

A RE-STUDY AND RE-INTERPRETATION OF THE GEOLOGY OF THE LIZARD PENINSULA, CORNWALL

D. H. GREEN

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I. PREVIOUS RESEARCH

The early published investigations of the geology of the Lizard district have been reviewed in sequence by Flett and Hill in the 1912 Geological Survey Memoir and again in the second edition of the Memoir in 1946. The foundations of the understanding of the complex sequence at the Lizard were laid by de la Bêche of the Geological Survey in 1839. A period of controversy and great activity followed in 1880-1900 in which the names of Bonney, Fox and Teall stand out as tackling the broader and more fundamental problems of the area. In 1906-1910 Flett carried out his classic survey, building on the discoveries of his predecessors and correlating evidence to give the detailed and coherent account published in the 1912 Memoir. The quality of the Survey mapping can hardly be surpassed in detail, care and completeness of coverage. Re-mapping in 1959 was not a case of moving established boundaries but rather of re-interpreting in the context of present-day geology, the observable relationships in the coastal exposures, and careful examination of the relatively few outcrops and quarries in the inland areas.

In 1937 Tilley made a detailed study of mineral assemblages in the Old Lizard Head Series at Pistil Ogo and Polkernogo. Also in 1937 and 1939 Hendriks published papers on the structure and stratigraphy of Cornwall in which the broader relationships of the Lizard area and the Lizard-Dodman-Start boundary were discussed. In 1938-39 Scrivenor published a series of short notes on different aspects of the Lizard geology and followed this up in 1949 by a general paper on the Lizard-Start problem. In this paper he concluded that the Landewednack Hornblende Schists are in fact a 'primary' hornblende-plagioclase gneiss formed by consolidation, in a stress field, of an appropriate dioritic magma. Further he disputes Flett's distinction between the

Traboe and Landewednack Hornblende Schists and maintains that the Lizard Boundary is not a major thrust-zone but simply the northern limit of the 'serpentine' and 'hornblende-gneiss intrusions' and their metamorphic effects.

The second edition of the Memoir (1946) revised by Flett, shows very little difference in interpretation south of the Lizard Boundary. Controversy on the Lizard structure and sequence has continued since the publication of the second edition of the Memoir. As mentioned above, Scrivenor's (1949) paper is in sharp conflict with Flett on the major issues. On the other hand, Hendriks (1959), in a paper on the large-scale structures of Cornwall, supports the idea of a major thrust between the Lizard rocks and the Palaeozoic rocks to the north. From exposures in Gerrans Bay, Roseland, where sheared serpentinite occurs in a flat thrust below the Nare Head pillow lava, Hendriks regards the serpentinite as intrusive along the thrust plane and also into the base of the pillow lava itself. This concept is extended to the Lizard as a whole and the 'serpentine' regarded as intrusive during major nappe thrusting in latest Devonian or possibly early Carboniferous time.

The most clearly stated alternatives to Flett's views on the structure and genesis of the main rock types are those of Sanders (1955). Sanders carried out some detailed mapping on the south-eastern corner of the Lizard Peninsula and disputed three of Flett's main conclusions, namely :

- (i) The 'serpentine' is a plug or dome-shaped mass intrusive into the mica and hornblende schists which surround it.
- (ii) The gneisses at Kennack, and Erisey in the interior of the peninsula, are later intrusives that have risen through the 'serpentine'.
- (iii) 'Serpentine' masses up to several acres in extent are included in these gneisses.

Sanders' own conclusions are that the 'serpentine' is a shallow thin sheet in this area, overlying the Landewednack Hornblende Schists and with its base at around the 180-200 ft. level. He regards the intimate mixing of serpentinite, acid gneiss and amphibolite in the Kennack area and south therefrom as a tectonic mixing and the mixed acid-basic gneisses of Kennack, Erisey, Poltesco and Pen Voose as merely the locally migmatized equivalent of the underlying Landewednack Hornblende Schist. Sanders concludes that the Lizard serpentinitized peridotite is an intrusive on the thrust plane between the Landewednack Hornblende Schists and an unidentified over-riding block.

The relevant evidence on these conflicting points of view will be discussed in later sections.

II. ROCK SEQUENCE AND RELATIONSHIPS

The rock units and rock types of the Lizard area as defined and used in the 1946 Geological Survey Memoir were found to be identifiable and mappable in the field and the nomenclature used by Flett is generally adhered to. The sequence of rock units in order of increasing age is

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- f. Palaeozoic, post-metamorphic rocks.
- e. Kennack gneiss and microgranite.
- d. Basaltic dykes and sills.
- c. Gabbro and troctolite.
- b. Peridotite.
- a $\left\{ \begin{array}{l} a_1. \text{ Old Lizard Head Series.} \\ a_2. \text{ Hornblende Schists of Landewednack and Traboe type.} \end{array} \right.$

The lithological map (Pl. 1) and locality map (Pl. 2) should be referred to in the following sections.

a₁. The Old Lizard Head Series.

The Old Lizard Head Series is a sequence of dominantly pelitic, thin-bedded rocks which are interbedded with the Landewednack Hornblende Schists. They are typically exposed from Polpeor to Caerthillian Cove and in this south-western corner of the area are considered to underlie the Landewednack Hornblende Schists.

The most common rock type is a quartz + feldspar + muscovite + biotite (or chlorite replacing biotite) schist and garnet-bearing assemblages are not uncommon. Hornblende or actinolite is present in some horizons and there are assemblages transitional to the hornblende + plagioclase assemblage of the Landewednack Hornblende Schist. Tilley (1937) has described in detail the cordierite-bearing assemblages from both south and north of the peridotite body and has drawn attention to the variety of assemblages present, the occurrences of kyanite and sillimanite together near Polkernogo and the occurrence of andalusite south of the peridotite at Pistil Ogo.

Tilley concluded that the rocks were a series of lavas, tuffs, quartzose and pelitic sediments which were folded at a high temperature, undergoing both thermal and dynamic metamorphism.

Tectonically the Old Lizard Head Series is characterized by a sub-horizontal metamorphic foliation parallel to the primary bedding. There is a 'b'-lineation due to mineral and fold-axis orientation on this plane; the folds are commonly recumbent and plunge in directions from 110° to 160° E. of N. The folding is generally incompetent with fold plunges in a very small area varying from 0°-90° in dip and similarly variable in bearing. In these features the rocks contrast with the regularity of foliation and lineation in the Landewednack Hornblende Schists.

