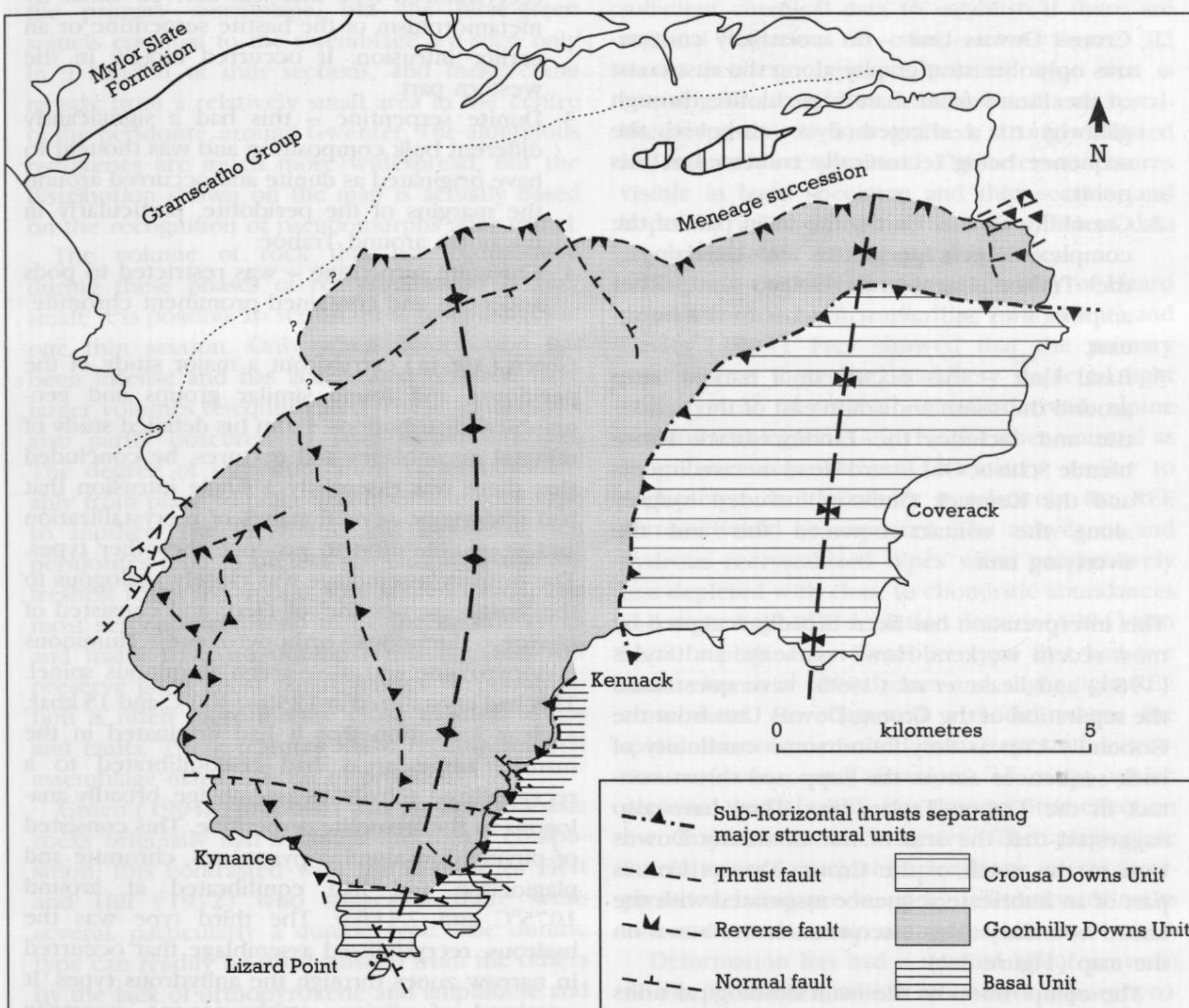


Figure 3.2 (left) Geological map of the Lizard, showing the main lithologies (modified from British Geological Survey Sheet 359; Green, 1964a; Leake *et al.*, 1990); and (above) their division into three tectonic units (after Bromley, 1979).

In the 1970s ophiolites became a topic of great interest and several workers interpreted the Lizard Complex in this light and, again, suggested that it was a thrust sheet. A borehole by IGS (now BGS) in the centre of the peridotite finally showed that it was only 360 m thick and proved its sheet-like form. Regional seismic studies have shown that the whole of the Lizard Complex is less than 1 km thick and that it is underlain by Devonian sediments. It is now well established that the Lizard Complex is relatively thin thrust sheet that overlies the south Cornish *mélange* at the top of an allochthonous nappe pile.

Bromley (1979) suggested an internal structure for the complex consisting of three thrust sheets, that were from top to bottom:

1. Crousa Downs Unit – an essentially continuous ophiolite stratigraphy along the east coast of the Lizard from mantle peridotite through gabbros to a sheeted dyke complex; the sequence being tectonically truncated at this point.
2. Goonhilly Downs Unit – the main part of the complex; largely peridotite and overlain by the Traboe Hornblende Schists and other amphibolites and metasediments to the north-east.
3. Basal Unit – this occurs in a narrow strip around the south and south-east of the peridotite and includes the Landewednack Hornblende Schists, Old Lizard Head metasediments and the Kennack Gneisses intruded roughly along the contact between this and the overlying unit.

This interpretation has been broadly accepted by most recent workers. However, Leake and Styles (1984) and Leake *et al.* (1990) have questioned the separation of the Crousa Downs Unit from the Goonhilly Unit as they found some continuity of rock sequences across the supposed thrust contact in the Traboe–Trelan area. They have also suggested that the arm of the Goonhilly Downs Unit to the north of the Crousa Downs Unit is part of an imbricate sequence associated with the Lizard boundary. This interpretation is shown on the map (Figure 3.2).

The composition of the main lithological units is reviewed below.

Peridotite

Various schemes have been suggested for subdivision of the Lizard peridotites, the two best known being those of Flett and Hill (1912) and Green (1964a), although none of them is totally adequate to encompass the current level of knowledge. Flett and Hill's scheme had four main types:

1. Coarse lherzolitic type – this was the least-deformed type and was called 'Bastite serpentine' after the prominent orthopyroxene pseudomorphs. It occurred in the central and eastern parts of the body.
2. Tremolite serpentine – a highly deformed recrystallized type that was derived either by metamorphism of the bastite serpentine or an earlier intrusion. It occurred mostly in the western part.
3. Dunite serpentine – this had a significantly different bulk composition and was thought to have originated as dunite and occurred around the margins of the peridotite, particularly in the north around Traboe.
4. Chromite serpentine – was restricted to pods and veins and contained prominent chromite.

Green (1964a) carried out a major study of the peridotite and found similar groups and geographical distributions. From his detailed study of mineral assemblages and textures, he concluded that there was essentially a single intrusion that had undergone several stages of recrystallization and re-equilibration to produce the other types. The primary assemblage was closely analogous to the 'bastite serpentine' of Flett, and consisted of olivine, aluminous orthopyroxene, aluminous clinopyroxene and olive-green aluminous spinel. This had crystallized at 1250–1300°C and 15 kbar, a clear indication that it had originated in the mantle. Large areas had re-equilibrated to a recrystallized anhydrous assemblage, broadly analogous to the tremolite serpentine. This consisted of olivine, low-alumina pyroxenes, chromite and plagioclase and had equilibrated at around 1075°C and 7.5 kbar. The third type was the hydrous, recrystallized assemblage that occurred in narrow zones through the anhydrous types. It consisted of olivine, orthopyroxene, pargasite amphibole and chromite and had equilibrated at 900°C and 5 kbar. Green (1964a) suggested that the dunite serpentine (Flett and Hill, 1912), was a highly serpentinized version of this. The sequence of assemblages with decreasing temperature and pressure gave rise to the model of a diapir rising from the mantle, into the crust and undergoing re-equilibration. It has since been shown that the actual form of the peridotite is sheet-like not diapir-like, but there is no reason to doubt the petrological evidence and mineral assemblages on which the model was based. Styles and Kirby (1980) suggested that the peridotite was possibly the sliced-off top of a suboceanic mantle diapir.

Green (1964a) produced a map that showed the distribution of the mineral assemblages. This is the most detailed map of peridotite variation available to date, but is possibly somewhat misleading. Large areas are shown as consisting of the primary assemblage, but the olive-green spinels essential to the assemblage are seen only in a handful of thin sections, and these come mostly from a relatively small area in the centre of the peridotite, around Gwenter. The aluminous pyroxenes are much more widespread, but the distribution shown on the map is actually based on the recognition of pseudomorphs after spinel.

The volume of rock that has equilibrated during these phases of recrystallization is very small; it is possible to see all three assemblages in one thin section. Only when deformation has been intense and has accelerated reaction have larger volumes re-equilibrated. These features are also partly obscured by later serpentinization. The degree of serpentinization varies considerably from place to place and from one rock type to another. The lherzolitic and amphibole-rich peridotites tend to be less serpentinized and the freshest rocks are around 30% serpentinized. The most serpentinized tend to be the dunitic types and many have no olivine remaining, but still preserve good ghost dunite fabrics. Serpentinization is often more intense close to shear zones and faults. These features make reliable mineral assemblage maps difficult to produce.

Green (1964a) proposed that all the ultrabasic rocks originally had a similar lherzolitic composition; this contrasted with the opinion of Flett and Hill (1912) who suggested there were several, particularly a dunitic type. The dunitic type can readily be distinguished from the others by the lack of orthopyroxene and amphibole and occurs in two distinct modes:

1. large bodies of regional extent that form part of the cumulate complex and will be discussed in a following section (dunite serpentine), and
2. as veins cutting through the primary type peridotite (chromite serpentine).

The latter is probably formed by the passage of melts or fluids through the upper mantle. More recent work, (Styles and Kirby, 1980; Leake and Styles, 1984) has shown that there is a wide range of bulk compositions that encompasses lherzolitic, harzburgitic and dunitic types, which is indicated by the range of Al_2O_3 and CaO contents (Figure 3.3). There does not seem to be a distinct division between lherzolitic and harzburgitic compositions, more a continuum; for example, both types can be found associated on the beach at Coverack. There are not yet sufficient chemical data to establish if there are regional variations in composition. Figure 3.2 shows just two types, a 'primary' type that is coarse grained and less deformed and a recrystallized type that is finer grained, strongly foliated and intensely recrystallized. This refers to features visible in hand specimen and thin section, and hopefully will be improved when sufficient data are available for meaningful subdivision.

The rare-earth-element geochemistry of Lizard peridotites has been studied by Frey (1969) and Davies (1984). Frey showed that the primary type (spinel lherzolite) had very depleted light REE, typical of residual, mantle-derived, alpine peridotites (Figure 3.4). This is rather unusual as they have major-element chemistry similar to undepleted mantle where a relatively flat REE pattern would be expected. The anhydrous and hydrous recrystallized types were progressively less depleted with close to chondritic abundances and slight light-REE depletion. Davies (1984) also found a plagioclase lherzolite type that had five times chondrite abundances and slight light-REE enrichment. He suggested a model where the spinel lherzolite resulted from repeated extractions of very small fractions of melts which depleted the light REE, but showed little effect on the major-element chemistry. The plagioclase lherzolite and pargasite peridotite were interpreted as being produced by infiltration of melts and associated mantle metasomatism.

Deformation has had a marked affect on most of the peridotites, which often have a porphyroclastic texture. Rothstein (1977), however, has reported evidence of an original cumulate crystal framework preserved between the later planar fabric.

Serpentinization is regarded as a prolonged,

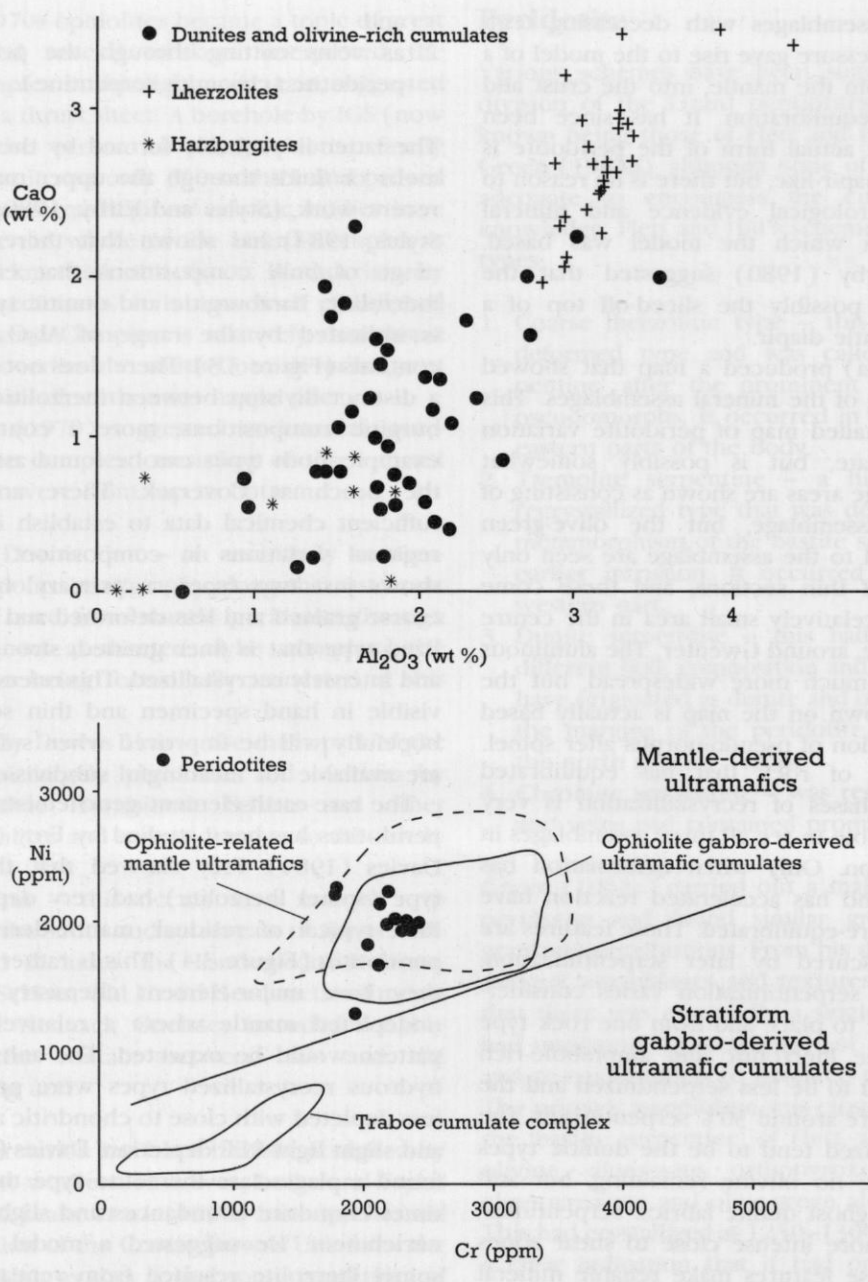


Figure 3.3 Distribution of Al_2O_3–CaO and Ni–Cr in Lizard peridotites, dunites and ultramafic cumulates (data from Parker, 1970; Kirby, 1979a; Leake and Styles, 1984) relative to typical ophiolite- and stratiform-related ultramafics (data from Rivalenti *et al.* (1981) and the literature).

retrograde alteration phenomenon. It probably started at relatively high temperatures, 400–500°C, with the formation of coarse lizardite associated with obduction in Devonian times and probably continues at the present time with the formation of fine chrysotile in veins, etc. due to the presence of groundwater.

Gabbro and dykes

The Crousa gabbro has had a rather turbulent history, with evidence of several closely spaced intrusive phases causing back-veining, autobrecciation and pegmatite formation. In many places there is evidence of deformation at various times,

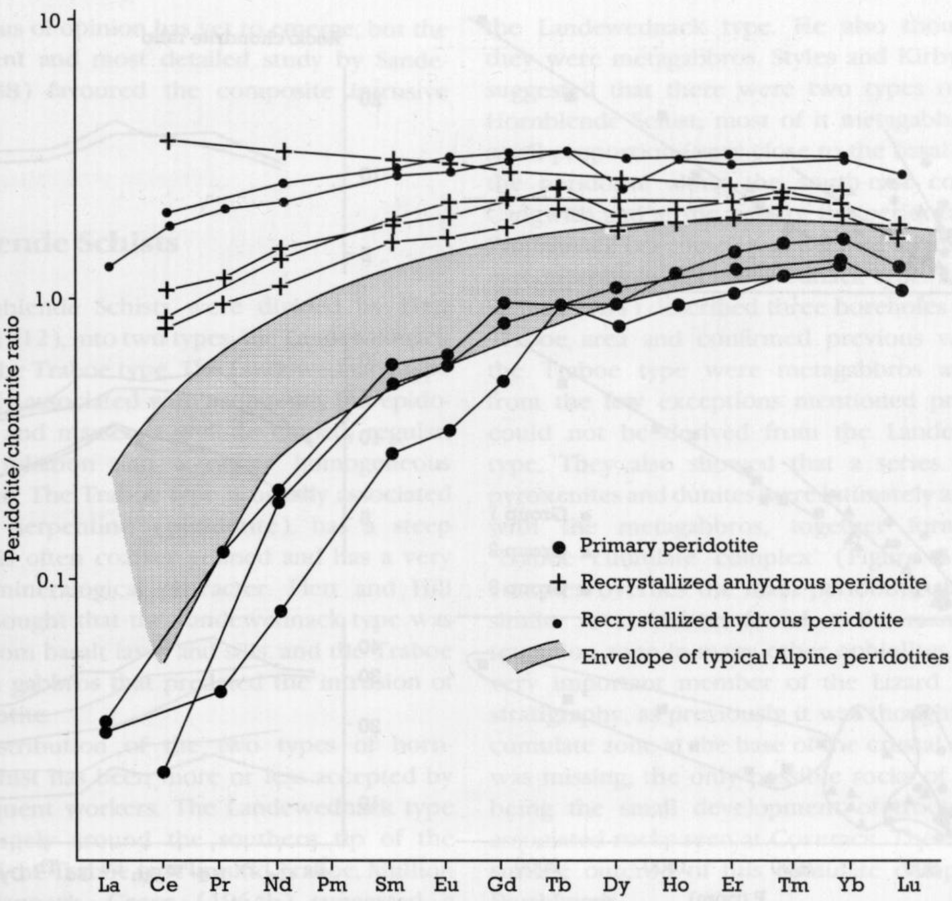


Figure 3.4 Chondrite-normalized REE data for the different assemblages of the Lizard peridotite (from Frey, 1969; Davies, 1984) and typical Alpine peridotites (data from Frey, 1984).

with flaser zones and shears with amphibolite and greenschist-facies mineral assemblages developed. Igneous lamination and layering are developed in a few places (Kirby, 1978), although, in general, apparent layering is due to secondary alteration.