The mineral assemblages of the Old Lizard Head Series are some indication of the complex interplay of thermal and dynamothermal metamorphism that typifies the Lizard. The occurrences of andalusite, cordierite and anthophyllite are suggestive of contact metamorphism in the hornblende-hornfels facies (Fyfe *et al.* 1958, pp.205-211). On the other hand the presence of staurolite, kyanite + sillimanite, almandine and epidote in various assemblages is more indicative of regional metamorphism in the almandine-amphibolite facies (Fyfe *et al.* 1958, p.228). The textures of the rocks are strongly lepidoblastic or granoblastic, with 'eyes' of andalusite or cordierite and elongate amphiboles or biotite, and are of typical dynamothermal character.

a., **The Hornblende Schists**

The Landewednack Hornblende Schists — The hornblende schists of Landewednack type are a monotonous series, at least 250 feet thick, of hornblende + plagioclase amphibolites. They have an extremely regular flat foliation with a pronounced mineral lineation produced by parallelism of hornblende prisms.

The rocks are characterized by medium-grained lepidoblastic texture with sub-hedral blue-green hornblende prisms; anhedral, commonly untwinned plagioclase and accessory sphene and magnetite. More calcic bands are common, particularly bands rich in salite and with epidote and less commonly with grossular. Epidote is common and varies from a minor constituent to areas with abundant bands, lenses and even veinlets of epidosite (e.g. Pen Olver). Its distribution probably reflects original calcic bands but also locally either introduction or redistribution of calcic solutions.

In the field the diagnostic features of these rocks are first the dominance of hornblende over other phases and secondly the horizontal foliation and pronounced 'b' lineation, distinguishing the Landewednack type from the Traboe type of hornblende schist. The lineation is due to parallelism of hornblende prisms and to elongation of the feldspar-rich and hornblende-rich lenses in a parallel direction. To a lesser degree it is the axis direction of minor, usually recumbent, folds within the hornblende schists. Such folding is not as common as, but is of a similar style to, that occurring in the Old Lizard Head Series.

The Landewednack Hornblende Schists are intruded by the peridotite, basaltic dykes and Kennack Gneiss. In the south-eastern part of the Peninsula the Landewednack Hornblende Schists are overlain and metamorphosed by the peridotite. *Similarly other contacts with the peridotite are either later fault contacts or contacts showing high grade dynamothermal metamorphism to yield the amphibolite and granulite assemblages called Traboe Hornblende Schist.* (Green 1964a, b).

Field and petrographic data indicate that the Landewednack Hornblende Schists are a metamorphic suite of almandine amphibolite facies, staurolite-almandine sub-facies, derived by regional metamorphism in a stress field with maximum compression directed E.N.E.—W.S.W., normal to the 'b' lineation. From chemical data, (Green 1964b) the pre-metamorphic rocks were a series of basalt lavas and/or sills with some dykes, tuffs and calcareous sediments. There is no evidence of a regional metamorphic gradient in the area in addition to the dynamothermal gradient due to the peridotite; the exposures in the east, north, west, south and south-east all have assemblages of the same metamorphic grade.

The Traboe Hornblende Schists — Flett (1912, 1946) gave the name Traboe Hornblende Schist to "a grey, feldspathic, non-epidotic and more coarsely crystalline hornblende schist . . . especially common in the district around Traboe and Polkerth. The foliation of these rocks is rough and irregular as contrasted with the flat parallel foliation of the epidotic hornblende schists, and coarse feldspathic veins and lenticles are often to be remarked in it". Flett also draws attention to the fact that the foliation in the Traboe Hornblende Schist is consistently near-vertical and strikes approximately north-south.

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Flett regarded the Traboe Hornblende Schists as intrusive rocks, forming a group of basic injections that immediately preceded the intrusion of the peridotite. He draws attention to the differing mineralogy of the two groups of hornblende schist, particularly to the lack of epidote and garnet, the presence of an augitic rather than a diopsidic pyroxene and the presence in some areas of brown hornblende in the Traboe Hornblende Schists.

The criteria that Flett used to define the Traboe Hornblende Schist are observable and valid ones and can be used to map the distribution of the types of hornblende schist. In the present examination of the Lizard area, careful examination of exposures near Mullion, Ryniau, Kilcobben Point, Devil's Frying Pan, Kildown Point, and particularly around Porthallow and Porthkerris, shows that the Landewednack Hornblende Schist passes transitionally into the Traboe Hornblende Schist. Chemical analyses show that the two rock groups have extremely similar compositions while detailed petrography and mineralogy (Green 1964b) lead to the conclusion that the Traboe Hornblende Schists are almandine amphibolite and granulites facies derivatives of the Landewednack Hornblende Schists. The agent of the dynamothermal metamorphism is the Lizard peridotite.

Near Porthkerris there is a structural and metamorphic transition between hornblende schists of the two types. As the peridotite bodies in the area are approached from south of Porthkerris there is a development of the 'Traboe character' of fluid folding on sub-vertical axial planes striking N.N.W.—S.S.E. or north-south. The pre-metamorphic and sub-horizontal foliation of Landewednack type becomes folded and, in more homogeneous horizons, completely overprinted by the sub-vertical, more irregular Traboe type of foliation. The two metamorphic foliations are consistently explained as forming in the same stress field in rocks of different rheidities¹. The Landewednack Hornblende Schists are considered to possess a 'b' lineation in a pre-metamorphic S-plane (primary bedding) and the Traboe Hornblende Schists are considered to have a b-c axial plane foliation developed in rocks where the controlling effect of pre-metamorphic foliation was inoperative due to decreased rheidity resulting from higher temperature or varying composition. This effect is well illustrated in several localities where there are foliation 'unconformities'

¹The rheidity (Carey 1954) of a substance is defined as the time required for the viscous term in the empirical strain equation

$$S = \frac{P}{\eta} + f(P) + \beta t + \frac{Pt}{\mu}$$

(Total Strain = Elastic + plastic + transient + viscous strain)

to become one thousand times as great as the elastic term. It is equal to $\eta/\mu \times 10^3$ seconds where η is a pseudo-viscosity for crystalline materials and μ is the rigidity of the material. The concept of rheidity is particularly necessary in deformation studies in geology since it stresses the importance of the time factor in determining the character, extent and type of deformation. Although numerical values for rheidity can rarely be ascribed to rocks the results of differing rheidities in rocks of different composition are evident in metamorphic and sedimentary terrains (e.g. Carey 1954), the classical examples being the low rheidity and thus fluid behaviour of marble relative to quartzites or gneissic rocks.

in which more massive bands in the Landewednack Hornblende Schists have sub-vertical foliation of the Traboe type.

The best exposures of the Traboe Hornblende Schist are those around Predannack Wollas and Predannack Head. These are characteristically of the assemblage brown-green hornblende + plagioclase + salite + opaque minerals and with proximity to the peridotite these pass into assemblages characterized by brown hornblende + augite, brown hornblende + augite + hypersthene and augite + hypersthene. Other exposures of the Traboe Hornblende Schists occur north of Kynance Cove, between Mullion Cove and Polurrian Cove, near Meaver and Tresprisson, near Tregadra, Trezise, Traboe, Rosuic, Kernewas, Porthkerris and Porthallow and in a very thin zone below the peridotite contact at Carn Barrow, Devil's Frying Pan and Kildown Point.

It is considered that all the exposures of Traboe Hornblende Schist are to be interpreted as developed in the dynamothermal aureole of the peridotite, acting on the moderate grade regional metamorphic assemblage of the Landewednack Hornblende Schist. There is no evidence that supports Flett's interpretation of these rocks as basic injections related to and immediately preceding the peridotite intrusion.

b. The Lizard Peridotite

The Lizard peridotite has an area of about 20 square miles and consists of one major and several minor bodies, obviously genetically related but of no provable physical connection. Primary mineral assemblages in the peridotite consist of olivine, orthopyroxene, clinopyroxene and spinel; aluminous amphibole and plagioclase are of secondary development in areas of high temperature recrystallization. Serpentinization is general throughout the whole peridotite but quite commonly does not affect more than 50% of the primary phases. The serpentine minerals are of the mesh-texture + bastite + cross-fibre chrysotile group and antigorite in its typical flare texture is not a common constituent. Chlorite and fibrous tremolite are common constituents; the spinel shows a sequence of breakdown reactions to give relict magnetite surrounded by chlorite and other minerals, and plagioclase is almost invariably saussuritized and secondarily altered.

Flett (1912, 1946) regarded the peridotite as a zoned intrusion of three serpentine 'magmas': an outer 'dunite serpentine', a median 'tremolite serpentine' and a central core of 'bastite serpentine'. The present investigation has shown that in reality Flett's classification roughly reflects a zoning in grain size and degree of mylonitization but in part the over-printing effects of serpentinization enter into it. It has been found practicable to classify and map the peridotite on the basis of a division into one primary and two recrystallized mineral assemblages, (Green 1964a). The *primary assemblage*, forming the core of the peridotite, consists of olivine, aluminous enstatite, aluminous and chromium-bearing clinopyroxene and olive green spinel in coarse anhedral texture. By increasing granulation of the olivine and bending and recrystallization of the pyroxene this assemblage passes into the typical *recrystallized anhydrous assemblage* of olivine, enstatite, chromium-bearing clinopyroxene, plagioclase and spinel in granoblastic texture with prominent augen of primary pyroxene

and lenticular porphyroblasts of spinel. The recrystallized anhydrous assemblage may contain orange-brown or pale brown hornblende as a minor accessory, usually replacing clinopyroxene. With increasing water content this passes into the *recrystallized hydrous assemblages* of olivine, pargasite and spinel.

c. **Gabbro**

Medium and coarse grained gabbro occupies a large part of the Lizard area in the neighbourhood of St. Keverne and its well exposed on the coast and in quarries at Porthoustock. Apart from this area the gabbro occurs in a large number of small dykes in the shore between Coverack and Kennack Sands and in the cliffs from Carn Barrow to Landewednack Church Cove. Inland, outcrops of gabbro occur east of Trenoon, west of Kingey, east of Treveddon, north of Worvas and at Ruan Minor and St. Ruan.

Near Coverack there are small dykes and intrusions of troctolite which are slightly earlier than the gabbro. The gabbro itself ranges from olivine-rich types to clinopyroxene + plagioclase rocks and is commonly strongly secondarily altered. The development of augen, flaser and schlieren gabbros in the small dykes has evoked a classical interpretation¹ of movement of the dyke walls while crystallization of the magma was in progress. The gabbro dykes at Lankidden Point near Carrick Luz show on their western margin a remarkable degree of foliation and high temperature granulation of the primary phases.

The general form of the main gabbro body suggests part of a ring intrusion with the peridotite of the Black Head area (primary assemblage) occupying the core of the ring. The outermost contact of the gabbro striking westwards from Porthoustock is a major curving fault, probably with the north side down-thrown. In a similar way the gabbro abruptly cuts off the marginal, recrystallized phase of the peridotite striking south-east from Traboe, for on strike from this within the gabbro ring, the peridotite has a very different mineral assemblage and direction of foliation. It is likely that across the rather narrow thickness of gabbro at Lankidden there is considerable differential movement and this has resulted in the spectacular development of augen gabbros in this locality.

The gabbro is a late-kinematic or post-kinematic intrusion unaffected by the regional metamorphism and not greatly affected by the regional stress field operative during the emplacement of the peridotite. Augen foliation and schistose structure in the gabbro is due to autometamorphism induced by movement of dyke walls as crystallization and cooling proceeded. The gabbro is very variable in both primary features (grain size, texture and composition) and in secondary features and warrants further detailed study.

d. **Basaltic Dykes**

Dykes and sills of porphyritic basalt occur commonly on the east coast of the Lizard from Porthoustock to Landewednack Church Cove and less commonly in the

¹ Flett, 1912, pp. 92-99.

peridotite and Traboe Hornblende Schist on the west coast. The least altered of the dykes are porphyritic, commonly with feldspar phenocrysts, less commonly with olivine and pyroxene pseudomorphs set in fine-grained secondary aggregates retaining relict basaltic texture. The dykes are in some cases foliated, the foliation being parallel to the dyke walls, and show mineralogical variation from actinolite-chlorite schists to green-hornblende, plagioclase, sphene amphibolites. The intrusions commonly have fine-grained, chilled contacts against peridotite, gabbro or the Traboe Hornblende Schist.

The dykes intruding the gabbro near Porthoustock form a prominent N.N.W.—S.S.E. trending swarm and this direction probably marks the tension direction of the regional stress field during their intrusion. In the area from Coverack to Landewednack Church Cove the dykes are more irregular but it is noticeable that the N.N.W.—S.S.E. trending sub-vertical dykes tend to retain their massive form whereas sills or shallow-dipping sheets of roughly E.—W. strike are commonly sheared (compare Figs. 1, 2, 3, 4) and invaded by the Kennack injection gneiss. The basaltic dykes cutting the Traboe Hornblende Schist-peridotite contact at Pol Cornick strike N.W.—S.E. and are considered to be part of the same suite.

e. Kennack Gneiss

Kennack Gneiss is the general name given to the late acid intrusives in the Lizard area. These intrusives are shown in the Geological Survey map as occupying quite large areas near Kennack, St. Ruan, Erisey and Goonhilly Downs, but owing to the very poor outcrop it is not possible to delimit accurately the extent of gabbro, serpentine, basaltic dykes and acid gneiss within these areas. Small bosses and irregular bodies of medium grained, non-sheared, quartz + oligoclase + orthoclase + biotite or muscovite microgranite do occur e.g. at the north end of Kennack Sands, but most commonly the coastal exposures show complex intermixtures of gabbro, amphibolite and contaminated acid injection gneiss. At the southern cove at Cadgwith there is a major acid dyke cutting the Landewednack Hornblende Schist and this sends out sills along the Landewednack Hornblende Schist and peridotite contact to the south. Smaller acid veins occur cutting the Landewednack Hornblende Schist in the quarry on the north side of Cadgwith, at Carn Barrow, Kildown Point and Pen Olver. By far the greatest amount of the acid gneiss occurs within the peridotite, particularly in close association with the basaltic dykes and sills.