The gabbros consist mainly of plagioclase and augite, with minor ilmenite and magnetite (Bromley, 1979). Olivine is also present, but is confined to the southern part of the outcrop. The top of the intrusive body is to the north, as there is evidence of progressive fractionation in that direction, as well as decreasing Mg/Mg + Fe in rocks and minerals and increasing incompatible elements such as titanium and phosphorus (Kirby, 1979a). There are also fractionated rocks such as hornblende diorites in the north. Leake *et al.* (1990) have described a second type of gabbro from the Trelan area which is a more fractionated type with iron-rich clinopyroxenes, a more sodic plagioclase and often considerable enrichment in Ti and Fe. Overall, the Crousa gabbros have low incompatible-element contents and light REE depletion which indicate derivation from a depleted mantle source and are consistent with an oceanic origin. In this respect they differ from the coarse-grained dolerites and gabbros in the rest of south Cornwall (Floyd, 1984).

In the north, between Godrevy Cove and Porthoustock, the gabbro is cut by numerous basaltic dykes that can occupy between 50 and 80% of outcrop; these are thought to represent the root zone of a sheeted dyke complex (Bromley, 1979). Similar, but much less numerous, dykes also occur in the main gabbro and peridotite further south (lower down in the ophiolite pseudostratigraphy) and some are part of the same sequence. The dykes were intruded throughout the cooling and solidification of the gabbro, as contact relationships show gradations from early, disrupted dykes without chilled margins to cross-cutting vertical dykes. Mineralogically, the dykes are aphyric and sparsely

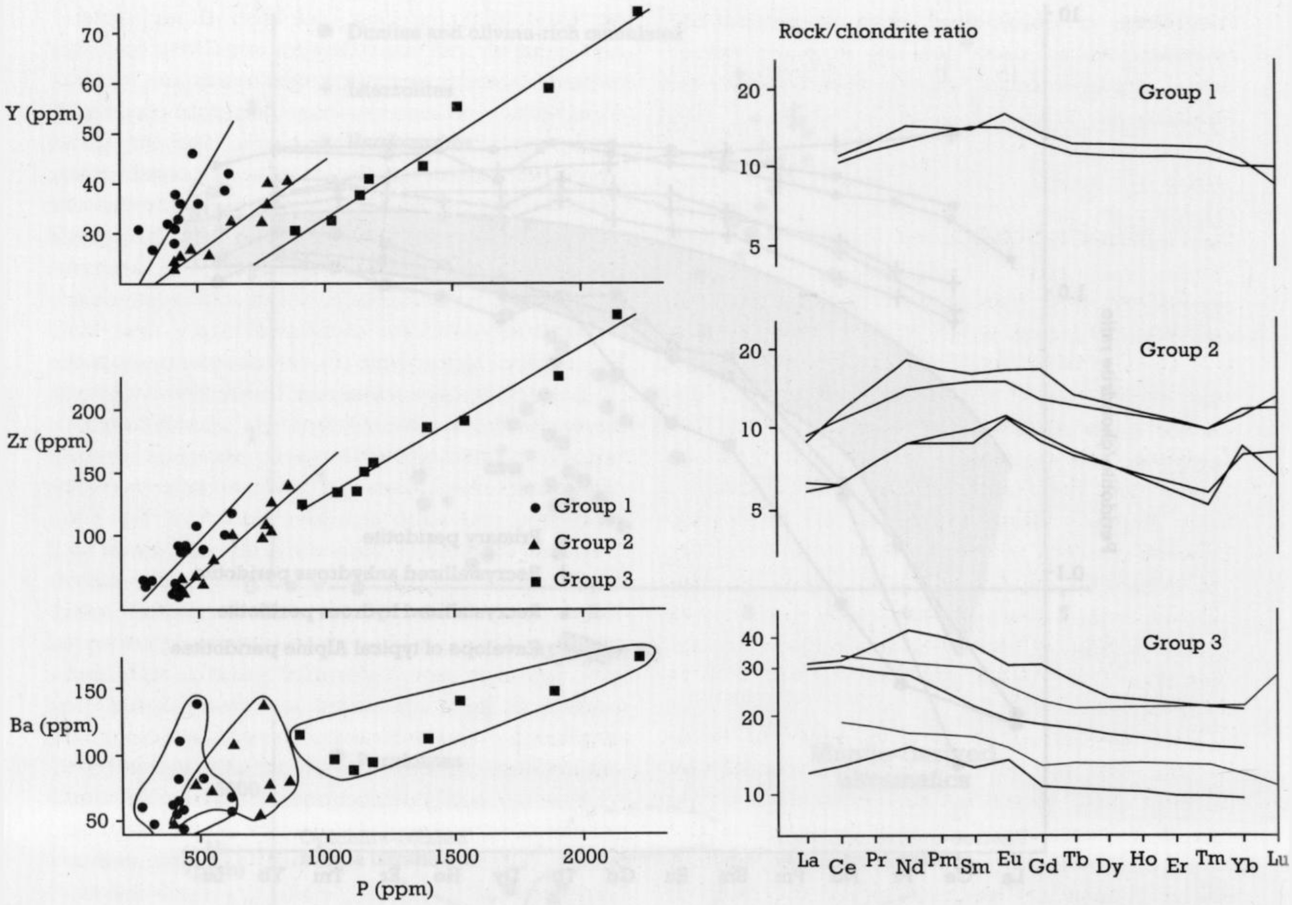


Figure 3.5 Incompatible-element and normalized REE patterns for the Lizard basaltic dykes, showing the distinctions between the three chemical groups (data from Davies, 1984; Kirby, 1984).

olivine- and plagioclase-phyric tholeiites as well as their amphibole-bearing metamorphosed equivalents (Kirby, 1984). They show variable incompatible element ratios and depleted to mildly light REE-enriched patterns (Davies, 1984; Kirby, 1984; Floyd, 1984). Three chemical groups (Figure 3.5) were identified by Kirby (1984), each with its own fractionation sequence involving mainly plagioclase, together with lesser olivine and clinopyroxene. Overall, dyke Groups 1 and 2 (with La/Nb <1, Zr/Nb *c.* 30 and depleted light REE patterns) are chemically similar to oceanic basalts (Kirby, 1984), whereas Group 3 (considered to represent the earliest dyke phase) is more enriched than either group 1 or 2 and was probably derived from a 'recently' light REE-enriched or metasomatized source, similar to that of the recrystallized peridotites (Davies, 1984).

Kennack Gneiss

The Kennack Gneiss is a series of interbanded acid and basic gneissose rocks that occur along the south-east coast of the Lizard, roughly at the base of the Goonhilly Downs structural unit. They have been controversial since the time of Bonney (1877b) and interpretations of their origin fall into two main groups:

1. migmatization of Old Lizard Head metasediments and Hornblende Schist by a hot over-riding sheet of peridotite (Sanders, 1955; Kirby, 1979b; Vearncombe, 1980; Malpas and Langdon, 1987);
2. composite intrusions of mafic and felsic magmas, probably along shear zones, followed by deformation (Flett and Hill, 1912; Green, 1964c; Bromley, 1979; Sandeman, 1988).

A consensus of opinion has yet to emerge, but the most recent and most detailed study by Sandeman (1988) favoured the composite intrusive model.

Hornblende Schists

The Hornblende Schists were divided by Flett and Hill (1912), into two types, the Landewednack type and the Traboe type. The Landewednack type is generally associated with sediments, has epidotic layers and masses, a well-developed, regular, flat-lying foliation and a rather homogeneous appearance. The Traboe type is usually associated with the 'serpentine' (peridotite), has a steep foliation, is often coarser grained and has a very variable mineralogical character. Flett and Hill (1912) thought that the Landewednack type was derived from basalt lavas and sills, and the Traboe type from gabbros that predated the intrusion of the peridotite.

The distribution of the two types of hornblende schist has been more or less accepted by all subsequent workers. The Landewednack type occurs largely around the southern tip of the Lizard and the Traboe type around Traboe, Mullion and Predannack. Green (1964b) suggested a radically different hypothesis for their origin. He proposed that all the hornblende schists had originated as basaltic lavas which had undergone amphibolite-facies regional metamorphism. Those close to the peridotite (Traboe type) had suffered an additional contact metamorphism during intrusion of the hot peridotite to form brown-hornblende granulites, whereas those immediately adjacent to the peridotite developed two-pyroxene granulites. He recognized several mineral assemblages formed at increasing temperatures and, on the basis of a few bulk rock analyses, suggested that the two types had similar compositions.

This interpretation has been rejected by most subsequent workers. On the basis of extensive field observations, Bromley (1979), suggested that the Traboe type were metamorphosed gabbros and basic dykes and not formed by the effects of metamorphism due to intrusion of the peridotite. Kirby (1979b), in addition to his field observations, produced numerous chemical analyses, which showed that although there was some overlap in composition, the Traboe type had a much wider range and could not be derived from the Landewednack type. He also thought that they were metagabbros. Styles and Kirby (1980) suggested that there were two types of Traboe Hornblende Schist; most of it metagabbro, but a small proportion (very close to the basal thrust of the peridotite along the south-east coast near Cadgwith and at the base of the peridotite in the Predannack borehole) was derived from 'contact' metamorphism of Landewednack type. Leake and Styles (1984) described three boreholes from the Traboe area and confirmed previous work that the Traboe type were metagabbros and apart from the few exceptions mentioned previously, could not be derived from the Landewednack type. They also showed that a series of metapyroxenites and dunites were intimately associated with the metagabbros, together forming the 'Traboe cumulate complex' (Figure 3.6). This complex overlies the main peridotite slab and is similar to cumulates found at the mantle–crust transition zone in many other ophiolites. This is a very important member of the Lizard ophiolite stratigraphy, as previously it was thought that the cumulate zone at the base of the crustal sequence was missing; the only possible rocks of this type being the small development of troctolite and associated rocks seen at Coverack. The only good surface outcrop of this cumulate complex is at Porthkerris.

The chemical composition of the Landewednack Hornblende Schists is very similar to ocean-floor basalt (Floyd *et al.*, 1976; Kirby, 1979b) and this is good evidence to suggest that they are part of an ophiolite complex. The Traboe Complex has more primitive chemical compositions but, as they are plutonic rocks that have formed by crystal fractionation, they cannot be directly compared with the Landewednack type which are dominantly metabasaltic lavas.

Mélange metabasalts

The south Cornish *mélange* (Barnes and Andrews, 1981) includes Mullion Island and the Meneage and Roseland areas (Figure 3.2); characteristically it contains many exotic clasts and huge blocks of basaltic parentage within a Middle–Upper Devonian argillite matrix. The larger blocks (Mullion Island, Nare Head) are composed of pillow lavas and pillow breccias, whereas smaller clasts include 'greenstones', aphyric and plagioclase-phyric basalts, dolerites and rare gabbros, together with

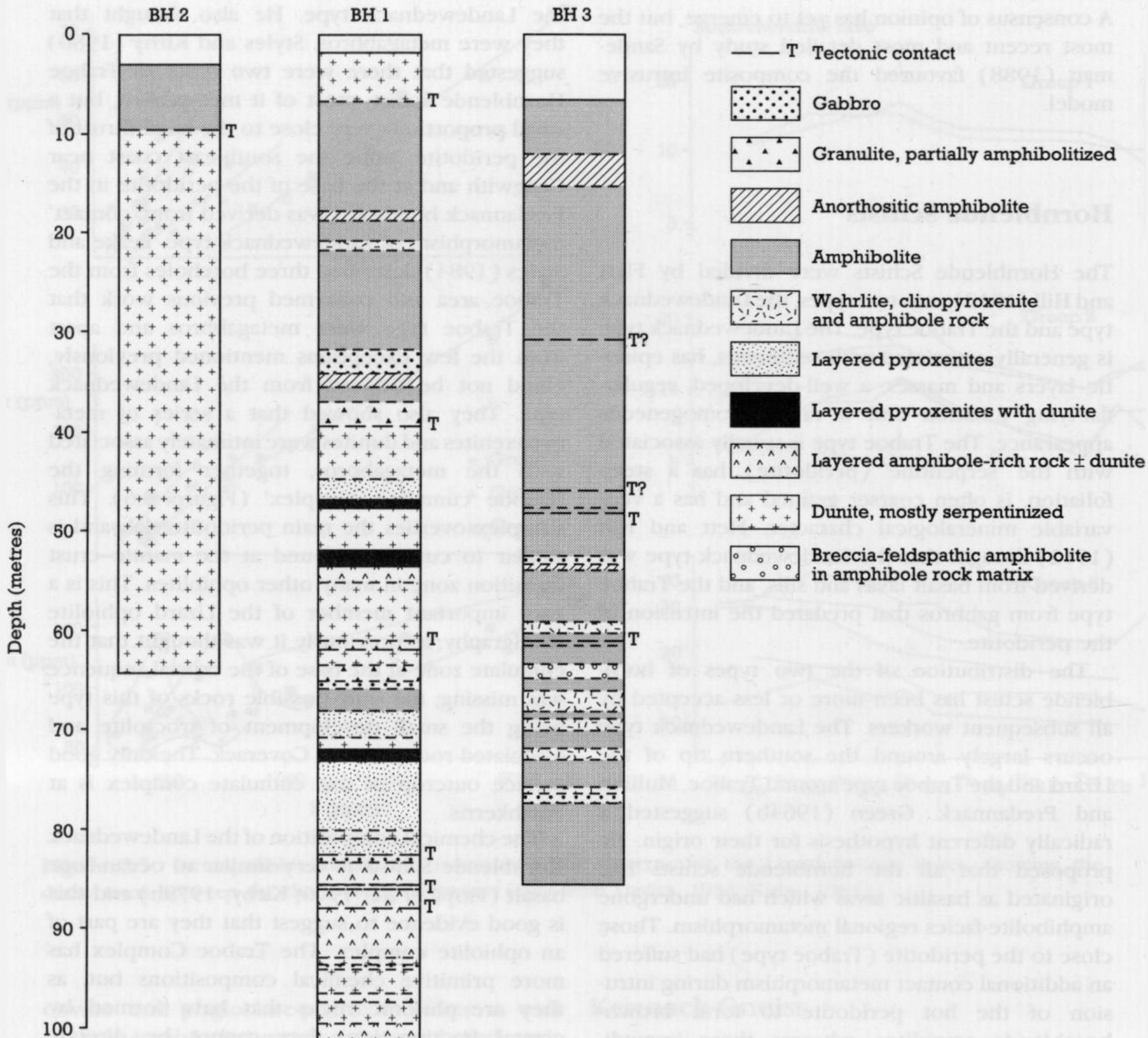


Figure 3.6 Lithological borehole logs for the Traboe ultramafic–mafic cumulate complex at Traboe, Lizard area (data from Leake and Styles, 1984).

their variably metamorphosed equivalents, including epidote–plagioclase–hornblende amphibolites (Barnes, 1984). Virtually all the basic rocks have undergone some degree of low-grade metamorphism, generally in the pumpellyite facies (Barnes and Andrews, 1981; Floyd, 1983). The Mullion Island pillow lavas show relict quench textures and primary calcic augite in a secondary groundmass (Floyd and Rowbotham, 1979).

Floyd (1984) demonstrated that the south Cornish metabasalts (including those in the *mélange*) were mainly tholeiitic and exhibited distinct incompatible-element ratios (Ce/Y, Nb/Y, Y/Zr) when compared with the rest of the basic volcanics in south-west England. In general, all the metabasalts and amphibolites within the south Cornish *mélange* have a range of chemical compositions from normal type to variably enriched, transitional-type MORB (Floyd, 1982a, 1984; Barnes, 1984). They are dissimilar to the ophiolitic basic rocks of the normal-type MORB composition in displaying slightly enriched incompatible-element patterns (Figure 3.7). It is concluded that the volcanic debris within the

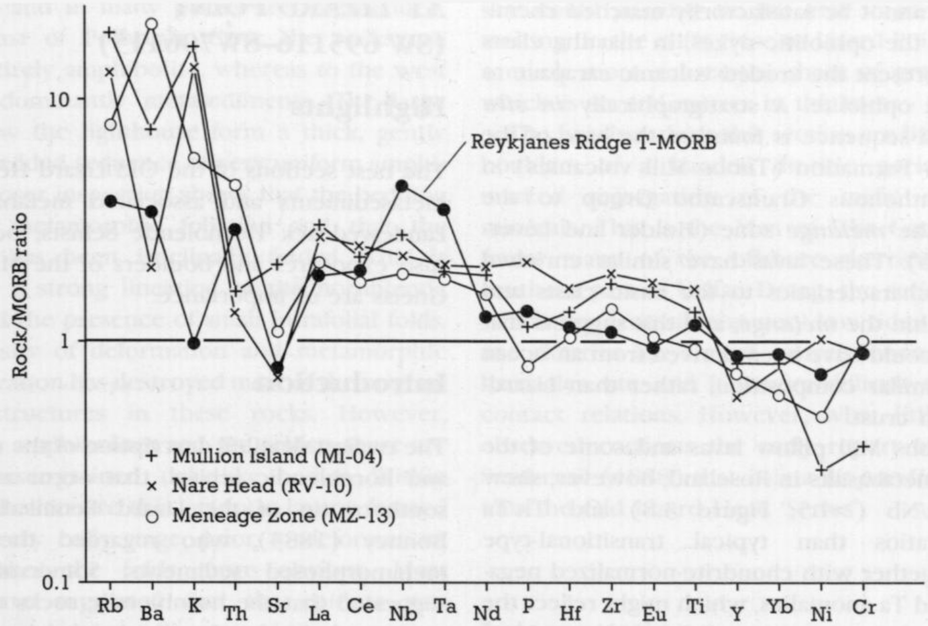


Figure 3.7 MORB-normalized multi-element patterns for selected *mélange* metabasalts compared with an example of transitional-type MORB from the Reykjanes Ridge.

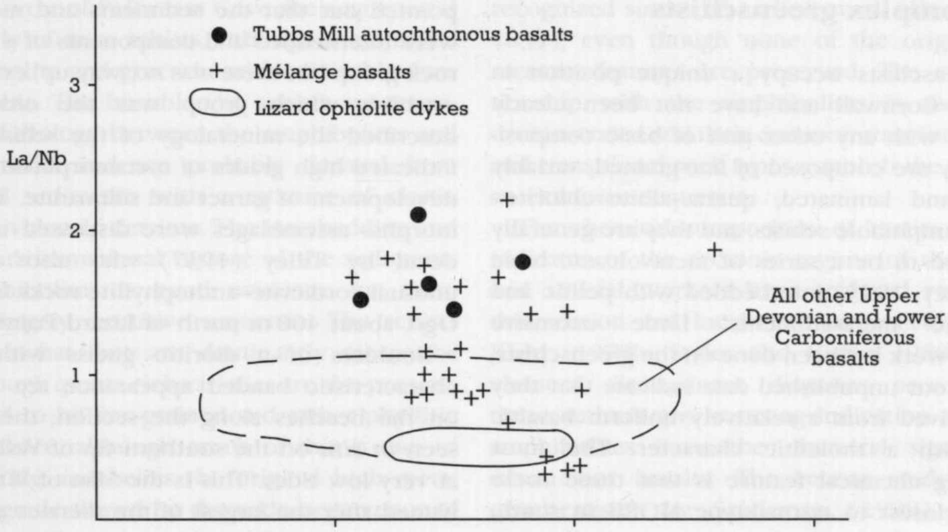


Figure 3.8 Diagram showing the variation in the La/Nb ratio for the Tubbs Mill pillow lavas and some of the *mélange* metabasaltic clasts relative to the Lizard dykes and Upper Devonian–Lower Carboniferous basic volcanics from south-west England.

mélange cannot be satisfactorily matched chemically with the ophiolitic dykes, in that the clasts do not represent the eroded volcanic carapace to the Lizard ophiolite. A stratigraphically *in situ* pillow lava sequence is found at the base of the Portscatho Formation (Tubbs Mill volcanics) in the allochthonous Gramscatho Group to the north of the *mélange* zone (Holder and Leveridge, 1986). These lavas have similar enriched chemical characteristics to the basic clasts and blocks within the *mélange*, and this suggests that the latter could have been derived from an ocean crust of similar composition, rather than Lizard-type ocean crust.