On Manacle Point, south of Porthoustock, there are a series of basaltic dykes, some of which are intruded and brecciated by leucocratic hornblende dioritic material. These are probably late stage intrusions directly related to the basalt rather than to the acid Kennack Gneiss.

The problem of the age and origin of the Kennack Gneiss — The discussion as to whether the Kennack Gneiss intrusions are older or younger than the serpentinized peridotite with which they occur has continued for over 50 years. Bonney maintained that these rocks are older than the peridotite and that the peridotite is intrusive into them. Lowe in 1900 and 1901 clearly and generally enunciated the evidence for

regarding the gneisses as a series of intrusions penetrating the serpentinite and foliated during their intrusion. Flett (1912 and 1946) gave a review of the controversy and considerable detail of individual exposures of the acid and mixed acid-basic rocks. Flett's conclusions are that the Kennack Gneiss is an injection gneiss of mixed acid and basic magma, intruded into dykes and sills during a period of irregular movement and crystallized to a varied series from a microgranite to foliated and contaminated biotite + hornblende + plagioclase gneiss.

Sanders (1955) returned towards Bonney's view of the age relations of the serpentinite and Kennack Gneiss but introduced the concept of tectonic inclusion as opposed to magmatic intrusion for the serpentinite bodies within the Kennack Gneiss. In the valleys of Cadgwith, Poltesco and Kennack, Sanders considered that the area mapped by the Geological Survey as largely Kennack Gneiss, was in fact (p.236) 'mainly hornblende gneisses, possibly similar to those south of Landewednack. Locally, the hornblende gneisses merge into hornblende migmatites with granitoid sheets . . .'. Sanders regarded the serpentinitized peridotite as a sheet intrusion on a thrust plane and that (p.238) 'the presence beneath the serpentine of hornblende gneisses preserving a generally low regional dip and (at Kennack) containing concordant granitoid sheets and interfoliations, suggests that these are the migmatitized equivalents of the Landewednack and Cadgwith hornblende schists'. He regarded the xenoliths of peridotite within the Kennack Gneiss as 'serpentine removed from the lower levels of the sheet during differential movement'. Areas of serpentinite at sea level i.e. 200 feet below the base of the postulated sheet in the Carn Barrow to Balk area, were interpreted as commonly being landslips or slipped talus blocks.

Sanders' interpretation can be shown to be a false one from careful mapping of excellent coastal exposures from Church Cove to Kennack Sands. The amphibolite component of the mixed injection gneiss + amphibolite bodies is megascopically distinct from the amphibolite of the Landewednack Hornblende Schist in containing relict plagioclase phenocrysts and/or aggregates or schlieren of hornblende replacing former ferromagnesian phenocrysts. There is a continuous and readily observable gradation between massive porphyritic basalt dykes and sills and amphibolites with very strong foliation and orientation of amphibole prisms. The acid injection gneiss commonly follows these sheared amphibolite horizons. In intruding within them the injection gneiss becomes contaminated with crystallization of biotite and hornblende, and introduces alkalis particularly into the amphibolites giving rise to green hornblende + plagioclase + biotite amphibolites. Two localities where the amphibolites derived from the basaltic sills, and amphibolites of the Landewednack Hornblende Schist occur together, are immediately at the base of the peridotite sheet at Kildown Point and Devil's Frying Pan. In both these localities sills of basaltic parentage can be distinguished megascopically by fine grain size, strong and silky foliation and relict plagioclase phenocrysts as augen. Microscopically they are strongly lepidoblastic rocks with a one-generation assemblage of green hornblende and plagioclase. The amphibolites of the Landewednack Hornblende Schist parentage can be distinguished megascopically by coarser grain size, more granoblastic texture and by

plastic folding. Microscopically they have minerals of several generations but characteristically the larger amphiboles have brown cores and retrogressive pale green or colourless rims or there is evidence of the former presence of pyroxene(s) replaced by amphibole aggregates.

There are quite commonly angular unsheared xenoliths of peridotite and more rarely of gabbro within the amphibolite, acid or composite phase of the Kennack Gneiss. The peridotite xenoliths, particularly in the acid rocks, are strongly rimmed with talc, chlorite, tremolite, quartz and carbonate replacing the serpentine and primary minerals.

Four field sketches of exposures which clearly show the relationships of peridotite, gabbro, basaltic intrusions and acid gneiss are shown in Figs. 1, 2, 3 and 4. Fig. 1 shows a clear example of basalt dykes cutting gabbro (intrusive into peridotite) and passing upwards into a sill. The sill contains blocks of peridotite stoped from the peridotite roof of the sill and there is variation in the degree of foliation between the normal sill material and the 'protected' parts between peridotite blocks. The acid gneiss forms a lit-par-lit injection gneiss in the amphibolite and also occurs as a flat vein cutting both gabbro and basaltic dykes. Fig. 2 is a good example of two basaltic sills, both largely altered to amphibolite and with lit-par-lit injection of a small amount of acid gneiss, connected by a basalt dyke with angular xenoliths. The dyke and patches in the sills retain their primary porphyritic texture very distinctly. Fig. 3 shows a stoped and slightly moved block of peridotite in a dyke of Kennack Gneiss (with small amphibolite stringers) intruding peridotite and gabbro and joining a composite sill of basic and acid material. Fig. 4 is a very complex part of the short platform and cliff-face at the north end of Pen Voose. Gabbro, transitional to flaser gabbro, intrudes peridotite and is itself intruded by irregular basic dykes. Later acid veins follow generally the same channels as the basic dykes and all the rock types are strongly secondarily altered with sericitization, uraltization and other retrogressive processes.