The Tubbs Mill pillow lavas and some of the *mélange* metabasalts in Roseland, however, show higher La/Nb (>1.5; Figure 3.8) and Th/Ta (>0.5) ratios than typical transitional-type MORB, together with chondrite-normalized negative Nb and Ta anomalies, which might reflect the influence of a subduction (back-arc?) environment. However, these minor chemical deviations could also have been generated by continental-crust contamination which, if the Gramscatho Basin was initially generated by the rifting of ensialic crust, might be expected for early segments of Devonian oceanic crust.

Start Complex greenschists

The greenschists occupy a unique position in southern Cornwall and have not been clearly identified with any other unit of basic composition. They are composed of fine-grained, variably foliated and laminated, quartz–albite–chlorite–epidote–amphibole schists, and they are generally considered to be a series of metavolcanic basic tuffs (Tilley, 1923) interbedded with pelitic and semipelitic metasediments. Little extensive chemical work has been done on the greenschists, although our unpublished data indicate that they were derived from a relatively uniform basaltic series with a tholeiitic character. The most interesting chemical feature is that these rocks are the closest to normal-type MORB in south-west England. In terms of the compositional variation exhibited by volcanic rocks in south-west England, therefore they have chemical characteristics that link them with the Lizard dykes and south Cornish *mélange* metabasalts. On this basis they could represent a volcanic segment of Variscan ocean crust docked against the Devonian parautochthon to the north.

A1 LIZARD POINT (SW 695116–SW706115)

Highlights

The best sections of the Old Lizard Head 'Series' metasediments and associated metabasalts, the Landewednack Hornblende Schists, occur here. Also exposures and boulders of the Man of War Gneiss are of importance.

Introduction

The earliest detailed description of the micaceous and hornblendic schists, that occur around the southern tip of the Lizard Peninsula was by Bonney (1883), who regarded them all as metamorphosed sediments. Somervail (1884) suggested that the hornblendic rocks were magmatic and this has been accepted by all subsequent workers. Flett and Hill (1912) give a full review of all earlier work, together with their own detailed descriptions of the range of metasediments. They regarded the hornblendic rocks as a series of metamorphosed basaltic lavas, tuffs and intercalated sediments and introduced the name Landewednack Hornblende Schists, derived from the hamlet one kilometre to the north. They pointed out that the sediments and metabasalts were interbedded and components of a coherent rock group but there was no 'way up' evidence to establish which group was the older. They described the mineralogy of the schists, which indicated high grades of metamorphism with the development of garnet and sillimanite. The metamorphic assemblages were discussed in greater detail by Tilley (1937) who also described unusual cordierite–anthophyllite rocks from Pistil Ogo, about 400 m north of Lizard Point.

Boulders of a dioritic gneiss with a very characteristic banded appearance are abundant on the beaches along the section; they can be seen *in situ* on the southern tip of Vellan Drang at very low tides. This is the Man of War Gneiss, named after the largest of the skerries and is the least accessible and least known of all the Lizard rock types.

Description

The Old Lizard Head metasediments and the Landewednack Hornblende Schists are intimately associated and in many places are interbedded. To the east of Polbream Cove the rocks are almost entirely amphibolite, whereas to the west they are dominantly metasediments. The large cliffs below the lighthouse form a thick, gently dipping, bedded sequence of very uniform amphibolites. Closer inspection shows that the bedding is also a metamorphic foliation and that the sequence has been isoclinally folded. This is shown by a strong lineation of the hornblende prisms and the presence of small intrafolial folds. The intensity of deformation and metamorphic recrystallization has destroyed most of the original igneous structures in these rocks. However, within the amphibolites and the schists there are a few coarser-grained, dyke-like bodies. Within the amphibolites are thin epidotic layers, formed during a very early stage, prior to deformation, which makes the folds more obvious. Most writers have suggested that the epidote was derived from calcic sediments. Also present are epidotic pods and cross-cutting veins that have clearly formed later. The majority of the rocks here give the impression that they are derived from a series of lava flows or sills, but, in a few places, horizons are present that have a less-uniform character and a fine-grained, fragmental nature that possibly could be derived from tuffs or volcaniclastic sediments.

To the west of Polbream Cove the sequence is dominantly of mica schists, although some layers of amphibolite and green hornblendic schists are also present. The hornblendic schists are transitional in lithology between the amphibolites and the sediments and are probably derived from tuffaceous sediments with a mixture of clastic and basic volcanic detritus. The interbedding and common deformational history of the sediments and amphibolites is good evidence for them being a largely extrusive sequence. The schists vary somewhat, but are dominantly muscovite rich, although quartz-rich varieties are also present. They tend to be fine-grained and rather phyllitic in appearance, although much of this is due to late shearing and belies the original high metamorphic grade shown by the wide occurrence of garnet, fine sillimanite and possibly kyanite.

At Pistil Ogo, associated with the greenschists, are the unusual cordierite–anthophyllite schists described by Tilley (1937) that have a characteristic blotchy appearance due to the clots of cordierite.

In a few places around Polpeor and Pistil Ogo, there are small pods of quartzofeldspathic material that could possibly be the first stages of partial melting. In the cliffs close to Lizard Point there is a much more substantial sheet of granitic rock which is several metres in thickness.

The beaches along this section are littered with boulders of a banded dioritic gneiss with a marked segregation of the mafic and felsic minerals. This is the Man of War Gneiss which forms many of the offshore skerries, and the southern part of Vellan Drang, the series of reefs which are accessible at very low tides. The reefs and skerries are almost entirely encrusted with barnacles, etc. and it is very difficult to see any contact relations. However, what little can be observed confirms the early report of Fox and Somervail (1888) that it is a *lit-par-lit* intrusion into the Old Lizard Head 'Series'.

Interpretation

This is the only site on the Lizard where the metasedimentary sequence can be clearly seen. The only other coastal section is a short section at Porthallow where it has been affected by intense shearing and alteration. Small, inland exposures are very poor and deeply weathered. The sedimentary origin of the rocks has been recognized since the earliest work (De la Beche, 1839), even though none of the original sedimentary features are preserved. The close relationship with the amphibolites is also clearly demonstrated and their common structural history and transitional rock types establish the former as an extrusive sequence.

The chemical composition of basalts is a good indicator of the tectonic regime of their origin and several workers have analysed rocks from this section and localities nearby (Floyd, 1976; Kirby, 1979b; Styles and Kirby, 1980). Trace-element discriminant diagrams presented by these authors give a strong indication that these amphibolites have the chemical signature of ocean-floor basalts. The recent study of REE geochemistry by Sandeman (1988) shows a generally flat pattern with about 20× chondritic abundances typical of mid-ocean ridge basalt (MORB). The recognition that the Landewednack Hornblende Schists have MORB affinities is important, as it connects this lower tectonic unit with the rest of the ophiolite complex. Their chemistry shows that they are not comagmatic with the other ophiolitic rocks, but this is not surprising, bearing in mind that the Lizard has features suggesting a slow-spreading centre and that small, transitory magma chambers would be expected rather than a single large one. This chemical type contrasts with most of the other basaltic rocks of south-west England, but is similar to the greenschists of the Start Complex.

The chemical data from the Man of War Gneisses (Sandeman, 1988) show that the contents of large-ion-lithophile elements, such as Sr, K, Rb and Ba, are high and that Ti is low compared with MORB. This indicates that they have similarities to arc-related rocks, which shows that they are not related to the Landewednack Hornblende Schists, but have a greater similarity to later magmatic episodes such as the Kennack Gneiss.

This site is very important in Lizard geology as it is the best section of the metamorphosed equivalents of the sea-floor sediments and basalts of the ophiolite complex. This upper part of the typical ophiolite sequence is never seen in its correct position in the Lizard ophiolite stratigraphy; it is only preserved in slivers attached to the base of the main ophiolite slab during obduction.

Conclusions

This site consists of metamorphosed sediments and magmatic rocks of the Lizard Complex. This includes the Old Lizard Head 'Series' (metamorphosed fine-grained sediments) and the Landewednack Hornblende Schists (metamorphosed basaltic lavas) which are intruded by the Man of War Gneiss (metamorphosed dioritic rocks). The Lizard Complex has been interpreted as a piece of ancient, early Devonian, oceanic crust (ophiolite) that was thrust to the north during the late Devonian. Studies of the chemistry of the 'basalts', show clear affinities with basalt erupted on the present-day ocean floor, at mid-ocean ridges. The later 'diorites' have a chemistry which is similar to that seen in the igneous rocks formed in modern island arcs at the margins of the oceans. This is the best site to examine sediments and volcanics which formed part of the floor of the Variscan ocean before it was subsequently destroyed by continent–continent collision.

A2 KENNACK SANDS (SW 734165)

Highlights

This is the type locality for the Kennack Gneiss Group, and it shows good exposures of 'primary' peridotite.

Introduction

The Kennack Gneiss Group is a series of interbanded mafic and felsic gneisses with associated gabbros, basaltic dykes and granites, that occur along the east coast of the Lizard, from Kennack Sands south to Church Cove, and in some of the valleys inland from there. They have been one of the most enigmatic and controversial rock groups of the Lizard Complex, and in this review they are covered by two sites, this locality and one at Polbarrow. To avoid repetition, the introduction for both sites is given here and the discussion at the end of the Polbarrow site description.

Early workers, and indeed most subsequent authors, have found this to be a most perplexing group of rocks. De la Beche (1839) recognized the intrusive nature of the banded gneisses into the peridotite, both here and at Parn Voose site (Polbarrow), but many other localities now attributed to the Kennack Gneiss were originally mapped as hornblende schist. Bonney (1877a) assigned the Gneisses to his 'granulitic group', and suggested that they were highly metamorphosed sediments, with the banding being an expression of the original sedimentary bedding. In contrast to De la Beche (1839), he proposed that the peridotite was intruded into the granulitic group. He noted the similarity of the gneissic rocks to those in north-west Scotland, which led him to suggest that these and the other metamorphic rocks of the Lizard were Archaean in age.

Teall (1887) described the felsic portion of the gneiss as intruding into the mafic and, therefore, that the rocks were igneous and not sedimentary. The banding was due to a 'rolling out' of this intrusive material under pressure, a kind of fluxion structure. Somervail (1888) described the intrusive nature of the felsic portion of the gneiss into the peridotite. Bonney and McMahon (1891) accepted that the banding of the gneisses might be due to fluxioning of mafic rock intruded by felsic rocks, but still maintained that they were older and that the peridotite was intruded into them. Lowe (1901, 1902) stoutly maintained that the 'granulitic group' was the youngest of the area, drawing attention to the conformable nature of the fluxion banding, the numerous inclusions and peripheral alteration of peridotite blocks in the gneiss.

This general view was accepted by Flett and Hill (1912) in the Lizard Memoir. Flett described the field relations in great detail showing that the felsic fraction intrudes the mafic fraction, and that both intrude the peridotite. The banding and many of the structures observed were due to the fluxioning together of composite intrusions of felsic and mafic magmas while they were still hot, together with some reaction to produce rocks of intermediate composition. He also recognized a group of granitic rocks, not accompanied by mafic rocks, that he called the Kennack Granite. Bonney (1914), however, was still reluctant to accept that the 'granulitic group' was younger than the peridotite. Flett's views were restated with little alteration in the second edition of the Lizard Memoir (Flett, 1946).

More recently, Sanders (1955) has restudied the Kennack Gneiss and the structures along the south-east coast of the Lizard. He made the then radical suggestion that the form of the peridotite was a thin sheet rather than the plug-like intrusion accepted by all previous workers. He also suggested that the Kennack Gneisses were a thin development immediately beneath the peridotite, formed by migmatization of the Landewednack Hornblende Schists.

Green (1964c), in his study of the Lizard, largely devoted himself to the peridotite, but also discussed the Kennack Gneiss. He generally accepted Flett's views suggesting *lit-par-lit* injection of felsic magmas into mafic sills, but thought that there was no need for actual mixing of the magmas.

Strong *et al.* (1975), in a brief paper proposing an ophiolitic nature for the Lizard, preferred Sanders' (1955) view that the gneisses were migmatites. Bromley (1979) discussed the migmatitic and intrusive models and favoured an intrusive origin by deformation of a felsic net-vein complex. Kirby (1979a) carried out a detailed field and chemical study, and came to the conclusion that the gneisses were probably formed by the migmatization of Old Lizard Head metasediments and Landewednack Hornblende Schists. Styles and Kirby (1980) described a borehole at Kennack where a considerable thickness of gneisses were intersected (150 m). They stressed the heterogeneity of the gneiss group and, with a few words of caution, supported the conclusion of Kirby (1979a).

Styles and Rundle (1984) carried out a Rb/Sr isotopic study of a granite vein from the Kennack borehole. They obtained an age of 369 ± 12 Ma (mid-Devonian), which finally put to rest any lingering thoughts that the gneisses might be Precambrian and, as the initial ratio was low (0.70424 ± 0.00009), they were unlikely to have originated from melting of old crustal material. They suggested that the source consisted of a high proportion of mantle or juvenile crustal material.

Subsequently, Barnes and Andrews (1986) have briefly described the field relations of the Kennack Gneisses, and suggested the simultaneous existence of felsic and mafic magmas. They reinterpreted Kirby's (1979a, 1979b) chemical data, and have suggested that the low incompatible-element contents of the felsic portion do not fit with an origin by melting of amphibolite, but by melting of depleted continental crust material. This mixing of such a magma with oceanic-basalt material possibly occurred in an intracratonic setting where ocean crust was being formed in a rift. However, Malpas and Langdon (1987) presented new major- and trace-element data to support an origin by melting of a mixture of Old Lizard Head metasediments and Landewednack Hornblende Schists, a model similar to that proposed by Kirby (1979b).

The most recent and most detailed study of all is that by Sandeman (1988), who produced maps at a scale of 1:1500 and described many field relations in great detail.

Sandeman (1988) points out the relationships between the different components and concludes that two magmas must have been present at the same time. The felsic was slightly later than the mafic and both physical intermingling and chemical mixing between the two magmas took place. His detailed chemical studies show that the magmas did not have any close relationship prior to their mixing during intrusion. The mafic magma has the chemical characteristics of a calc-alkaline basalt, probably associated with a volcanic arc. After mixing with the granitic magma the composite 'magma package' was intruded along shear zones and faults.

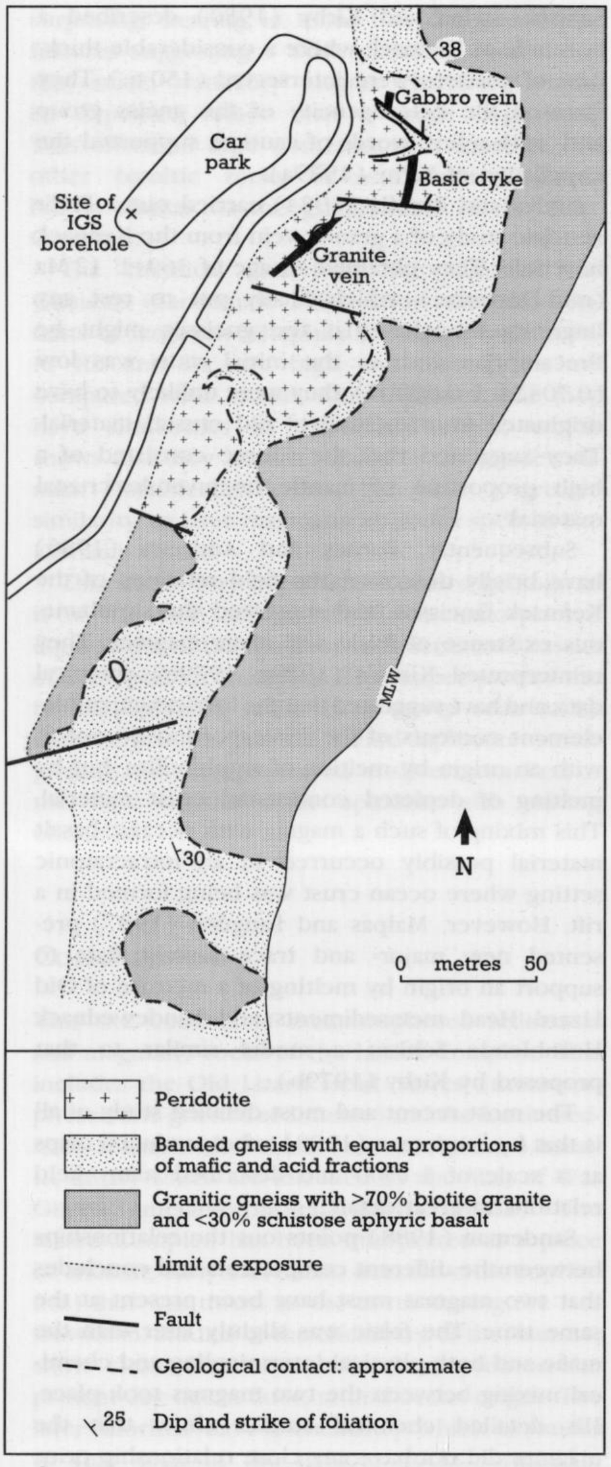


Figure 3.9 Geological sketch map of the Kennack Sands site (A2).

Description

The outcrops along the cliffs and foreshore to the south of the stream at Kennack Sands are some of the best to show the relationships between the various components of the Kennack Gneiss Group and other rock types including peridotite, basaltic dykes and gabbro veins. A sketch map shows the main features (Figure 3.9).

The outcrop in the low cliff a few yards south of the stream shows some of the classic features of the Kennack Gneiss; it was figured by Flett and Hill (1912). Here a vein of banded gneiss intrudes the peridotite as a steep, dyke-like body, with faulting along the northern contact. The felsic portion of the gneiss is slightly younger than the mafic which it cross-cuts locally, but they appear to have been intruded essentially together. The banded gneiss vein truncates a gabbro pegmatite vein to the north and a basaltic dyke to the south, demonstrating that it is the latest intrusive phase in the vicinity.

The banded gneisses in the outcrops close to the cliff are generally of the finely banded variety with subequal proportions of the felsic and mafic components, in bands usually a few centimetres thick (Figure 3.10). In many places, it can be seen that the felsic portion is the younger, particularly in the more mafic varieties where they are cut by numerous thin felsic veins. The degree of deformation is always high, and at least two phases of high-temperature folding can be seen.

The large rocks lying further from the cliffs are composed largely of granite gneiss sheets, several metres in thickness with much thinner interlayers of mafic gneiss. On the seaward side of one of the first large rocks encountered, is a vein of gabbroic to dioritic composition with abundant subrounded xenoliths of gabbro and numerous plagioclase xenocrysts. The large plagioclases, so clearly xenocrysts in this rock, are probably of a similar origin to the 'phenocrysts' in the more homogeneous, fine-grained dioritic rocks nearby.

At Thorny Cliff there are distinctive hybrid rocks. They consist of a monzodioritic host containing blocks of a fine mafic rock. The mafic rocks have a marked lobate outline and appear to have undergone partial digestion by the more felsic host. This is good evidence that here has been assimilation of the mafic rocks to form hybrids of intermediate composition.

The peridotite exposed along the cliffs at Kennack is relatively fresh, often showing only

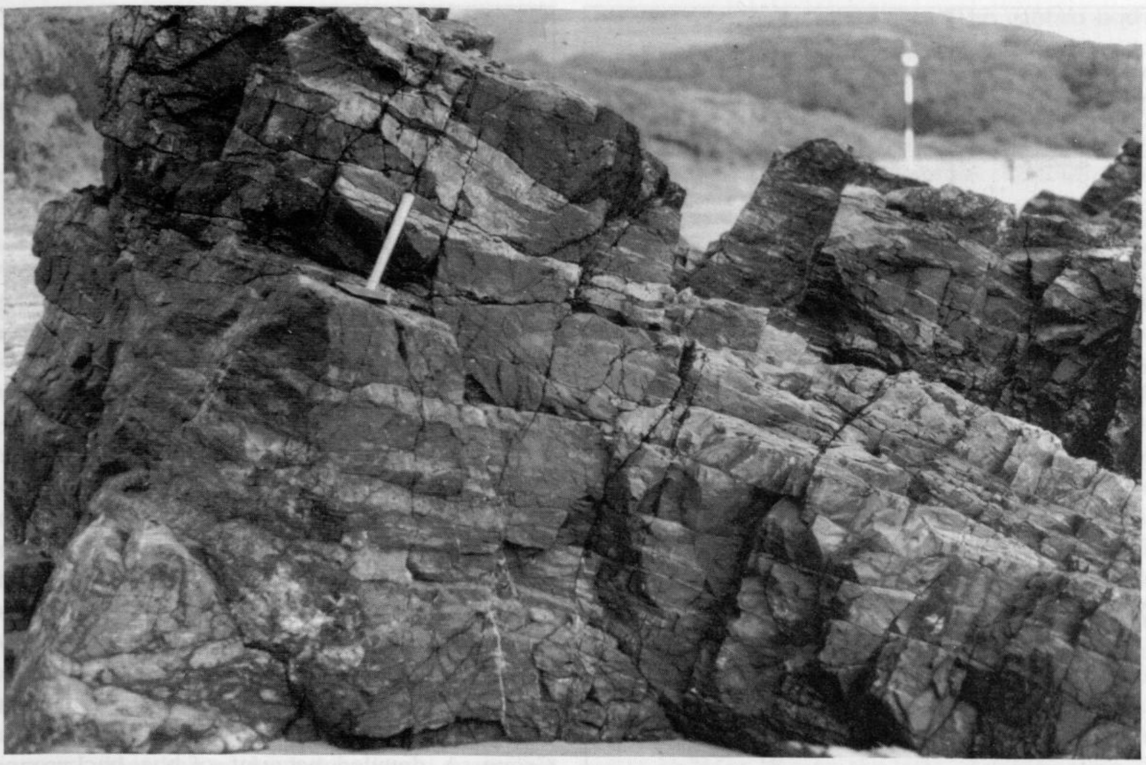


Figure 3.10 Banded gneiss, Kennack Sands. (Photo: M.T. Styles.)

around 50–60% serpentinization. The rock is very dark green, with prominent, large, bronzy orthopyroxenes up to 10 mm in size and small, dark-green clinopyroxenes. There is a steep foliation trending roughly north–south and a compositional banding due to variation in the proportion of pyroxene, with thin pyroxenite bands in a few places. The contacts between peridotite and the felsic portion of the gneiss are characterized by marked alteration with the formation of various secondary minerals, including talc and chlorite. However, the most striking alteration is to an asbestiform magnesian amphibole.

The features seen along this beach section clearly show that the felsic portion of the gneisses is younger than the peridotite and also the pegmatitic gabbro and basic dykes.

Interpretation and conclusions – see Polbarrow – The Balk below

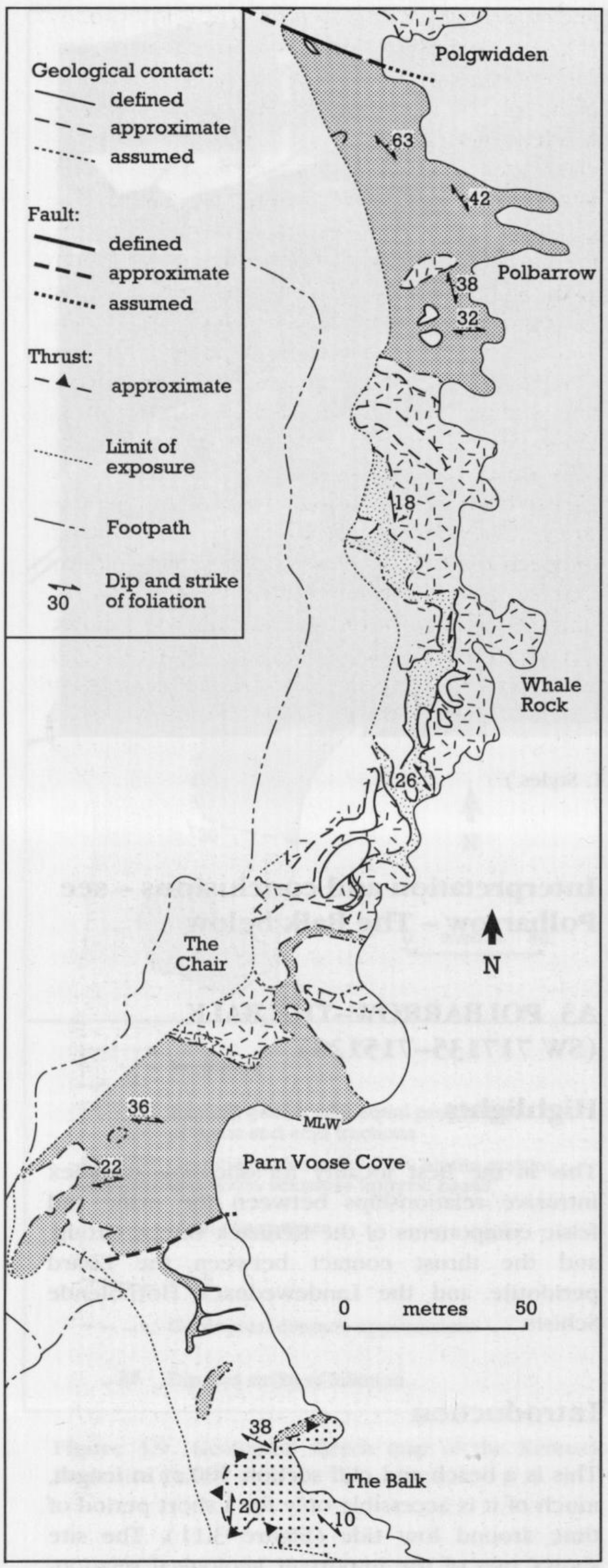
A3 POLBARROW–THE BALK (SW 717135–715128)

Highlights

This is the best locality for showing complex intrusive relationships between the mafic and felsic components of the Kennack Gneiss Group, and the thrust contact between the Lizard peridotite and the Landewednack Hornblende Schists.

Introduction

This is a beach and cliff section 500 m in length, much of it is accessible only for a short period of time around low tide (Figure 3.11). The site shows two of the important geological relationships of the Lizard Complex. First, that between the Landewednack Hornblende Schists and the



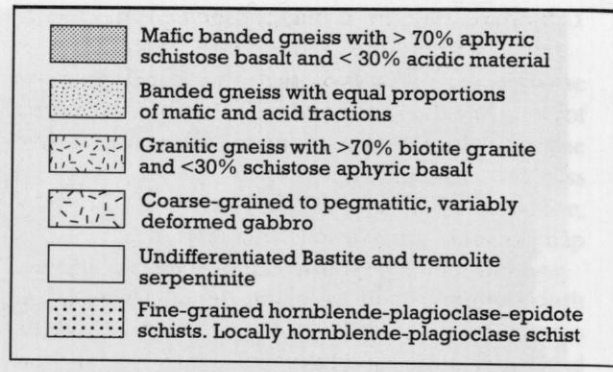


Figure 3.11 Geological sketch map of the Polbarrow–The Balk site (A3) (after Sandeman, 1988).

overlying Lizard peridotite in the southern part of the Complex, and, secondly, between the gabbros and felsic and mafic components of the Kennack Gneiss. The relationships seen from Parn Voose along the coast, past Whale Rock to Polbarrow, show a deformed intrusive complex of gabbro and banded gneiss, and are most important in an assessment of the origin of the Kennack Gneiss Group. A detailed account of the background research on the Kennack Gneiss Group was given previously with the Kennack Sands site description.

Description

The contact between the Lizard peridotite and the Landewednack Hornblende Schist is seen at The Balk, along the road leading into the old quarry from Church Cove and around the lower part of the old quarry face. The Landewednack Hornblende Schist is a dark, slightly banded, schistose amphibolite with a flat-lying foliation. Close to the contact with the overlying peridotite, the amphibolites are noticeably more gneissose. Some of this is possibly the effect of metamorphism, locally induced by the overriding peridotite, similar to that described by Green (1964c) at a similar contact north of Cadgwith. There are also some deformed pods of gabbro at this horizon. The actual contact with the peridotite is highly sheared, with a fairly gentle dip to the north-west; locally there is calcite and altered sulphide mineralization along the thrust plane. The thrust is offset by small, late, upright faults in several places. The peridotite also shows the effects of intense shearing and, in the quarry and on the beach below, blocks can be found with augen of orthopyroxene in a highly sheared matrix of streaky serpentinite, a peridotite mylonite. This section clearly shows that the peridotite was thrust over the Landewednack Hornblende Schists at relatively high temperatures; it is not an intrusive contact.

There is little outcrop between the Balk Quarry and Parn Voose Cove where the rocks are very different. The south side of the cove appears to be along a fault as, along the south wall, the peridotite is at sea-level, but at the back of the cove it is at the top of the cliff, some 50 m higher. A few outcrops and most of the boulders in the cove are dominantly mafic gneiss with thin veins of felsic material such as that figured by Flett (1946, p. 104). The gneiss has been highly folded and bears a striking resemblance to migmatites from high-grade metamorphic terranes. Much of the rock around the back of the cove is a medium- to coarse-grained gabbro (Figure 3.12), locally sheared and cut by flaser zones. Along the western side of the cove, xenoliths of peridotite and gabbro are included in banded gneiss.

Further north, between Parn Voose and Polbarrow, along the rocky ledges (only accessible at low tide), the relationships with the banded gneisses are most clearly seen. The gabbro body at the back of Parn Voose is quite extensive and forms much of the rock for some 500 m, but in many places it is intruded by thick sheets of banded gneiss. The intrusive relations are very clear, and there are numerous xenoliths of peridotite and gabbro within the gneiss. The gabbro intrudes into the peridotite and these are then in turn intruded by the banded gneiss. Often at the margins of the felsic gneiss, there is a rock of intermediate composition which has lobate contacts with the mafic rock and appears to have reacted with it. In some places, offshoots of felsic gneiss finger out into the gabbro, and in others, lenses of gabbro are streaked out within the foliation of the gneiss. The two rock types have clearly been deformed together at high temperatures. Many of the features of the contacts between the felsic gneiss and the gabbro suggest that the gabbro was hot and relatively soft at the time of injection of the gneiss. This was pointed out by Flett and Hill (1912) and Kirby (1979b). The peridotite appears to have acted as rigid blocks during the plastic deformation of the other rocks showing that, at the time of deformation, it was crystalline peridotite not serpentinite which

Figure 3.12 Acid-veined gabbro at Parn Voose. (Photo: M.T. Styles.)

would have had much weaker mechanical properties.

Interpretation (Kennack Sands and Polbarrow–The Balk)

The introduction to both Kennack Sands and Polbarrow showed that there has been a long-running controversy over the origins of the Kennack Gneiss Group. Proposals fall into two main groups:

1. migmatization of various mixtures of pelitic metasediments and hornblende schists, and
2. late composite intrusions of felsic and mafic magmas.

The outcrops within these sites are the most important for assessment of the origin of the rocks as they encompass the widest range of lithologies of this diverse group.

The finely banded, highly deformed rocks seen at Kennack and Parn Voose bear a striking resemblance to migmatitic rocks from high-grade terranes. At localities such as Polpeor local 'sweat outs' of granitic material suggest that local melting might have occurred in places where the temperature was a little higher. Similarly, at Porthkerris, local melting of the amphibolite seems to have taken place, so the circumstantial evidence for anatexis is present. However, even at Kennack the evidence (Sandeman, 1988) shows that the very banded rocks are restricted to the cliffs and innermost foreshore rocks and that overall there is a zonal arrangement. This zonal pattern was most clearly seen in some of the smaller outcrops, to the east of Kennack and at Little Cove Poltesco, but can also be demonstrated at Kennack. On the outer rocks is a granitic core, with few mafic rocks, followed farther inshore by a mixed, interbanded zone and finally a dominantly mafic zone with little granitic rock, close to the cliff. Such a regular pattern found at several localities is difficult to explain by a migmatitic origin, although some original interlayering of sediment and amphibolite as proposed by Styles and Kirby (1980) might be plausible.

The field evidence from Kennack and Parn Voose is somewhat equivocal, but could be used to support a migmatitic origin. The proportions of felsic and mafic rocks are roughly correct, but the rocks have been so extensively deformed that any original contact effects or cross-cutting intrusive relations have been smeared out. The field relations around Whale Rock leave much less doubt as to the origin. It is the opinion of Flett and Hill (1912), Green (1964c), Sandeman (1988) and the author that the relationships seen here where the rocks are least deformed, are the key to the whole group. Here there are clear composite intrusions, with mafic magmas closely followed by felsic magmas and abundant evidence of hybridization processes. The location of the intrusions seems to be controlled by structural features, particularly flat-lying thrusts and, to a lesser extent, minor offshoots along steep faults. At Polbarrow and Parn Voose it may be the 'basal' thrust of the peridotite, but at Kennack a thrust within the lower part of the peridotite is also possible.

A borehole was drilled in 1980 by the Institute of Geological Sciences (now British Geological Survey) in the car park at Kennack (Figure 3.9), about 100 m north-west of the site described here (Institute of Geological Sciences, 1982). This penetrated some 150 m of Kennack Gneiss with interlayers of peridotite (Styles and Kirby, 1980). Such a thickness was much greater than expected, as most previous models had suggested that the gneiss was essentially a thin development at the base of the peridotite sheet. It would be difficult to generate such a thickness of gneiss by melting, as there would be a problem in achieving sufficient heat; sandwiching the protolith material between slabs of peridotite is one of the few possibilities. There is no real problem about the thickness if the origin was intrusive.

Kirby (1979b) and Malpas and Langdon (1987) put forward chemical data which they interpreted as supporting a migmatitic origin. The chemical compositions of parent rocks, felsic anatectites and mafic restites seemed to fall on linear trends, as would be expected if they were related by partial melting. The composition of granitic fractions was also similar to minimum melt compositions. The chemical data of Sandeman (1988), with a much larger number of samples, do not clearly show these important linear trends. He has suggested that only the felsic fractions show linear trends, and that the mafic rocks show either scattered or possibly curved distribution. The trends suggested by Malpas and Langdon (1987) may be a fortuitous accident of their small, and hence unreliable, data set. A summary of this new data (Sandeman *et al.*, in prep) is given below.

The mafic magmas that formed the mafic portion of the gneiss are quite distinct from the Landewdnack Hornblende Schists and most of the ophiolite dykes that have oceanic affinities. They are light-REE-enriched and have affinities with volcanic arcs and show evidence of crystal fractionation. The mafic magma chambers were intruded by felsic magmas, leading to the magma mingling which, on intrusion into the peridotite, etc., gave the very banded gneisses and some mixing and hybridization to produce intermediate magma types. In most cases, these phenomena can only be assumed from the chemical characteristics, and only at localities such as Whale Rock can they actually be seen. The subsequent intense deformation of possibly hot, incompetent rocks accentuated the degree of banding and gneissic appearance of these mixed rocks.

It is interesting to note that the two most detailed studies by Flett some 80 years ago, based entirely on field relations, and by Sandeman with the aid of modern geochemistry, have come to essentially the same conclusion. The Kennack Gneisses are a series of composite mafic and felsic intrusions that subsequently have been extensively deformed.

Conclusions (Kennack Sands and Polbarrow–The Balk)

These are important sites showing the juxtaposition by a major thrust plane of the Lizard peridotite and the Landewednack Schist, two constituent major parts of the Lizard Complex. A wide range of igneous rocks including gabbros, and acidic and basic gneisses, are also exhibited. Although the association of metamorphic and igneous rocks is complex, a sequence of events may be determined that helps to interpret the magmatic structure of the oceanic crust and upper mantle.

Peridotite occurs as blocks in the gneisses. Gabbro intrudes the peridotite and is in turn intruded by gneiss, the last dated to around 370 million years before the present (early to mid-Devonian). The intimate mixing (and, in places, hybridization) between basic and acid gneisses has been the subject of much debate. It is now thought to have been the product of the mixing of two very different but contemporaneous magmas. These sites tell us much about the development of the Lizard Complex as a slice of ancient ocean floor that was finally thrust over continental crust during late Devonian times.

A4 KYNANCE COVE (SW 684133)

Highlights

Primary and recrystallized types of peridotite are well exposed here, and the relationships between these rocks and granite veins, basic dykes and hornblende schist are clearly seen at a locality that is readily accessible.

Introduction

Kynance Cove is one of the few places on the west coast of the Lizard where it is possible to descend the large cliffs. Here, the two main types of peridotite, the primary and recrystallized types are juxtaposed by a fault. In the gap between Asparagus Island and the mainland, and in the cliffs going northwards to Lawarnick Cove, are a variety of granitic, amphibolitic and banded gneisses within the peridotite. This area has not been discussed in many publications, and only Flett and Hill (1912) have described it in detail and published a sketch map. There have been no major controversies about the interpretation of the rocks in this area.

Description

The east side of Kynance Cove has a large wall formed of the primary-type peridotite, though the rock is probably more easily studied on the paths leading down to the cove. It is a coarse, partially serpentinized peridotite with prominent, bronzy orthopyroxenes and a distinct coarse steep foliation. When at its freshest it is a dark, green-black colour, but many samples from this area have been slightly hematized to give a dull red-brown. In the rocks at the base of the cliff there are several basaltic dykes cutting the peridotite. A large fault runs roughly parallel to this western side of the cove and, in the central and western parts the peridotite, is of the recrystallized type. This has a distinct, closely spaced, metamorphic foliation with prominent augening around orthopyroxene porphyroblasts. Amphiboles are common in this type, and most rocks are reddish or brownish due to oxidation of the iron minerals.

Granitic sheets several metres in thickness are present between Asparagus Island and the mainland and also in the cliff to the north towards Lawarnick Cove. They are quartz–feldspar rocks with a little muscovite, and little or no foliation is developed. They do, however, show some boudinage structure. These features distinguish them from the acid fraction of the Kennack Gneiss. Similar granite sheets are also found at several other localities along the west coast of the Lizard. There is often a marked reaction zone at the contact with the peridotite, forming zones of talc and chlorite representing the migration of chemical components across the contact. Silica has moved into the peridotite to form talc, and magnesium migrated into the granite to form chlorite.