The field evidence from these exposures and from the whole of the Lizard coastline is adequate to reject Sanders' hypothesis that the Kennack Gneiss is the migmatitized equivalent of the Landewednack Hornblende Schists. The general conclusion from the field mapping is that the basaltic magma intruded the peridotite and peridotite-gabbro complex in two main forms—as N.N.W.—S.S.E. trending dykes and as gently north or N.E. dipping sills or sheets. The sills were almost invariably sheared (indicating possibly a regional thrusting or flattening movement) and the following acid intrusions (the Kennack Gneiss) found their greatest ease of penetration along the channels of the basaltic magma, particularly the sheared gently-dipping sills. This explanation differs essentially from that of Flett (1912, 1946) only in that actual mixing of acid and basic magmas is not considered necessary to produce the lit-par-lit composite sills.

f. Palaeozoic Post-Metamorphic Rocks

The 'Lizard Boundary' (Flett 1912, 1946) is the series of faults and unexposed contacts which divides the metamorphic and igneous terrain of the Lizard Peninsula

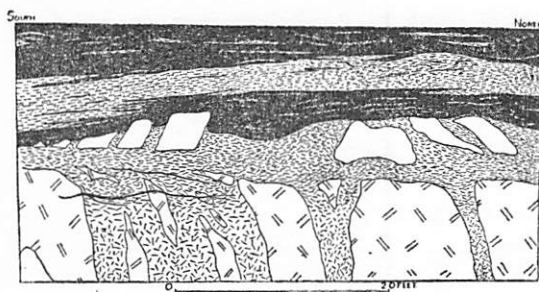


Fig. 1. Cliff section near Whale Rock (for key to stippling see Fig. 4).

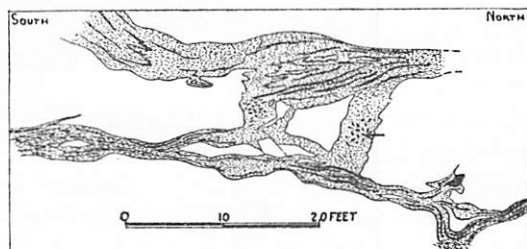


Fig. 2. Cliff section between The Balk and Pen Voose (arrow indicates relatively undeformed pseudomorphs after pyroxene phenocrysts).

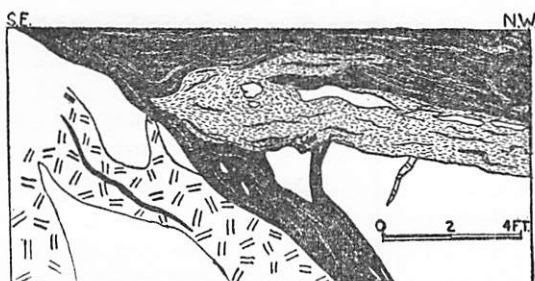


Fig. 3. Cliff section north of Whale Rock.

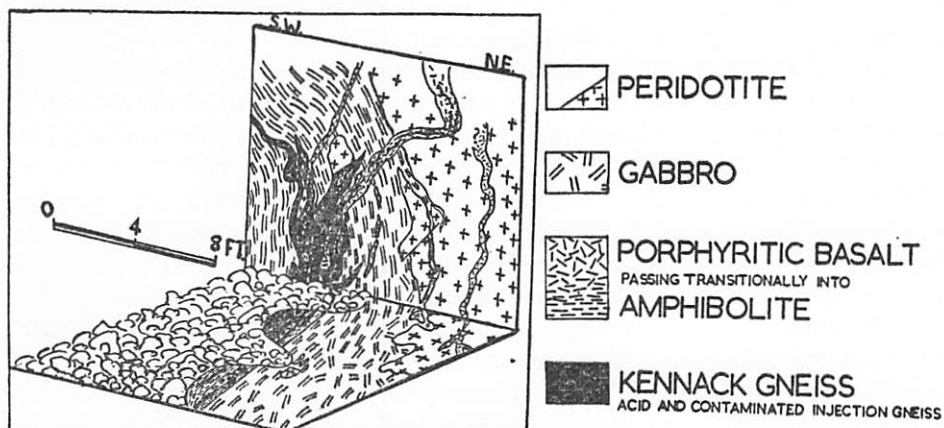


Fig. 4. Cliff section at the northern end of Pen Voose.

from the folded, cleaved but non-crystalline Palaeozoic sediments to the north. On the east coast the boundary immediately south of Porthallow is a normal fault dipping to the south. The rocks to the north have been regarded, particularly by Flett, as a strongly sheared mega-breccia of lenses and pods of more competent rocks, including quartzite, amphibolite, conglomerate and spilite, in incompetent silts and clays. This zone has been called the Meneage Breccia by Flett (1946) and interpreted as a tectonic breccia developed between the overthrust block of the Lizard Complex and the over-ridden Palaeozoic sequence to the north.

In 1949 Scrivenor disputed Flett's conclusion that a major break existed between the Lizard rocks and the Palaeozoic sediments to the north and postulated that the Old Lizard Head Series are the metamorphosed equivalents of the Palaeozoic sediments. A parallel hypothesis is that the Landewednack Hornblende Schists are the metamorphosed equivalents of the Palaeozoic spilites, particularly those of Mullion Island. This latter hypothesis was tested in the present study.

The normal fault emerging at the coast near Polurrian would, if continued along strike, pass north of Mullion Island including the island in the Lizard Complex to the south. Immediately opposite Mullion Island on the mainland at Ryniau the higher grade Traboe Hornblende Schist passes locally into lower grade Landewednack Hornblende Schist with the typical sub-horizontal foliation, N.N.W.—S.S.E. lineation and banded character reflecting primary bedding. Care was therefore taken to examine Mullion Island closely, first for evidence of a metamorphic gradient across the island increasing towards the mainland and secondly to seek evidence of minor faulting as a lead towards the position of any major fault.

The rocks of Mullion Island are predominantly spilitic pillow lava forming several flows and with interbedded chert and black siltstone. The spilites have no metamorphic foliation although some pillows show slight polishing of the pillow surface or local cleavage in the inter-pillow glassy selvages. The thin bedded radiolarian cherts do not show megascopic metamorphic effects but one exposure of a four feet thick horizon of cherts and silts has six recumbent folds in a distance of eight feet, plunging at angles from 5° to 30° in directions from E.N.E. to N.W. — this is very probably a slumping effect or drag due to the overlying basalt flow.

Thin sections of the spilites from the most easterly point on the island (nearest the mainland), the centre, and the most westerly accessible point show variation in the primary features of the basalt (grain-size, texture and degree of crystallinity) but no variation in metamorphic grade. All are characterized by relict fresh, primary pink titan-augite, by albitized plagioclase laths in random texture and interstitial fine chlorite, epidote, opaque oxides, calcite and albite. There is no evidence of any prograde metamorphism of the interstitial material to approach the regional metamorphic assemblage of blue green hornblende, andesine-oligoclase, sphene, epidote, salite. An examination of the former glassy selvage of a pillow shows devitrification and colloform and spherulitic crystallization of chlorite minerals but no directed texture or growth of medium grade metamorphic minerals. The chert bands show colloform and spherulitic crystallization but no evidence of granoblastic recrystallization to give quartzites. A thin section of black siltstone from between two lava flows

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contains angular quartz separated by tiny muscovite and pale brown, pleochroic ?stilpnomelane in parallel growth — this is a slate or phyllite in which the growth of muscovite and ?stilpnomelane may be due to metamorphism by the overlying spilite flow.