Within the rocks in the centre of the gap between the base of the cliffs and Asparagus Island, is a block of amphibolite. The contact relations are not clear, but it appears to be of the more banded Traboe type rather than the massive Landewednack-type amphibolite. This and the presence of banded gneiss a little to the north in Lawarnack Cove, suggest that this is close to the lower contact of the peridotite.

Interpretation

Kynance Cove shows the two main peridotite types, the primary and recrystallized types, in close proximity. However, this is not a transitional contact that records the sequence of events of how one is formed from the other. The two rock types with their contrasting mineral assemblages and previously formed structural fabrics, have been juxtaposed by late, steep faults. The intrusive relations and contact alteration of the late granite sheets are well-displayed.

The presence of the Traboe type amphibolites both here and in George's Cove, 2 km to the north, is of regional structural interest. Their presence and the bodies of Kennack Gneiss here and further south at Pentreath suggest that this level is close to the base of the peridotite sheet similar to the east coast. The base of the peridotite is clearly offset in numerous places by late faults, such as that at the east side of Kynance Cove. It is generally close to sea-level both here and at George's Cove, but is downfaulted to somewhat deeper levels in the intervening area. Previous discussions of the structure of the peridotite, covered in the introduction to the chapter, and particularly Green (1964c), suggested that, although the contact on the east coast might be flat lying, that on the west coast was steep, and consistent with a diapir-like form. The evidence outlined above, however, points to a structure similar to the east coast, although less well exposed, and hence does not support a diapir-like form.

Conclusions

Here outcrops of both primary and recrystallized Lizard peridotite are seen to be cut by later granitic veins and basaltic dykes. The peridotite represents a slice of upper mantle, thrust over younger rocks of the then continental margin, during the late Devonian. It forms part of the ultramafic base to the Lizard ophiolite, being formed at high temperatures and pressures in the mantle prior to subsequent recrystallization and serpentinization. The site at Kynance Cove therefore presents graphic evidence for the juxtaposition of Lizard rocks with an oceanic origin carried on the back of a major thrust over the top of continental crust.

A5 COVERACK COVE–DOLOR POINT (SW 784187–SW 785181)

Highlights

This is the best section through the contact between the peridotite and gabbro units; this contact is thought to be the Mohorovičić discontinuity between the mantle and oceanic crust of the Lizard Complex.

Introduction

This has been a classic area of Lizard geology since the intrusive relations of the various rock types were described from here by Flett and Hill (1912). These authors demonstrated the intrusive sequence of peridotite, troctolite, gabbro and basic dykes, and produced several field sketches and a map to illustrate this. Green (1964a) showed that the peridotite was a mantle rock and thought that the gabbro was a later ring-intrusion following emplacement and uplift of the peridotite. The area became of great significance after ophiolite models for the Lizard had been proposed (Bromley, 1979; Kirby, 1979b; Styles and Kirby, 1980), as this was then considered to be the transition zone from the crust to the mantle, and thus represent the Moho. This was addressed particularly by Kirby (1979b), who studied the zone in detail and drew attention to the troctolites and associated rocks that are probably representative of a thin sequence of transition zone cumulates. Davies (1984) carried out a Sm/Nd isotope study of a gabbro sample from Coverack and produced a mineral–rock isochron that showed a crystallization age of 375 ± 34 Ma (mid-Devonian).

Description

The section at Coverack is a broad sweep of beach that is covered at high tide, but numerous, low, rounded, rocky outcrops are seen at low water (Figure 3.13). The magmatic stratigraphy consists of three main divisions, an ultrabasic division to the south, a central interbanded division and a northern gabbro division (Figure 3.13).

The ultrabasic division consists largely of the primary type peridotite, the 'bastite serpentine' of Flett and Hill (1912). The peridotites exposed here, particularly around Dolor Point, are some of the freshest on the Lizard, being only around 30% serpentinized in some cases. They are dark-green, coarse-grained rocks that consist largely of olivine with conspicuous orthopyroxene. Clinopyroxene is also present; its abundance varies from 5–10%. Thus there are both harzburgites and lherzolites, but they form part of a continuous spectrum and are not significantly different rock types. Many samples contain a brown chrome spinel and a few exhibit a small amount of plagioclase. The peridotites have a coarse subvertical foliation that trends roughly north-south. This is a high-temperature porphyroclastic texture that here, as in many other ophiolites, is ascribed to solid-state flow that occurred in the upper mantle beneath the spreading centre. Dunites occur as pods several metres in size around the west side of the harbour and also as a series of veins on the south side of Dolor Point. The dunites are conspicuous by their lack of orthopyroxene and reddish colour as the olivine is usually totally serpentinized. The origin of the dunites will be discussed in detail under 'Lankidden' below, but essentially they are thought to have been formed by the passage of picritic melts through the mantle.

At the northern part of this division, some 50 m north of the harbour, is the famous Coverack troctolite. This is a very distinctive rock composed of white plagioclase and red serpentinized olivine. Rarely, the olivine has survived alteration and then the rock is dark green and black and actually looks more like the gabbros than the 'typical' troctolite. Thin-section examination shows that many of the rocks are not true troctolites, as they contain more than 10% clinopyroxene and are, in fact, olivine gabbros, but they are still distinctly different from the main gabbro. The proportion of feldspar to mafics also varies substantially from 20 to 80% feldspar, although most have roughly equal proportions. The troctolite forms two sheet-like bodies, but it and the peridotite are cut by numerous sheets of pegmatitic gabbro and fine basic dykes. The intrusive sequence of these rocks is superbly displayed in the classic locality, close to the sea wall beneath the graveyard, described and figured by Flett and Hill (1912). Here it can be seen that the troctolite intrudes the peridotite (Figures 3.14 and 3.15), and is itself cross-cut by the gabbro sheets, and all three are intruded by the basic dykes.

The central division, some 200 m wide, consists of peridotite cut by numerous sheets of gabbro pegmatite. The thickness of these sheets varies from a few centimetres up to tens of metres. The thicker gabbro sheets tend to form the lower ground between the more prominent peridotite rocks. There are many small bodies of dunite within this area and, in the centre of the zone roughly in front of the store, is a much larger dunite body around 20 m in diameter (Figure 3.13). Many of these gabbro sheets are somewhat deformed and foliated, and, in several places, discrete high-temperature shear zones are seen with a streaky mylonitic fabric. Basaltic dykes are quite abundant, and at one location a dyke cuts through the shear zone, showing that magmatism continued after the onset of deformation.

The northern division is composed of gabbro with a few xenoliths of very altered peridotite and a few basic dykes. The peridotite blocks are all very altered being serpentinized and carbonated. Where the foliation can be seen, it varies from block to block, which contrasts with the very consistent N–S trend in the peridotites further south and implies that these blocks are detached xenoliths. The gabbro, generally referred to as

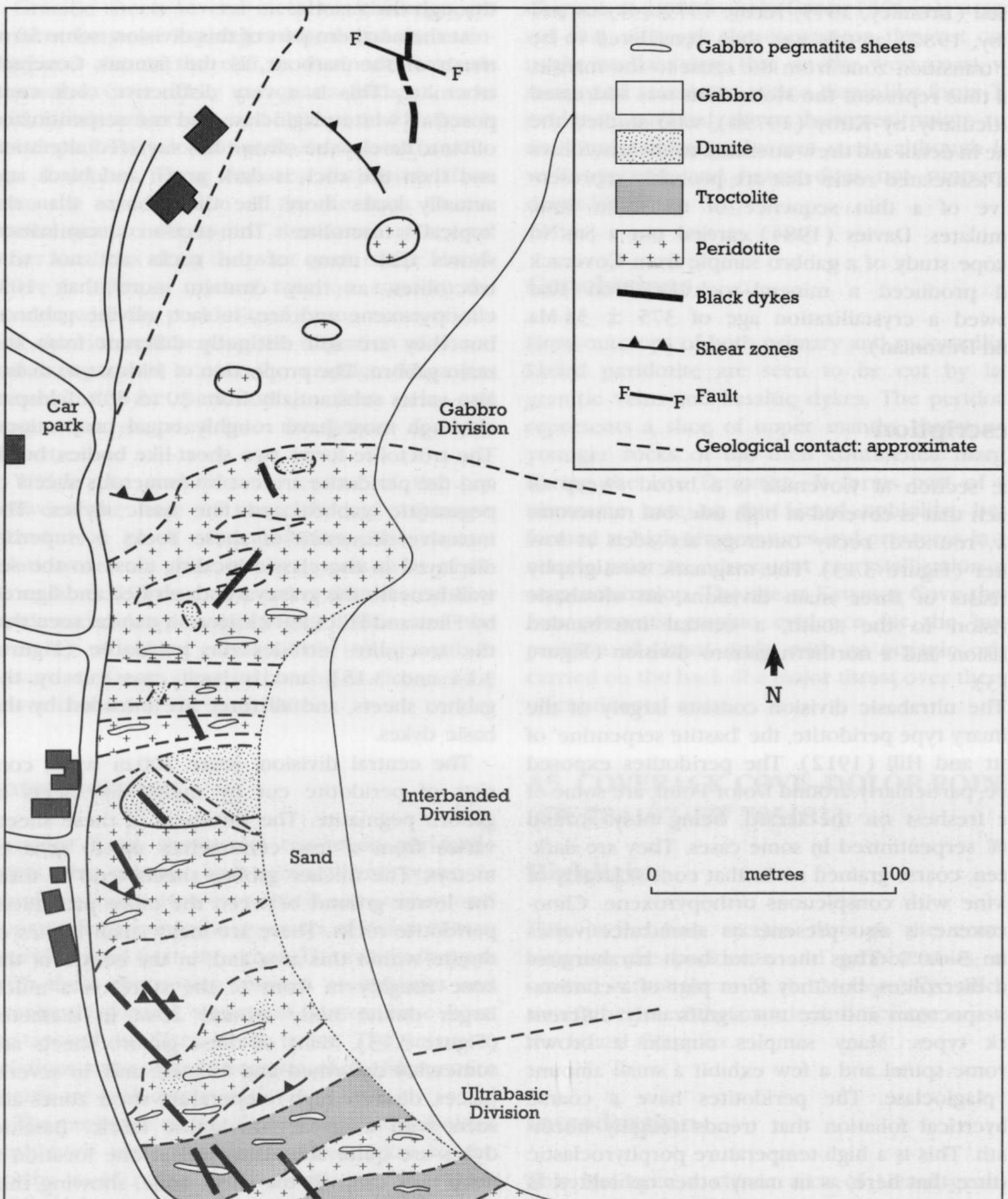


Figure 3.13 Geological sketch map of the Coverack site (A5).

the Crousa Gabbro, is a coarse-grained rock composed largely of plagioclase and augite with olivine, minor ilmenite, brown hornblende and rare biotite as primary constituents. When fresh, the gabbro is very dark coloured, almost black, as the feldspar is very dark purple in colour and thus can easily be mistaken for an ultrabasic rock. Many of the rocks have undergone some hydrothermal alteration which saussuritized the feldspar, turning it white and giving the rocks a typical mottled gabbro appearance. In many rocks, augite is partially or extensively altered to green hornblende. There are shear zones within the gabbro which have a NW–SE trend. At the northern end of the section, in the low cliffs and small outcrops sticking out through the beach boulders, two distinct generations of dykes can be seen. Early dykes have been pulled apart and broken up in the gabbro, whereas the late dykes have sharp planar margins, although even these are affected by late faults. There is a particularly good example at the northern end of the beach with distinct phenocryst-free, chilled margins. This dyke contains fresh olivine which is rare in dykes on the Lizard.

Interpretation

The principal interest of the site at Coverack is the excellent exposure of the transition from mantle to crust in an ophiolite sequence. It is not, however, a typical ophiolite succession, as the substantial cumulate sequence of dunites and pyroxenites separating the mantle peridotites from the gabbros, is missing. Such a sequence only seems to be present here as a very minor constituent represented by the dunites and troctolites. At this junction, but inland to the west, there is the Traboe cumulate complex which could represent a much thicker development (Leake and Styles, 1984). It does not reach the coast, but seems to be cut out laterally by the intrusion of the Crousa Gabbro, which is a later intrusion. The section at Coverack is therefore atypical for an ophiolite, due to the intrusion of later gabbro; possibly off-axis magmatism occurred as suggested by Badham and Kirby (1976). The chemistry of the gabbro was studied by Kirby (1979b), who showed that it was progressively fractionated when traced from south to north, with such features as Fe/Mg ratio and Ti and P

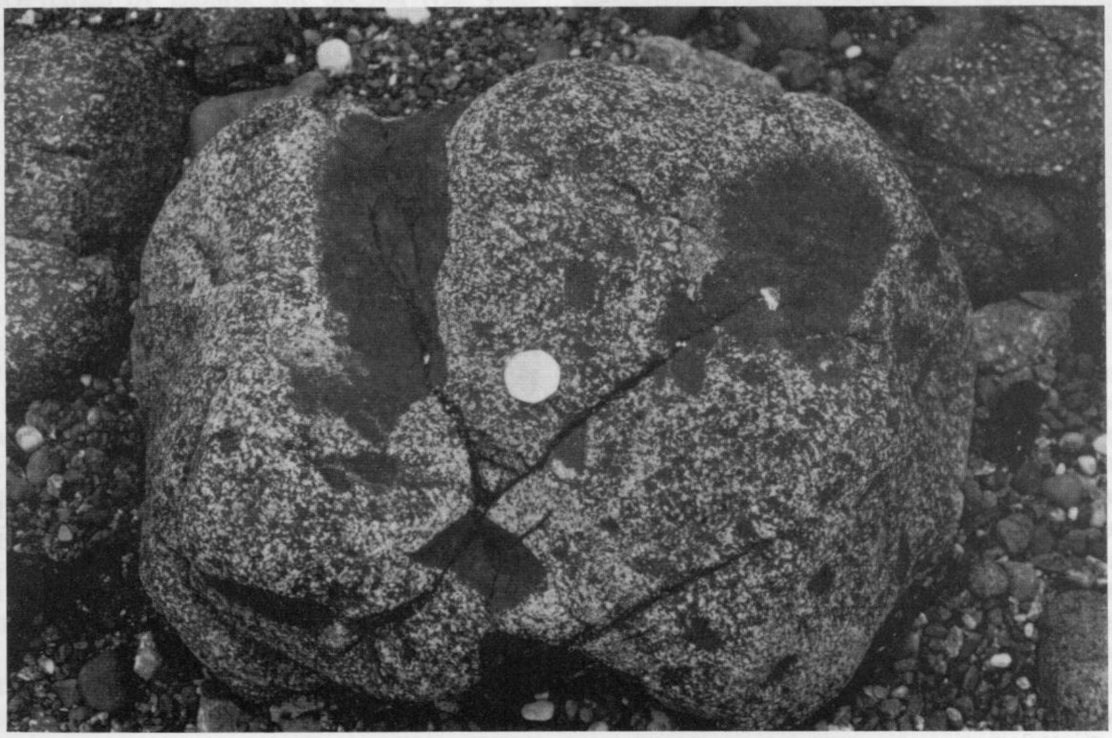


Figure 3.14 Xenoliths of peridotite enclosed within troctolite, Coverack Beach. (Photo: M.T. Styles.)

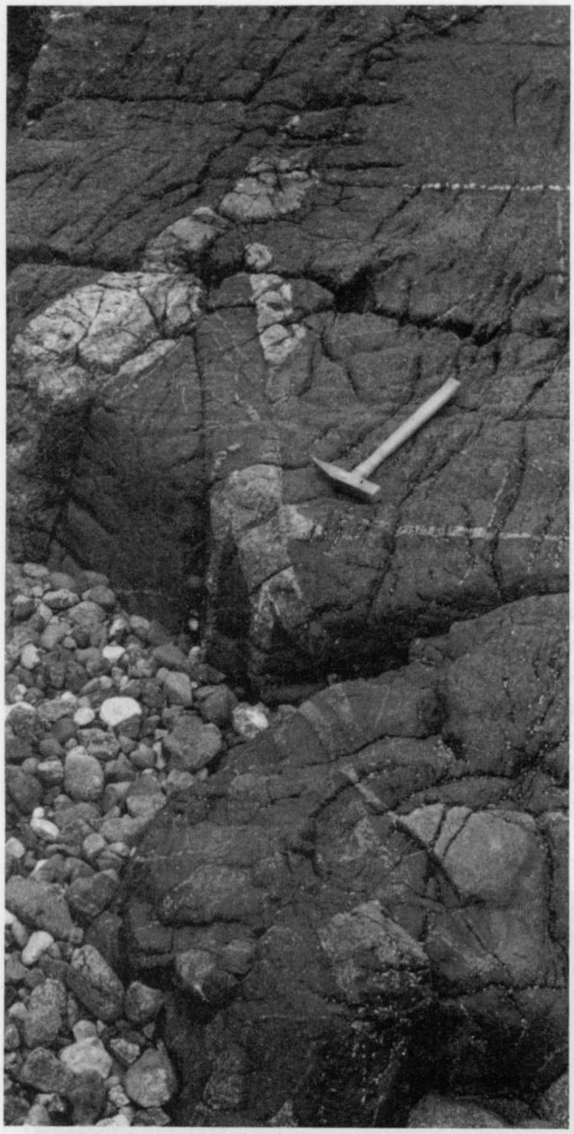


Figure 3.15 Troctolite veining peridotite, Coverack. (Photo: M.T. Styles.)

contents increasing in that direction. The overall chemical features were consistent with it forming from a magma with MORB-type chemistry.

The basic dykes are an important part of the geological framework at Coverack, but as they form the main feature of the following Porthoustock site, they will be discussed in detail there. The chemistry of the dykes suggests that they are not derived from the same magma as the gabbro, that is, they are not cogenetic. The trace-element ratios of such elements as P, Zr, Y and Ti, V are distinctly different and show they are not derived from the same source. However, this is not surprising: there is field evidence that some dykes cut shear zones through the gabbro, showing a clear time gap between the two intrusive phases.

Overall, the site at Coverack is one of the most important on the Lizard; it shows clearly the intrusive relations and hence time-sequence of many of the main rock types. The difference in fabrics between the peridotites and gabbros shows they were deformed at different times, in totally different regimes. The peridotites have a pervasive porphyroclastic texture that is typical of that formed by solid state 'creep' in the mantle at very high temperatures, perhaps 1000°C. The gabbros, in contrast, have deformation in discrete shear zones with amphibolite-facies metamorphic assemblages showing temperatures of 500–600°C, formed after the gabbros had crystallized and cooled in the ocean crust. The section as a whole records the transition from mantle to crustal rocks in an oceanic-type sequence, a fossil Moho.

Conclusions

The dominant basic and ultrabasic rocks at this site represent a sequence or section through ancient oceanic lower crust and upper mantle respectively, and is thus equated with the oceanic crust–mantle boundary – the Mohorovičić Discontinuity. The gabbro, with a radiometric age of around 370 million years before the present, represents the consolidation of a deep crustal magma chamber emplaced below a spreading ridge; a very different environment to many of the basic rocks in the rest of south-west England. Basaltic dykes cut both each other and the gabbros and peridotite, enabling a sequence of events to be determined for this part of the Lizard Complex.

A6 PORTHOUSTOCK POINT (SW 810217)

Highlights

This site displays the best development of the dolerite dyke swarm, which is interpreted as the sheeted-dyke complex of the Lizard oceanic crust.

Introduction

Dolerite dykes are present in small numbers cutting most rock types of the Lizard Complex, although within the Landewednack Hornblende Schists and Old Lizard Head metasediments they are clearly deformed and not necessarily of the same generation as those discussed here. At Coverack (discussed above), they form a small percentage of the outcrop but, going north through the gabbro, the proportion of dykes gradually increases. Around Leggan Cove there is a dramatic increase in the abundance to around 25%, and in the West of England Quarry at Porthoustock they form about 50% of the outcrop. Locally near the old pier and Porthoustock Point, they form around 80% of the rock with only thin gabbro screens separating the dykes. Flett and Hill (1912) described and figured this great abundance of dykes and commented on the fact that, although many dykes looked very fresh in the field, with sharp straight sides and chilled margins, thin-section studies showed them to be totally altered to actinolite, albite, etc. Dolerites with fresh olivine and pyroxene are rare in the Lizard dykes.

Bromley (1973, 1979) drew attention to the great number of dykes; from his field observations he divided them into three groups and suggested an order of intrusion. The first formed were olivine-phyric, and in some places exhibited a granular texture. They are often disrupted and back-veined by gabbro. The second type were plagioclase-phyric, had chilled or phenocryst-free margins and were occasionally veined by hornblende diorite. The youngest set of dykes are fine-grained, aphyric plagioclase hornblende rocks. He saw no evidence that they had originally contained olivine and pyroxene and suggested that they might be primary amphibolites. This last type is by far the most abundant at Porthoustock.

Kirby (1979, 1984) studied the dykes in detail both in the field and chemically. He also found three groups broadly similar to those of Bromley (1979), but thought that the dykes with the amphibolite mineral assemblages must be older than those with olivine. This is the opposite sequence to that suggested by Bromley (1979). Chemical data showed that the later (olivine) dolerites were the most primitive, with MORB-like characteristics, and that the earlier (aphyric) ones were more fractionated with a slightly calc-alkaline nature (Kirby, 1984).

Davies (1984), as part of his geochemical study of the Lizard, analysed dykes from Porthoustock. He divided the dykes into early and late types along the same lines as Kirby (1984), producing high-quality REE data. He showed that the early dykes were light-REE-enriched and could have been formed by melting of plagioclase lherzolite, similar to that analysed from Coverack. The later dykes were MORB-like, light-REE-depleted and could be formed by melting of pargasite harzburgite. He suggested a model for the generation of the Lizard, similar to the Red Sea, with early rifting, mantle metasomatism and production of light-REE-enriched magmas followed by later MORB-like magmatism.

Sandeman (1988) analysed the dykes as an adjunct to his study of the Kennack Gneiss, and showed the same chemical types as Kirby (1984) and Davies (1984), but suggested, like Bromley (1979), that the aphyric dykes were late, not early. He showed that their light-REE-enriched chemistry was like the basic fraction of the Kennack Gneiss, and suggested that all the rocks with more calc-alkaline affinities are associated with a late, arc-related phase of magmatism, rather than an early rifting phase.

Description

The best places to see the intrusive relations between the various types of dykes and the gabbro are the beach sections around Leggan Cove and Manacle Point, and in the now-disused West of England Quarry. The southern side of the quarry, where the face cuts across the strike of the dykes, is the most informative. The early disrupted dykes and many features of the gabbro, such as shear zones, are best seen in Leggan Cove. At the northern end of the cove is one of the small, late, hornblende diorite bodies that are thought to be differentiates of the gabbro magma. These diorites can be seen veining the dykes in several places.

The sections in the quarry are dominated by the abundance of dykes that form around 50% of the rock exposed. They are mostly of the dark-green aphyric type and are generally around 1 m in thickness. The sides of the dykes are usually fairly straight, and chilling is often seen at the margins. Dykes are seen to intrude other dykes of the same type in many places, but cross-cutting relations between dissimilar dykes are rare. On the upper level of the south wall of the quarry, small veins of a very leucocratic plagioclase diorite invade the aphyric dykes. This is probably the plagiogranite of Davies (1984). The whole sequence is cut by late, steep faults that have calcite veining along them.

Figure 3.16 Sheeted, basic dykes at Porthoustock Point. The dykes locally form about 80% of the outcrop with only thin gabbroic screens separating them. (Photo: M.T. Styles.)

Along the beach, just east of the old pier on the north side of Porthoustock Point, the abundance of dykes is at its greatest, forming around 80% of the outcrop (Figure 3.16). They are separated by thin screens of coarse gabbro and this is thought to be part of a sheeted dyke complex. The abundance of dykes increases northwards at Porthoustock, but unfortunately the sequence is truncated and the rocks on the north side of the Cove are very different. It is generally held that a concealed, large fault must run along the valley and out through the cove. The rocks exposed along the north side of the cove are highly deformed amphibolites, with numerous mylonitic zones. Generally, they appear to have been formed from quite coarse-grained precursors with a substantial proportion of finer rocks. Whether this is actually a highly sheared version of the dyke complex is open to speculation, but chemical data to test such a hypothesis are not yet available.

Interpretation

The dyke complex at Porthoustock is a major feature of the Lizard geology that has been recognized since the earliest geological surveys (De la Beche, 1839). The recognition by Bromley (1979) that this is a sheeted dyke complex is important as this is a significant feature in the categorization of the Lizard as an ophiolite. This is also the best example of an ophiolite–sheeted dyke complex in the whole of the UK.

Various workers have studied the dykes and there is agreement that several types of dykes are present, but exactly how they should be divided and what the time relations are is not yet clear. Cross-cutting relations between the different types seem to be few, partly because the different types have their main developments in different places. The aphyric types are most abundant in the north around Porthoustock, whereas the porphyritic types are most abundant in the south, around Coverack. There is a certain logic to extensively altered dykes being earlier than much fresher ones, but as they are in different places and in different structural and possibly hydrothermal regimes, this cannot be accepted without corroboratory evidence. If, for example, the source of fluids causing alteration was high-level hydrothermal systems such as are present in many modern ocean ridges, then the rocks highest in the sequence would be the most altered.

The chemical data that are available show clearly that there are at least two distinct types of dykes: olivine- and plagioclase-phyric MORB-types with light-REE-depleted patterns and the aphyric, light-REE-enriched types. The MORB-like dykes are closely similar to the gabbro, but the aphyric dykes are more evolved and not directly related magmatically. This is in accordance with the field relations, as the aphyric dykes do not root down into the gabbro – as the dykes in several ophiolite complexes do where the dykes are essentially comagmatic with the gabbros. Both Davies (1984) and Sandeman (1988) have produced essentially plausible models to account for the chemical variation. Davies (1984) suggested an analogy with the Red Sea, where initial rifting was associated with calc-alkaline magmatism and was followed by later MORB magmatism. Sandeman (1988), in contrast, suggests that the early MORB magmatism was followed by arc-related magmatism. Both the dykes and the Kennack Gneiss, known to be one of the later rock types, were associated with this later phase. This latter model has the attraction of simplicity, as there is a simple evolution from MORB-like to arc-related magmatism, whereas Davies' model would presumably have, in addition to the MORB magmatism, both an earlier rifting-related phase (to form the aphyric dykes) and a later arc-related phase (to account for the Kennack Gneiss).

A definitive work on the dykes, with the detailed field observation and chemical study to back it up, has yet to be carried out. The uncertainty that remains from current work cannot be resolved with the present data. This is, however, a very important site for the history of the Lizard Complex and the excellent features of igneous geology that can be seen here.

Conclusions

At this locality are seen rocks formed at a deep level in a portion of ancient ocean crust. The particular interests are the basalt and dolerite dykes, the site of which represents the channelways for melt feeding the sea-floor lavas above. One of the processes of growth and expansion of present-day oceanic crust is the repeated injection of magma in the form of near-vertical dykes below the spreading centre. At Porthoustock, many such dykes occur, cutting through the older gabbro, and are so closely packed that they make up the majority of rock on the foreshore. Although the chemistry of the dykes is variable, overall they are akin to various types of basalt formed in modern ocean ridges. This site plays a key part in the interpretation of the Lizard Complex, affording definite evidence for the presence and processes that contributed to the growth of early Devonian-aged oceanic crust to the south of what is now South-west England.

A7 PORTHALLOW COVE – PORTHKERRIS COVE (SW 798232–SW806226)

Highlights

The boundary fault of the Lizard Complex is uniquely exposed here; within an imbricate zone, the highly deformed mafic and ultramafic rocks of the Traboe Cumulate Complex are best exposed at this locality.

Introduction

The boundary between the igneous rocks of the Lizard Complex and Devonian sediments to the north is of major geological importance. It has been a point of controversy since the earliest research, and the first Lizard Memoir (Flett and Hill, 1912) left it as an open question, due to disagreement between the two authors. The position of the boundary can easily be located within a few tens of metres, but whether it is a major thrust separating Archaean rocks from Ordovician slates, or a faulted contact bringing together rocks of a similar age (Ordovician?) with different metamorphic grade, was disputed at an early stage. The second version of the Lizard Memoir (Flett, 1946) considered new evidence and favoured a major thrust contact. Controversy broadly along these lines has continued for many years between those who considered the Lizard Complex a thrust mass, possibly part of a much larger Lizard–Start thrust sheet (Hendricks, 1939;

Styles and Kirby, 1980), and those who thought it an upfaulted block of basement (Bromley, 1979; Matthews, 1981). Barnes and Andrews (1984) showed that there was no noticeable increase in metamorphic grade in the Devonian Meneage Formation immediately beneath the Lizard Complex. During the final emplacement of the ophiolite it was no longer above the ambient regional temperature of around 250–350°C.

Description

There are no exposures of the Lizard Complex–Devonian sediment boundary inland, and it can only be seen on the west coast at Pollurian and to the east at Porthallow. The contact at Pollurian is a very distinct, late, steep fault with fault breccia, gouge and slickensides. It separates amphibolites from the Devonian mudstones of the Meneage Formation. The boundary at Porthallow is much less clear, and it seems that the controversy cannot be resolved solely on the basis of the field relations at these localities.

To the south of the Lizard boundary at Porthallow, is a thin zone of Old Lizard Head metasediments and then, south of this for some two kilometres, a spectacular section of the Traboe-type hornblende schists. At Porthkerris Cove there is Traboe-type hornblende schist to the north and Landewednack-type to the south. The main differences between the two are that the Landewednack type has been supposed to be derived from basaltic lavas and tuffs and the Traboe type from either contact metamorphism of the Landewednack type (Green, 1964b), or from metagabbros (Flett and Hill, 1912; Bromley, 1979; Styles and Kirby, 1980). Leake and Styles (1984) proposed that the Traboe type, as seen at Porthkerris, was part of a Traboe cumulate complex which also included dunites, pyroxenites and anorthosites (Figure 3.17). This occurred

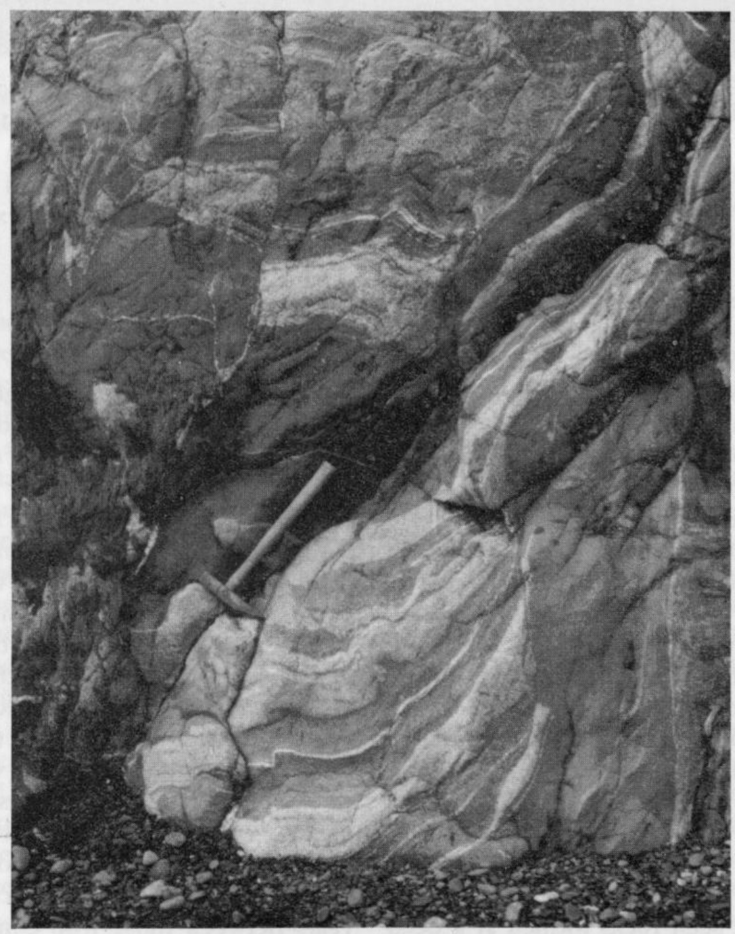


Figure 3.17 Interlayered basic and ultrabasic cumulate rocks, Traboe-type schists, Porthkerris. (Photo: M.T. Styles.)

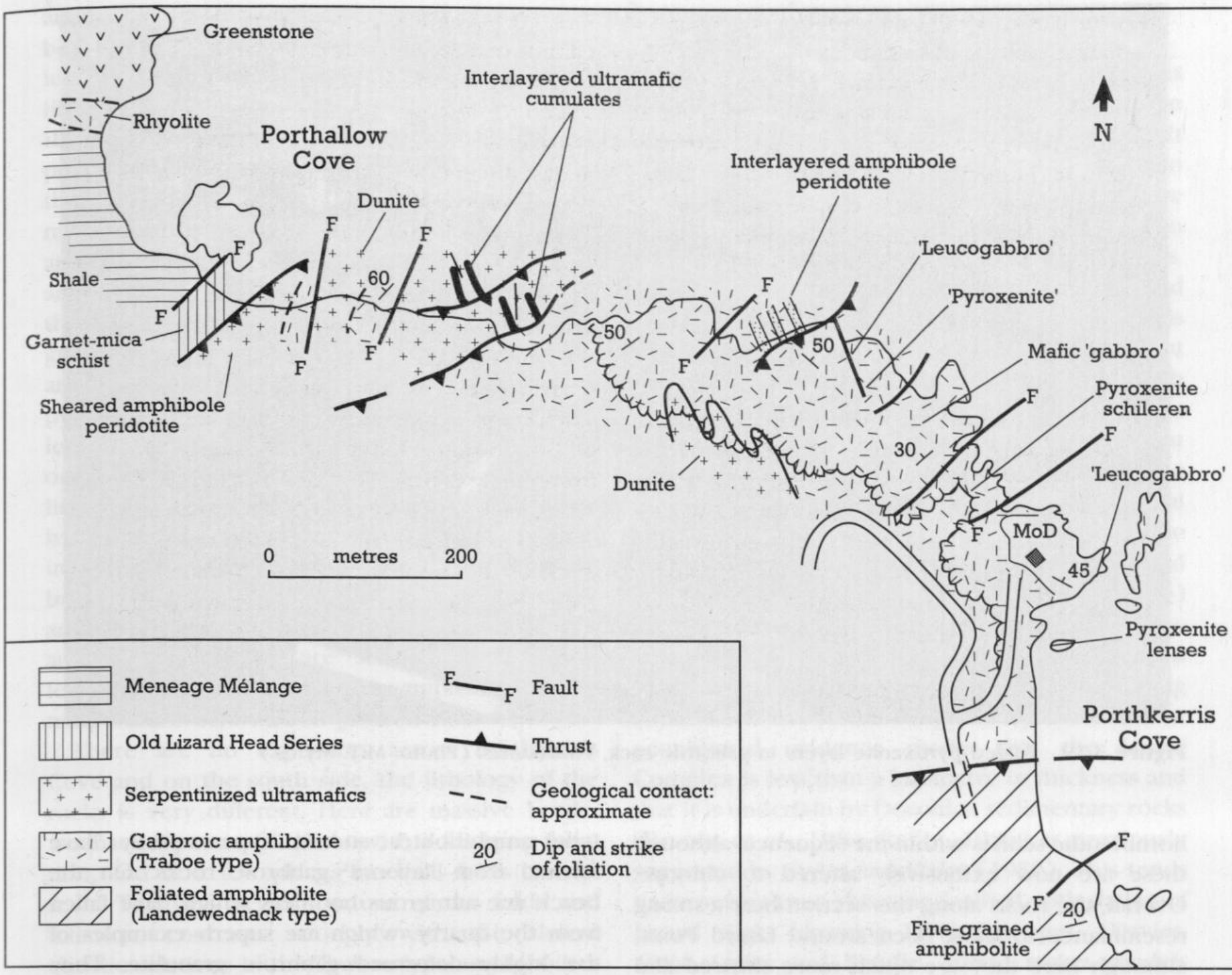


Figure 3.18 Geological sketch map of the Porthallow Cove–Porthkerris Cove site (A7).

extensively inland, but the only good surface outcrop of the cumulate complex was at Porthkerris. This site is an excellent one at which to see the relationships between the different types of hornblende schists.

This section will be described starting at Porthallow and proceeding southwards to Porthkerris Cove, a continuous section of nearly 2 km where a tremendous variety of rocks is encountered (Figure 3.18). On the north side of the cove at Porthallow, are greenstones with pillow-like structures and altered rhyolites within the turbidite mudstones of the Roseland Breccia Formation (Holder and Leveridge, 1986). On the south side of the cove the first rocks encountered are fine-grained, cleaved mudrocks with a gentle southerly dip. They do not contain visible mica. The first few inlets along the cliff are along deeply eroded, steep faults dipping to the south, and the second one brings together the previously mentioned mudrocks with the fine-grained mica schists of the Old Lizard Head 'Series'. Thin-section studies show that these rocks have recrystallized mica and small garnets and thus are quite distinct from the adjacent sediments. This is indeed the contact between the Lizard Complex and the Devonian sediments, a late fault. The outcrops are very weathered, but the schists have a strong, flat-lying, schistosity and abundant evidence of intense shearing, including mylonitic fabrics seen in thin section. On the beach are large boulders of a pink quartzofeldspathic rock that have fallen from the quarry, the Porthallow Granite Gneiss of Flett and Hill (1912). This rock contains garnets in addition to the quartz, feldspar and mica and in the author's opinion are more likely to be metamorphosed quartzofeldspathic sediments than granite. There are also

Figure 3.19 Folded pyroxenite layers in gabbroic rock, Porthkerris. (Photo: M.T. Styles.)

hornblendic schists within the sequence, although these are now extensively altered to chlorite. Overall, the rocks along this section bear a strong resemblance to those seen around Lizard Point, although here they are much more sheared and retrogressed.

To the east the Old Lizard Head metasediments are overlain by a very altered, carbonated, amphibole-bearing peridotite. The contact between the two is a thrust. The schists are epidotized and chloritized, and near the contact are mylonitized but there is no evidence of high-temperature alteration and it is assumed that the peridotites were 'cold' at the time of thrusting.