There are on the island, several small faults striking almost north-south, dipping to the east and with drag effects indicating movement downthrowing to the east. The lack of any metamorphic gradient on the island and the presence of these minor faults is strong evidence for the presence of a major fault, striking north-south and downthrowing to the east, passing between Mullion Island and the mainland. This fault would intersect or be the continuation of the Lizard Boundary Fault at Polurrian (striking N.E.—S.W.) and would to the south probably swing again to a N.E.—S.W. strike as there is no evidence for its presence on Predannack Head. (See Pls. 1 and 2.)

The Treleague Quartzite — Several specimens of more massive sediments in the crush breccia north of Porthallow have angular grains of quartz and feldspar with some secondary growth of chlorite, quartz, sericite and calcite. It may be significant that specimens of Treleague Quartzite (Flett 1946) show a very similar clastic texture and degree of recrystallization to these sediments. The Treleague Quartzite occupies an anomalous position being bounded by faults on all sides, intruded by dolerite sills but clearly not subjected to regional metamorphism of the Old Lizard Head Series and Landewednack Hornblende Schist type. The metamorphics south of the Lizard Boundary are wholly recrystallized, medium-grained lepidoblastic or granoblastic rocks with mineral assemblages characteristic of a moderate grade of regional metamorphism. On the other hand the Palaeozoic rocks are typically of primary igneous textures (spilites) locally modified by shearing, or of primary clastic texture also variably modified by shearing. Many of the rocks are fine grained chlorite phyllites but in any sequence there are beds or lenses preserving more completely the primary sedimentary textures and mineralogy. In summary, the Palaeozoic rocks are characterized by low grade dynamic metamorphism localized in thrust zones and local incompetent horizons.

The conclusions of Flett and Hill (1946) and of P. T. Carr (1960) place the Treleague Quartzite as younger than the metamorphism of the Old Lizard Head Series and Landewednack Hornblende Schist but older than the peridotite, gabbro and basalt igneous intrusions. The present study shows that the regional metamorphism and peridotite intrusion were probably roughly synchronous events but that the basaltic intrusions were of later, Caledonian age. It is considered that there are two possible explanations of the relationships of the Treleague Quartzite, consistent with the fragmentary evidence available :

a. The Treleague Quartzite is a downfaulted block of Lower Palaeozoic sediments, unconformably overlying the Lizard crystalline rocks, post-dating the regional metamorphism and peridotite intrusion but preceding the Caledonian basaltic and acid igneous intrusions. The dolerite sills within the quartzite (Carr 1960) may be the expression in the previously overlying flat quartzites, of the basaltic dyke swarm in the gabbro to the south-east.

b. The Treleague Quartzite is an upthrust block (a horst or thrust lens) of Palaeozoic from beneath a southward-dipping, postulated Hercynian thrust zone forming the Lizard Boundary.

The first of these hypotheses is preferred as more probable.

III. STRUCTURAL GEOLOGY

1. The Form of the Peridotite Intrusion

Flett regarded the peridotite as a plug or stock-like intrusive with steep contacts, commonly faulted. At the other extreme Sanders (1955) considered that the peridotite was a flat and fairly thin sheet overlying the metamorphic rocks.

The detailed mapping of the exposures near Porthallow and Porthkerris (Fig. 5) shows that the peridotite forms a series of domes and anticlinal highs intruding vertically into the hornblende schists. Similarly the small peridotite bodies north of Mullion Cove, near Meaver and at Parc Bean Cove are all small plugs or 'highs' on the roof of a larger peridotite body and are indicative of vertical, diapiric intrusion of the peridotite.

The contact of the major peridotite body on the west coast near Pol Cornick (Green 1964b, Fig. 5) is also steeply dipping or vertical although rendered complex by the mobile behaviour of the pyroxene granulites in the metamorphic aureole. The northern contact around Burnoon and Tregadra is not well exposed but probably is a series of domes plunging to the north—this is interpreted as a roof area of the major peridotite body. The contact area striking south-east from Lower Relowas to Kernewas is steeply dipping to the south-west or locally, near Polkerth, to the east.

The only other area where there are contacts between the regional metamorphic rocks and the peridotite is in the south-eastern part near Cadgwith. It is in this area that Sanders (1955) regarded the peridotite as a sheet overlying the Landewednack Hornblende Schists and this can be shown to be locally true by careful examination of coastal and inland exposures from Kildown Point south to Lizard. The details of the structure in this area can be seen by reference to Pls. 1 and 2, and the perspective diagram, Fig. 6. The base of the peridotite sheet is an undulating surface dipping at low angle (5-20°) to the west and north-west. This contact appears at different levels in the cliffs due to the effects of a series of roughly east-west normal faults.

The peridotite immediately overlying the Landewednack Hornblende Schist is invariably the olivine-pargasite assemblage but 20-30 feet from the contact the peridotite has the coarse, primary assemblage with local rather than general crushing and recrystallization. The banding and incipient augen foliation in the primary peridotite in this area strikes east-west or S.E.—N.W. but is not strongly developed. The pargasite-olivine assemblage also does not show as strongly lepidoblastic texture as in the northern and western outcrops.

At Kildown Point (Fig. 6) foliation in the pargasite-olivine assemblage ten feet above the contact dips at 45° to the south-west, nearer the contact it swings in strike and dip to 70° S.S.W. and then to vertical dip, roughly east-west strike. At three feet