From here southwards, for about 150 m, are seen interlayered dunite serpentinite and gabbroic granulites, the contacts probably being tectonic rather than intrusive. The dunite serpentinite is a fine-grained, green-black rock, with small chlorite pseudomorphs after spinel. It is traversed by a network of joints that are the site of later chrysotile formation. The orthopyroxene-bearing, 'bastite serpentine', so familiar elsewhere in the Lizard peridotite, is absent. The amphibolites are fine grained and have a banded appearance but a granular texture, and in thin section contain small clinopyroxenes. These are Traboe-type amphibolites and it appears they have formed from 'layered' gabbroic rocks. On the beach are numerous boulders which have fallen from the quarry, which are superb examples of the highly deformed gabbroic granulite. They show very clearly the effects of high-temperature plastic deformation and shearing (Figure 3.19). Several phases of folding can be seen in the 'layered' gabbros, and classic fold interference patterns are developed.

For about 150 m to the east of another fault, the sequence is largely dunite serpentinite with several interlayers of a pale-grey rock. The observable field relations suggest that this is an early, possibly primary interlayering, but that some of the repetition is due to folding. Thin sections show that these are not basic rocks as might be expected, but are composed of Mg hornblende and chlorite, and probably derived from some kind of aluminous ultrabasic rock, possibly a spinel pyroxenite. This part of the section ends at another thrust, and the remainder of the section can be seen in the quarry at Porthkerris.

At the western end of the quarry are fine-banded amphibolites, and on the seaward slabs at Pol Gwarra are several metre-thick layers of amphibole peridotite. On the small promontory between Pol Gwarra and Pedn Tierre, is a body of leucogabbro, which appears to retain a layering-like feature, even though it is highly deformed. In this area, shear zones abound: many have gabbro pegmatites associated with them and it is possible that the shearing may have induced partial melting in the very hot, basic rocks. To the east around Pedn Tierre, is an area of very dark amphibolites and amphibolitized pyroxenites. To the east of a fault in an inlet there is a fine, granular amphibolite with *schlieren* of pale-green amphibole that contain relicts of rare clinopyroxene. These 'pyroxenite' *schlieren* are usually lensoid and highly deformed but whether they originally formed layers cannot now be established. Very good examples of shear zones that have subsequently been folded can be seen immediately north of the Ministry of Defence buildings (Figure 3.18). The rocks to the south and east of the buildings are largely leucogabbroic amphibolites. There are scattered pyroxenite lenses and many superb examples of high-temperature deformation phenomena.

There are no exposures across Porthkerris Cove and on the south side, the lithology of the rocks is very different. Here are massive Landewednack-type amphibolites with a flat-lying foliation, and in a few places isoclinal folds can be seen. The very regular nature of the folds and foliation, contrasts strongly with the almost chaotic relations in the Traboe-type amphibolites to the north. The contact between the two types cannot be seen, but in the overgrown roadway at the back of the cove there are mylonitized amphibolites, of rather indeterminate nature, which suggest that the contact is possibly a thrust fault.

Most of the rocks along this section have a northerly dip to the foliation, but the 'stratigraphy' in the Traboe rocks youngs to the south. Allowing for some minor movements with later faulting, the sequence from north to south is dunite, pyroxenite, gabbro with pyroxenite, leucogabbro. This implies that the sequence is overturned relative to normal ophiolite 'stratigraphy'. The structures seen in the quarry at Porthkerris suggest a large fold plunging north, that the steep foliations in the wall of the quarry are the steep limb and the floor of the quarry is on a short flatter limb. This folding gives rise to the apparent diapiric shape referred to by Green (1964c) and Flett and Hill (1912).

Interpretation

The section between Porthallow and Porthkerris is well exposed and has received much attention from geologists, as outlined in the introduction. It is an excellent location to study two of the main controversies of the Lizard Complex, the nature of the Lizard boundary and the relations between the Traboe and Landewednack Hornblende Schists.

The contact between the Old Lizard Head schists and the Roseland Formation mudstones is a late, steep fault; as it is on the west coast at Pollurian. However, the schists immediately south of the fault have a gently dipping mylonitic fabric that is truncated by the fault, which suggests that thrusting was important at an earlier stage. The observable field relations show that the actual contact is a steep fault, but can this necessarily be extrapolated to signify the nature of the Lizard boundary in a wider context? Flett (1946) pointed out that the boundary has a sinuous trace across the north of the peninsula, which would be more compatible with a gently dipping structure rather than a simple steep fault. Recent geophysical evidence shows that the Lizard Complex is less than a kilometre in thickness and that it is underlain by Devonian sedimentary rocks (Brooks *et al.*, 1984; Rollin, 1986) as previously suggested by Styles and Kirby (1980). This tends to favour a thrust sheet, and, allied with dating of Lizard rocks showing Devonian ages, (Davies, 1984; Styles and Rundle, 1984) makes models involving upfaulted basement blocks untenable.

The question of the two types of amphibolites may now be examined here. Green (1964c) maintained that the effects seen at Porthkerris were due to the metamorphism of essentially homogeneous Landewednack-type amphibolites by the intrusion of peridotite: seen at the top of the quarry, and in a fault block on the beach at Porthallow. The aureole where these effects occurred was some 350 m wide, with an outer limit through the bay at Porthkerris and unaffected amphibolites at the south side of the bay. The metamorphic assemblages developed in the 'aureole' were clinopyroxene, and, in some places, two-pyroxene granulites. These can be found at Porthkerris, even though most of the rocks are extensively retrogressed.

The most recent authors have questioned this interpretation, and have pointed out the wide range of rock types from dunite to anorthosite (Bromley, 1979; Styles and Kirby, 1980) and also the wide range of chemical compositions of the

Traboe-type (Kirby, 1979b; Leake and Styles, 1984), which are markedly different from the Landewednack-type amphibolite. For this huge variety of bulk compositions to be produced from a homogeneous parent, would require chemical mobility of large amounts of material on a scale of tens of metres, and require a very fortuitous final distribution. In the light of the observed chemical inhomogeneities on a millimetric scale preserved in many rocks, this is extremely unlikely. It is much more likely that the variation in bulk compositions is essentially primary and that this is a fragment of a cumulate complex very similar to that in the Traboe area described by Leake and Styles (1984). It is important to note that none of the peridotites in this area are the 'typical' lherzolite or harzburgite mantle peridotites seen in most of the Lizard: they are mostly dunites and minor amphibole peridotites which are typical of the Traboe cumulate complex. The features seen here therefore cannot be taken as showing the relations between mantle and crustal rocks and extrapolated to the rest of the ophiolite.

The rocks in this site are in a series of thin thrust slices that form an imbricate zone at the base of the ophiolite nappe close to the Lizard boundary. Within these thrust slices are the only good exposures of the Traboe Cumulate Complex – a series of rocks formed by the high-temperature deformation of cumulates from magma chambers in the lower oceanic crust. The composition of coexisting ortho- and clino-pyroxenes is controlled by the temperature at which they formed. Hence analysis of coexisting pyroxenes can be used to calculate their temperature of formation by geothermometry. Pyroxene geothermometry using the method of Wells (1977), gives temperatures in the range 900–1050°C, for granulites from the Traboe cumulate complex in the Traboe area (Styles, unpublished data). This is much hotter than normal regional metamorphism, and probably indicates the breakup of hot, newly formed crust, rather than prograde metamorphism of colder rocks.

Conclusions

This locality is situated at the faulted boundary between hornblende schists of the Lizard Complex which are juxtaposed with low-grade 'normal' Devonian sedimentary rocks typical of most of south-west England. The Hornblende Schists here are part of the metamorphosed mafic–ultramafic unit within the Lizard Complex and representative of a segment of ancient ocean floor thrust subsequently into the adjacent continental margin. The thrust slice is now terminated by a high-angle steep fault that separates it from the continental sediments of the rest of Cornwall. The site provides evidence for major Earth movements that brought together rocks formed in very different environmental situations.

A8 LANKIDDEN (SW 756164)

Highlights

An important high-temperature shearing event that occurred shortly after the emplacement of the Lizard gabbro is best developed at this locality.

Introduction

The cliffs around the prominent gabbro headland of Lankidden have many spectacular geological exposures but they have received only passing interest from most previous workers. Teall (1886, 1888) described the 'beautiful augen structure in the gabbro' and Flett and Hill (1912) mentioned that there were numerous gabbro dykes to either side of 'the great spectacular dyke of Carrick Luz' (the rocks at the southern tip of Lankidden). Green (1964c) also noted these features and suggested movement of the dyke walls during intrusion had produced them. Kirby (1979b) interpreted it as a feeder to the main Crousa gabbro magma chamber. Styles and Kirby (1980) suggested that the thrusts seen here represented the major thrust zone that separated an upper, eastern tectonic unit from a lower western unit. Bromley (1979) had, however, maintained that the thrust was further east at Poldowurian just east of Kennack. Recent work further north, inland by Leake *et al.* (1990), suggests that there is little evidence for a major thrust or the existence of the two major tectonic units, and that the thrusts, although spectacular at Lankidden, are only of local importance.

Description

The cliff-bounded headland of Lankidden, with the site of a Bronze Age castle at the southern tip,

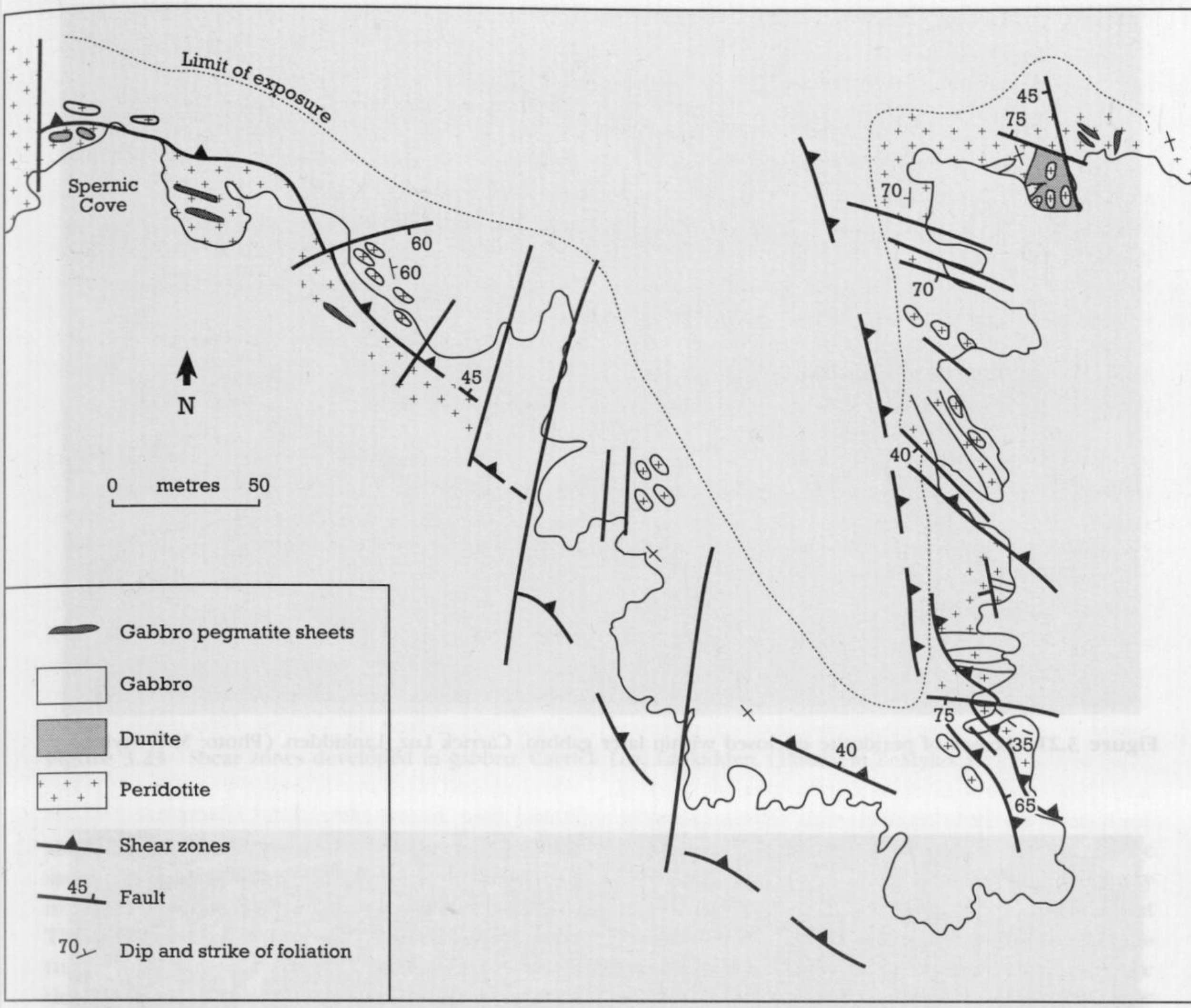


Figure 3.20 Geological sketch map of the Lankidden site (A8) showing distribution of outcrops between landward exposures and low-water reefs.

is an area of outstanding beauty. The headland is largely formed of a sheet or dyke of coarse gabbro around 100 m in thickness and dipping around 45° to the east. In most places the contacts with the peridotite are highly sheared; they can be seen in Spernic Cove to the west and Lankidden Cove to the east (Figure 3.20).

The peridotite is the coarse, primary type, with prominent orthopyroxene crystals, up to 5 mm in size, in a matrix of partially serpentinized olivine. A coarse, rough foliation is present that is essentially vertical and trends north–south.

In Spernic Cove, the western contact between the peridotite is not a sharp one and there are numerous inclusions of peridotite within the gabbro and thin gabbro veins in the peridotite below the main contact (Figure 3.21). The foliation in the flaser gabbro dips at around 45° to the east. This sheared contact is truncated by one of the many late faults at the small cove on the west side of Lankidden; it is presumably offset out to sea as it is not seen further south on the headland.

The outcrops further south on this west side, show a superb range of features produced by the high-temperature deformation of a coarse-grained gabbro. At one end of the range are the coarse, augen-bearing, flaser gabbros (Figure 3.22), with augen of clinopyroxene up to several centimetres in size, in a fine schistose matrix of recrystallized plagioclase and pyroxene. Thin sections show that the augen of clinopyroxene are now partly

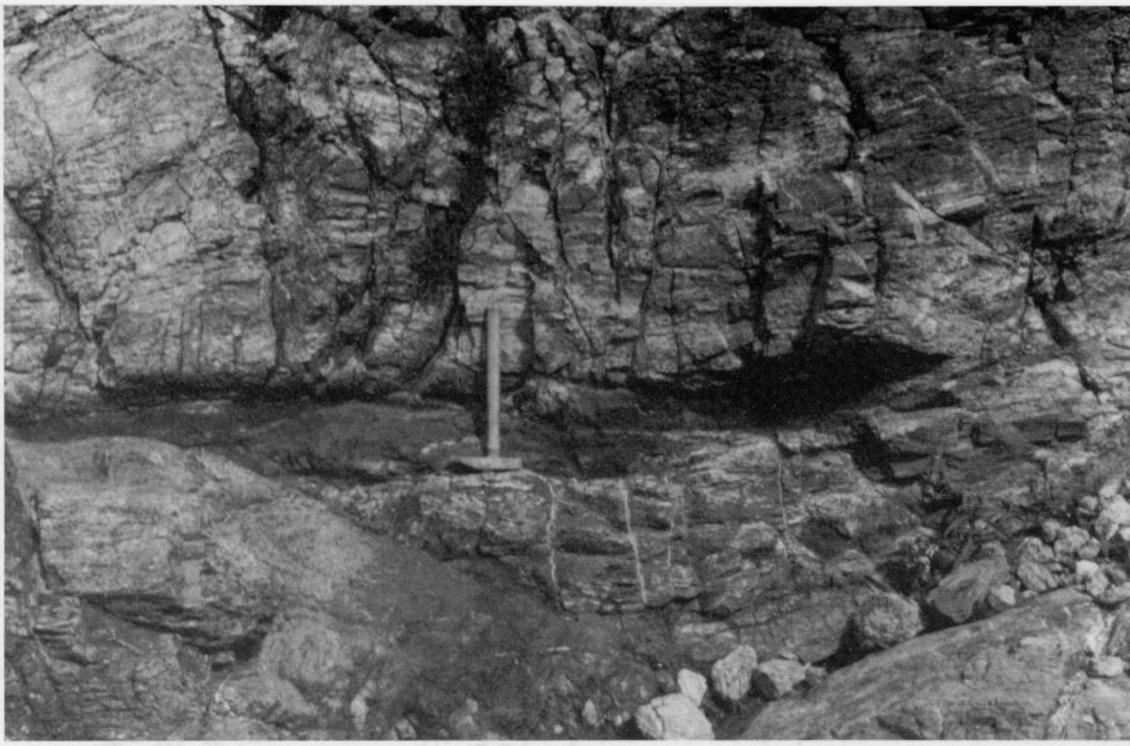


Figure 3.21 Lenses of peridotite enclosed within later gabbro, Carrick Luz, Lankidden. (Photo: M.T. Styles.)

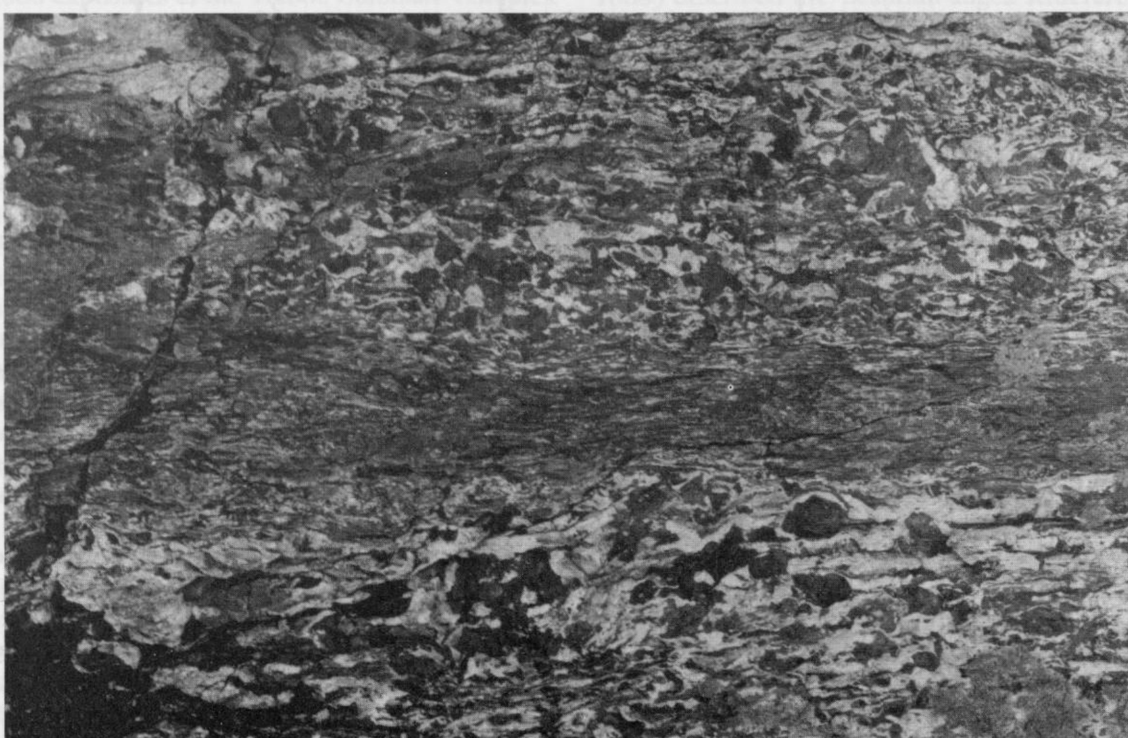


Figure 3.22 Flaser gabbro, Carrick Luz, Lankidden. (Photo: M.T. Styles.)