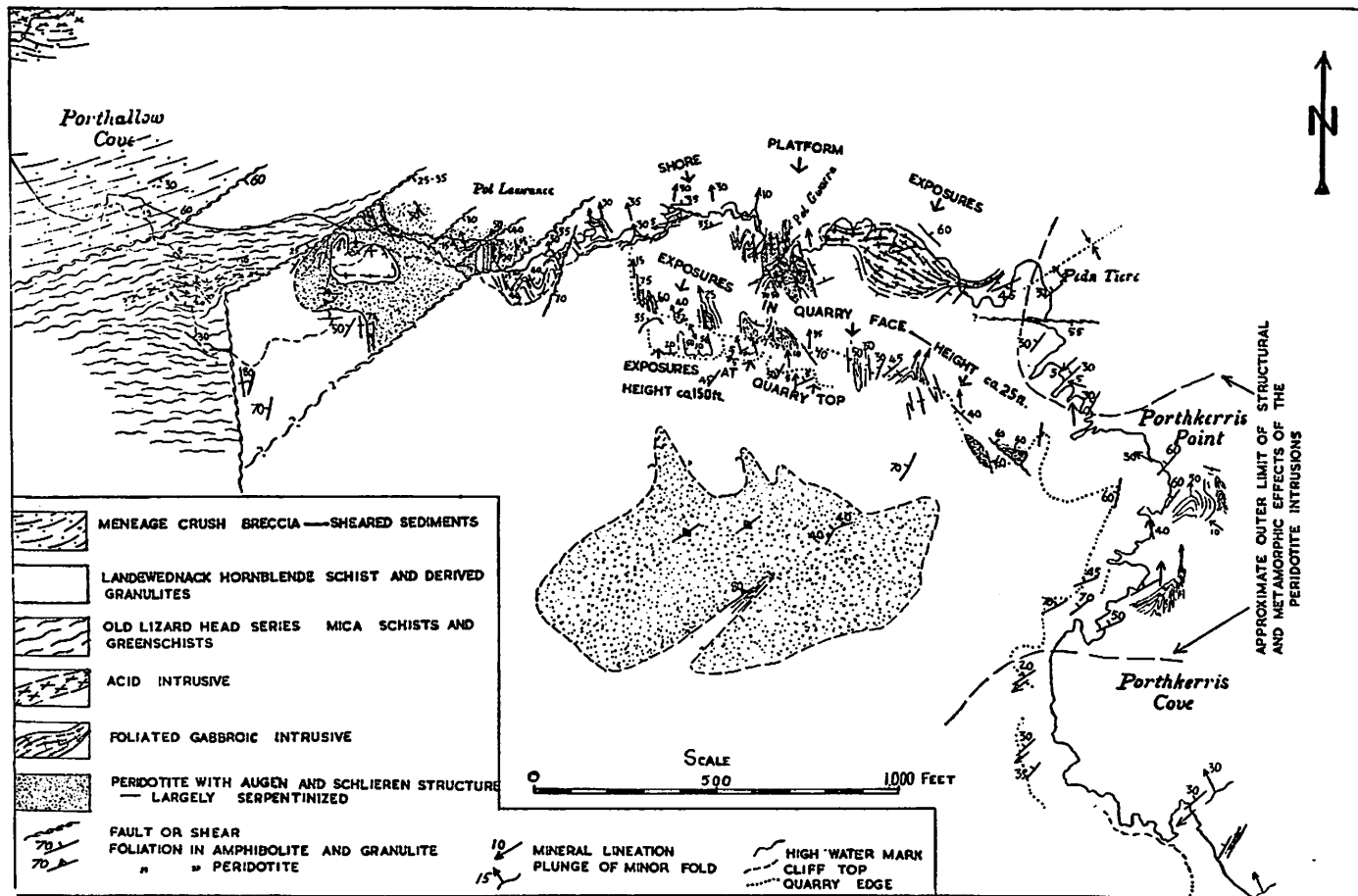


Fig. 5. Detailed geology of the peridotite contacts between Porthallow and Porthkerris Cove.

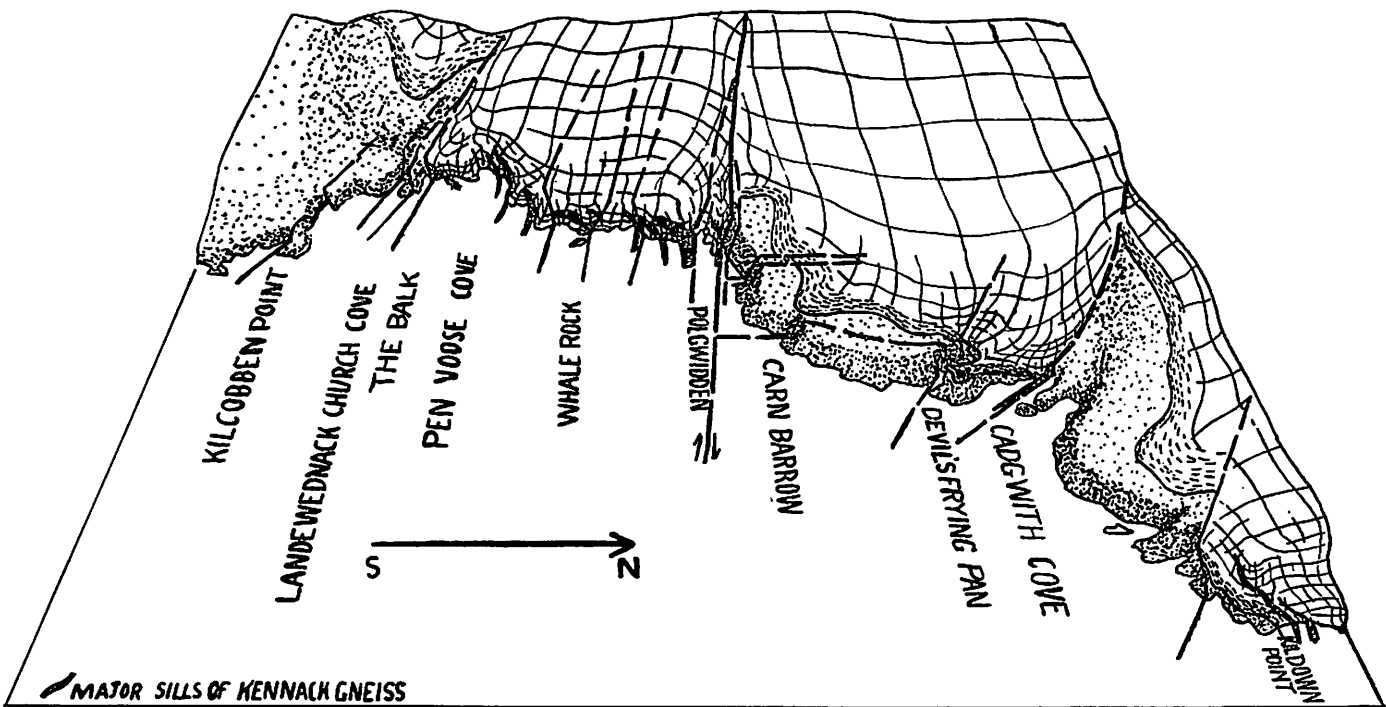


Fig. 6. Perspective sketch of the south-east part of the Lizard Peninsula showing the sheet-like form of the peridotite overlying the Landewednack Hornblende Schist(stippled) and the basal zone of olivine + pargasite peridotite (dashed).

from the contact the foliation strikes east-west and dips at 40° N. and as close to the contact as can be observed it is dipping at 20° to the north. The contact zone itself is slightly obscured by a six inch zone of talc and amphibole and by the intrusion of thin amphibolite and acid gneiss sills along the contact. The general effect is that of drag of the mineral foliation towards an east-west strike and shallow dip paralleling the contact, with increasing proximity to the contact. A similar effect can be seen on the south-west wall of the Devil's Frying Pan where foliation in the pargasite-olivine assemblage swings from $120^{\circ}/60^{\circ}$ N.E. at five feet from the contact to $100^{\circ}/30^{\circ}$ N. nearer the contact. Another structure indicating the same sense of movement occurs at the base of the peridotite within the Devil's Frying Pan on its north-east face. In this case a small drag at the base of the serpentine affects the underlying amphibolite and indicates north over south movement.