Figure 3.23 Shear zones developed in gabbro, Carrick Luz, Lankidden. (Photo: M.T. Styles.)

altered to hornblende. Much plagioclase is now saussuritized, although some fresh crystals remain in rocks that have large feldspar porphyroblasts. The presence of pyroxene shows that temperatures must have been at least 600°C during deformation. Where the rocks have been deformed to a greater degree, a considerable reduction of grain size has taken place, and fine 'gabbro schists' give way to streaky mylonites in the zones of most intense shearing (Figure 3.23). All these features can be seen within a few metres of each other, at many places along the west side of Lankidden, but are perhaps best exemplified in the small gully, near the southern tip. Late, basic dykes can be seen cutting through the shear zones.

Along the eastern side of the headland, access is more difficult and relationships more complex. This appears to be the intensely gabbro-veined 'hanging'-wall of the main intrusive sheet, and there are numerous small shears and gabbro veins. Both the peridotite and gabbro are intensely hematized, and this can make identification of rock types difficult.

The small rock promontory in the centre of Lankidden Cove, to the east of the headland, has the best examples on the Lizard of the dunite veins that cut through the peridotite. In many places, the dunites form single veins or pods, but here they form a series of criss-crossing anastomosing veins up to 3 m in thickness. The veins are composed of serpentinized olivine and, in many places, small stringers of chromite and *schlieren* of partly digested peridotite. The margins of the veins are not sharp, but diffuse and gradational over a distance of 1–2 cm, with the prominent orthopyroxenes of the peridotite decreasing in abundance into the vein. These features suggest that this is a high-temperature phenomenon with wall-rock reaction involved.

Interpretation

The cliffs along the west side of Lankidden show with great clarity the effects of high-temperature shearing deformation of various intensities in a coarse-grained gabbro, producing intense banding and augening. This was recognized long ago by Teall (1888) and is the best example in south-west England, and possibly the whole of the UK.

The dunite veins are of considerable interest, even though their origin has yet to be definitely established. Flett and Hill (1912) suggested they were formed from a separate 'chromite serpentine' magma, distinct from the bastite serpentine (primary peridotite). Green (1964a), however, thought they were just the result of extreme serpentinization of the primary peridotite. It is the author's view that they are a high-temperature phenomenon, as outlined above, and that they were possibly the pathways of picritic melts ascending through the hot upper mantle. As the melts passed up through the mantle, they crystallized olivine, and the heat of crystallization – and possibly some fluid from the magma – was sufficient to cause local partial melting of the wall rock which was already close to its solidus. This caused the melting of pyroxenes: the lowest-melting fraction in the peridotite, and produced the diffuse margins that may now be observed. Whatever their origin, these dunites are a significant feature of the Lizard peridotite, and this is the best exposure.

The outcrops around Lankidden give superb examples of many phenomena of interest to both igneous petrologists and structural geologists. They are of relevance to studies of Lizard geology and of geological phenomena in general. Such is the clarity of these features, that their interpretation has changed little during the last 100 years.

Conclusions

The outcrops here are composed of sheared gabbros and altered peridotites of the Lizard Complex. The gabbros are demonstrably younger than the peridotite, and contain included fragments of the latter. The sheet-like gabbro body has suffered deformation at high temperatures, such that it is heavily sheared, with the development of intense banded texture with augen (German, meaning literally 'eyes') – large remnant crystals set in a finer crushed matrix. Dunite (an olivine–rich peridotite) occurs as veins and represents mantle-derived ultramafic melts which solidified within the peridotite host rock.

A9 MULLION ISLAND (SW 660175)

Highlights

The best-developed pillow lavas (submarine basalts of mid-ocean ridge type) in the Lizard area can be dated here by their association with fossiliferous cherts of Devonian age.

Introduction

Mullion Island is situated about 0.5 km south-west of Mullion Cove, off the west coast of the Lizard. It is one of the classic areas of Variscan greenstone and, although depicted on early nineteenth century maps of the region, little was known about the rocks and their association with the Lizard mainland. The morphology of the volcanics and their recognition as pillow lavas, together with their association with cherty sediments, were initially described by Fox (1893) and Fox and Teall (1893). Whereas basic volcanics and minor intrusives occur in the choatic Meneage Zone to the north of the Lizard Complex, Mullion Island was the best example of pillow lavas in the area, and possibly represented part of the same tectonic province faulted off from the Lizard (Flett, 1946). Modern ideas extend this view, whereby the lavas represent either a megaclast or a thrust slice incorporated within the tectonosedimentary *mélange* of southern Cornwall (Barnes and Andrews, 1981). Mullion Island thus forms part of the Roseland Breccia Formation (Holder and Leveridge, 1986) that incorporates all the *mélange* rocks within a thrust slice directly below the Lizard thrust segment.

A Frasnian age for the Mullion Island pillow lavas was reported by Hendricks *et al.* (1971) on the basis of conodonts extracted from the associated siliceous limestones. This is the same as the age of the *mélange* matrix of the Roseland Breccia Formation, which contains many basaltic clasts of generally similar chemistry to the Mullion Island pillow lavas (Floyd, 1984; Barnes, 1984).

Description

The site comprises the whole of the island and exposes about 30–35 m stratigraphical thickness of pillow lava (Figure 3.24). On the basis of the draping of pillows over each other and their interrelationships, the sequence is the correct 'way up'. The lava tubes are orientated approximate east–west, although in view of their likely disorientation during incorporation into the *mélange*, this cannot be used to infer the

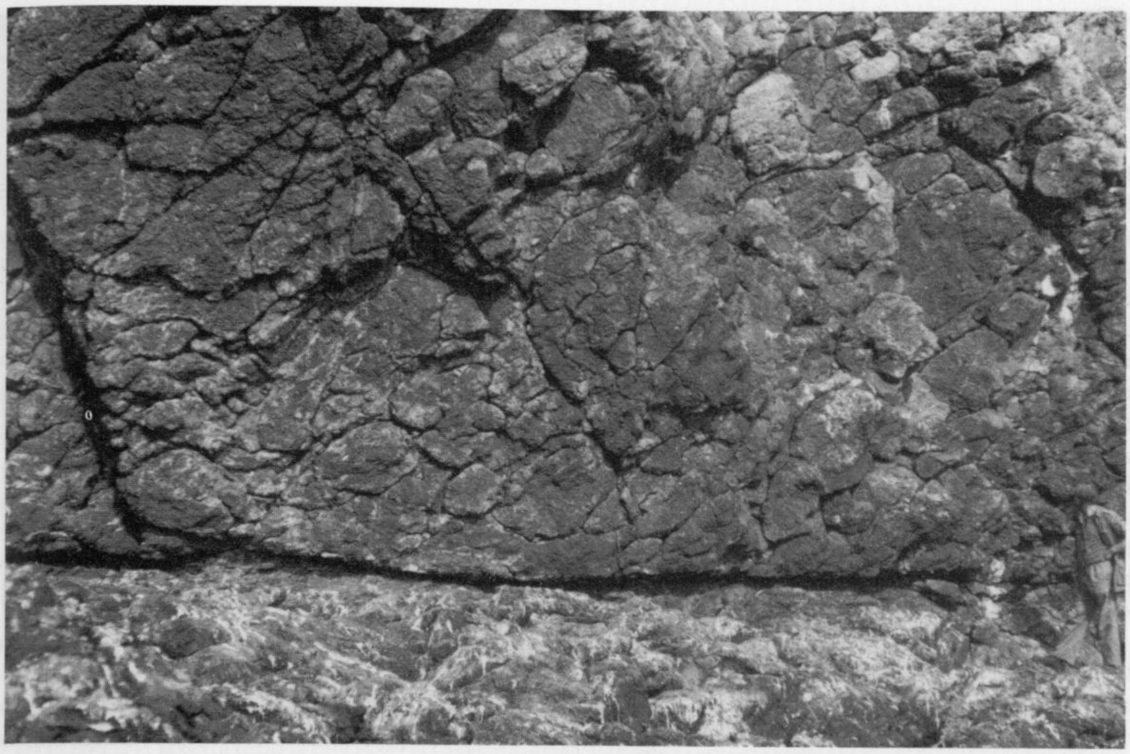


Figure 3.24 A spectacular development of pillow lavas, of Frasnian age, on Mullion Island. (Photo: P.A. Floyd.)

direction of lava flow. Most of the lavas are fractured and a number of subhorizontal shear or movement zones cut through the sequence. At a high point on the island is a *c.* 100-cm-thick sedimentary sequence of alternating siliceous argillite and intermittent, irregular, pinkish radiolarian chert (recrystallized), conformable with and overlying the pillows.

The pillow lavas are elongate, draped tubes, with nearly circular or ovoid cross-sections ranging from 0.15 to 1.2 m in diameter. Although some pillows have virtually no vesicles, most exhibit concentric zones of small vesicles 1–2 mm in diameter that hardly diminish in size towards the rim portions. Vesicle infillings are generally chlorite with a little quartz or calcite. A few pillows have a large, central, unfilled vacuole, left after the tube had been drained of lava. Interpillow material may not always be present, but is generally either cherty argillite or a grey carbonate. As well as the pillow lavas, thin, intrusive sill-like bodies may also be seen forming part of the low, sea-swept platforms on the south of the island.

The lavas look relatively 'fresh' compared with many similar exposures in south-west England with the interiors being bluish, although the fine-grained and originally glassy margins are pale green and heavily altered and fractured. Microscopic examination indicates that the lavas are aphyric tholeiites with variable, fine-grained quench fabrics that grade from the rims to medium-grained subophitic textures within the cores of large tubes. Primary minerals – plagioclase, brownish (sometimes zoned) clinopyroxene, ilmenite – are relicts set in a secondary mineral matrix (Figure 3.25) indicative of the pumpellyite facies of regional metamorphism (Floyd and Rowbotham, 1979). It is the development of the secondary phases (chlorite, pumpellyite, amphibole) that give the outer portions of the tubes their greenish tinge.

Interpretation

The significance of this site within the magmatic framework of south-west England mainly concerns the importance of the pillow lavas in the tectonic development of southern Cornwall. Although there are other good exposures of Upper Devonian pillow lavas, the Mullion Island basalts are distinctive in that they are:

Figure 3.25 Photomicrograph of pillow lava from Mullion Island. Primary plagioclase, zoned clinopyroxene and ilmenite are set in a secondary pumpellyite-facies mineral matrix. (Photo: P.A. Floyd.)

1. relatively fresh, retaining primary quench-textured clinopyroxene with enhanced contents of Al, Ti and Na (Floyd and Rowbotham, 1979),
2. tholeiites with a mildly enriched MORB-like chemistry (Floyd, 1984), and
3. were subsequently metamorphosed in the pumpellyite facies.

These features distinguish them from the highly altered (no primary phases present), alkali-basalt pillow lavas of north Cornwall and the incompatible-element-enriched tholeiites in the Mylor Formation of the Penwith Peninsula to the north. In terms of relict and secondary mineralogy, and their particular chemical composition, they have an affinity with the other MORB-like clasts within the *mélange* of the Roseland Breccia Formation of southern Cornwall. In the context of the tectonic model for this area during the late Devonian, they are therefore representative of the volcanic portion of the tectonically disrupted oceanic crust of the Gramscatho Basin. Along with the Lizard ophiolite, they are among the remaining segments of the oceanic floor of the Rhenohercynian zone of northern Europe.

Apart from the relatively rare preservation of primary minerals in south-west England pillow lavas, the clinopyroxenes are distinctive in having abundances of minor components (Al, Ti and Na) that are more typical of alkali basalts than tholeiites. This feature emphasizes the importance of crystallization history (the relative order of phase growth) in governing the composition of pyroxenes in basalts (Floyd and Rowbotham, 1979). For MOR-type basalts the Mullion Island lavas have relatively high contents of U (>1 ppm) which is mainly resident in altered (originally glassy) matrix (Williams and Floyd, 1981) and was largely absorbed during early sea-water alteration.

Conclusions

This site represents an isolated relict of the volcanic portion of an ancient oceanic floor with basalt lava flows and minor sediments. The lavas were extruded on the sea-floor in the form of bulbous, tube-like 'pillows' and exhibit textures indicative of rapid quenching by the cold seawater. The basalts have compositions similar to some modern-day lavas formed at mid-ocean ridges and, together with the Lizard Complex, provide evidence for the existence of an ocean during the Devonian period, to the south of a continental area.

A10 ELENDER COVE–BLACK COVE, PRAWLE POINT (SX 769353–SX 769356)

Highlights

This is the best section through the highly deformed and metamorphosed oceanic basalts of the Start Complex.

Introduction

This locality lies on the west side of Prawle Point, the southernmost landward extremity of the so-called Start Complex (Figure 3.26). The southernmost peninsula of south Devon makes up this complex, which exhibits a range of variably schistose rocks of different aspect to the Lower Devonian argillites and phyllites to the north. The actual age of the complex is not known, although it is generally assumed to be Devonian (Dineley, 1986), with a structural history not dissimilar to that in south Cornwall generally (Marshall, 1962; Hobson, 1977). Many tectonic syntheses have suggested that the Start boundary fault is a continuation of the important Perranporth–Pentewan Line (Sanderson and Dearman, 1973; Sadler, 1974; Matthews, 1977) and that it is not linked to the Lizard–Dodman Thrust (Hendricks, 1939). In this context, the Start Complex junction has been interpreted as either:

1. originally a low-angle thrust that emplaced the Start Complex over the Devonian to the NNW (Coward and McClay, 1983);
2. a basement fault forming a terrane boundary to southern pull-apart, ocean-crust-floored, basins (Holdsworth, 1989).

Thus, apart from the special lithological characters of the magmatic rocks at this site, the whole complex has an important tectonic place in the early Variscan geology of South-west England.

The Start Complex exhibits two main groups of schists (Ussher, 1904; Tilley, 1923): metasedimentary micaceous greyschists and metavolcanic greenschists, together with minor variants of mixed sedimentary and volcanic character. The greenschists exhibit two simple end-member mineral assemblages: chlorite–epidote–albite and hornblende–epidote–albite. Mineralogical and chemical data (Tilley, 1923) indicate that initially the greenschists constituted a series of basaltic lavas which were subsequently highly tectonized and metamorphosed to a low grade. Relative to the low-grade greenschist-facies sediments to the north, the Start Complex schists belong to the same intermediate P–T facies series, but were produced at slightly higher pressures (Robinson, 1981). Illite crystallinity and phyllosilicate cell parameters link the Start Complex metamorphic regime to that of south Cornwall generally, rather than the lower-pressure environment to the north of the Perranporth–Pentewan Line (Primmer, 1983b).

Early, major-element, chemical data established the basaltic character of the metavolcanic greenschists (Tilley, 1923), whereas trace-element data (Floyd, unpublished) indicates that they constitute a series of essentially undifferentiated tholeiites with a MORB chemical signature. This feature is clearly important in elucidating the tectonic evolution of south Cornwall during the Devonian, and it indicates that the Start greenschists originally constituted a volcanic segment of the Variscan ocean floor.

Description

The site comprises the steep cliffs and coves on the west side of Prawle Point; it can be reached via the coastal path. Typical lithological (and small-scale structural) features are well displayed in the section, with low-strain areas exhibiting greenschists in their least-deformed state.

The greenschists are fine to medium grained; they are characteristically schistose with fine banding produced by variations in mineralogy and grain size. Petrographically, they comprise associations of amphibole, chlorite, epidote, clinozoisite, albite and sphene, with accessory calcite, pyrite, quartz, white mica and iron oxides. Rapid changes in lithology are common, with intimately interbanded chlorite-rich, epidote-rich and white mica-rich assemblages. Pyrite is abundant in some layers. Quartz is frequently present in the form of fine, banding-parallel metamorphic segregations

Figure 3.26 The rocky cliffs of Elender Cove expose metavolcanic greenschists of the Start Complex. Elender Cove, near Prawle Point, Devon. (Photo: David Noton Photography.)

or veinlets. Albite may form large (few millimetres-sized) porphyroblasts, which are emphasized by the weathering and stand out in relief on the rock surface. Small, resistant 'nodules' composed mainly of epidote and quartz are also characteristic of some layers, and these testify to element migration during metamorphism prior to the superposition of the enclosing deformed tectonic fabric. Tilley (1923), however, described similar epidote nodules as the metamorphosed products of infilled lava vesicles. It is unlikely that infill material would retain its nodular shape after the deformation suffered by the volcanics: it would be sheared out into lenticular bodies, as seen in less-deformed lava sequences.

Interpretation

The original nature of the volcanics is problematic, and this is difficult to pronounce on this at this site, or indeed anywhere else in the Start Complex. Tilley (1923) suggested that the greenschists represented a series of basalt lavas and sills, although typical lava features, such as curved pillow-lava surfaces, have not be observed. The delicate nature of the fine laminations and rapid changes in lithology, especially in low-strain areas, strongly suggests that much of the sequence was composed of basaltic volcaniclastics (tuffs) rather than lavas. However, elsewhere the sequence shows greater variability in terms of gross banding, which could reflect original differences between lava flows, sills and tuffaceous material, all now heavily sheared to a degree of schistose uniformity.

On the basis of their lithological and chemical characteristics, together with tectonic considerations, the Start greenschists are related to the south Cornish nappe–thrust belt and compositionally have their counterpart in the basic rocks of the Lizard Complex and *mélange*. One of the most significant features of this site is that the greenschists are tholeiitic, with a depleted normal-type MORB chemistry, much more primitive than any ocean-floor basalt recognized in south Cornwall. In this respect they have affinities with some of the Lizard dykes and the Landewednack hornblende schists with depleted incompatible-element contents. Thus, one of the main reasons for the inclusion of a Start greenschist site is the tectonic significance of the MORB character of the metavolcanics. This suggests that they represent another segment of Devonian ocean crust at the western end of the Rhenohercynian Basin along with the Lizard ophiolite and MORB-like basaltic clasts within the *mélange*. Like the allochthonous units of south Cornwall with their remnants of ocean floor, the Start Complex was subsequently docked adjacent to the magmatically distinct Lower Devonian autochthon to the north.

Conclusions

Here occur highly deformed and altered rocks which were once basic rocks of volcanic origin. Their chemistry indicates that they are basalts with a composition similar to those currently forming at mid-ocean ridges. Rocks formed on an ancient ocean floor have little in common with basalts in the area to the north of Start or in Devonian volcanic sequences extensive in south-west England. They do equate, however, with basaltic rocks found in south Cornwall (including the Lizard Complex), being similarly formed as ancient ocean floor. Both areas, therefore, represent exotic terranes thrust and welded on to the margins of a northern continental plate in late-Devonian times.