The actual plane on which the peridotite overlies the amphibolite is an undulating surface as shown by exposures on Carn Barrow, Kildown Point and Devil's Frying Pan. On the northern side of the sea-entrance to the Devil's Frying Pan the surface has a small-scale drumlinoid appearance with the normal 340° E. of N. lineation but elongation of the drumlin-like domes in the underlying amphibolite in a direction 60° E. of N. The Kildown Point exposure shows a cluster of elongate (1-3 feet) lenses of peridotite plunging at 340° and included within the amphibolite at a level probably about three feet below the base of the peridotite sheet. The amphibolite at this exposure of the flat contact (as at the others, see Green 1964b) shows evidence of high grade metamorphism and the peridotite inclusions have the appearance of more rigid boudins in amphibolite and granulite with fluid folding. Fig. 7 shows a hypothetical sequence by which the peridotite, intruding and metamorphosing the Landewednack Hornblende Schist as a sill-like body, could come to

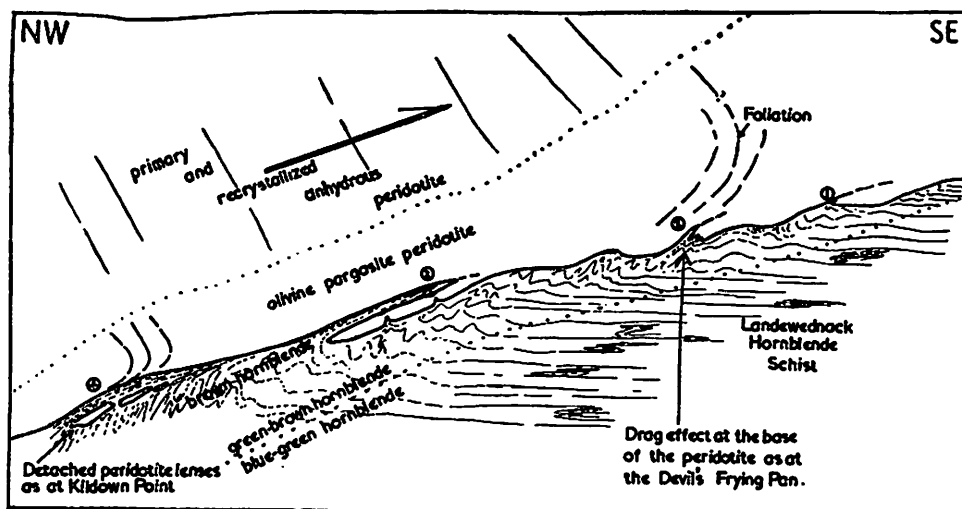


Fig. 7. Diagram illustrating a possible origin for peridotite lenses below the base of the peridotite.

have fragments from its base included within the amphibolites as observed at Kildown Point.

The contacts at Kildown Point and Devil's Frying Pan locally show the presence of the 340° E. of N. 'b' lineation and also fluid folding of Traboe Hornblende Schist type on N.N.W.—S.S.E. axial planes. Later injections of sheared porphyritic basalt sills and acid microgranite or gneiss sills tend to obscure the primary structures.

On a general view the south-eastern contact of the peridotite shows discordance of the contact attitude to the moderately dipping, E.-W. striking foliation of the peridotite but a tendency for this to pass into concordance at the actual contact. This tendency involves drag effects consistent with an overall intrusion of the peridotite from north to south over the Landewednack Hornblende Schists. Effects within the amphibolites themselves are consistent with recrystallization in the regional stress field coupled with local high grade metamorphism by the overlying peridotite sheet.

The general form of the Lizard peridotite is that of a vertical or near-vertical diapiric or plug-like intrusive, probably elongate in the N.N.W.—S.S.E. direction. There is a lip-like extension at the south-eastern end of the peridotite where the peridotite has apparently intruded horizontally as a sill within the flat-lying regional metamorphic rocks.

2. Faulting

Many of the faults of the Lizard are described in earlier studies. However no coherent pattern or even sequence of faulting has emerged and the same faults, particularly those forming the boundaries of the peridotite, have been described by different authors as normal faults and as thrusts.

In the following sections the faults are grouped into a suggested pattern and the field evidence for their character and postulated continuations is given in some detail. It is essential in arriving at the primary structure of the peridotite that these faults be analysed and the movement on them reversed. In this way also a picture of the changing stress field in the area can be built up and this should be consistent with evidence from textures and attitudes of the metamorphic and igneous rocks.

(a) **EARLY FAULTING.** The earliest series of faults following the emplacement of the peridotite are N.-S. faults in which the core and more central parts of the peridotite are thrust upwards and westwards over the marginal areas. A major fault of this type is exposed in a cove between Lion Rock and Kynance Cove and can be traced north across Kynance Rivulet. In this exposure the fault has a N.N.W. strike and 30°-40° dip to the east. A fault of the same character must lie between Mt. Carlees and Long Alley farms and can then be roughly traced north between peridotite of recrystallized type to the west and peridotite of the primary assemblage and variable foliation attitude to the east. The contact between the hornblende schists and the peridotite from near Penhale to Clahar is not well exposed but the evidence is that the marginal recrystallized phase of the peridotite is absent and peridotite of the primary assemblage and with banding of east-west strike abuts directly against the hornblende schist. It is concluded that this contact is a reverse fault contact in

which the peridotite in the core of the intrusion is thrust westwards over Landewednack Hornblende Schist forming the roof of the body.

A similar fault can be seen half-way up the cliff on the south side of Georges Cove. The fault dips at about 30° to the E.S.E. and brings rocks of the anhydrous recrystallized peridotite assemblage with a consistent N.N.W.—S.S.E. foliation to overlie an extremely complex marginal zone of granulite, amphibolite and olivine-pargasite peridotite with variable foliation trend. On the south side of George Cove the fault zone is intruded by several veins of pink microgranite (Kennack Gneiss) and the fault can be traced north by intermittent outcrops of the microgranite to an exposure in a quarry east of Predannack Wollas. In this quarry an augen-rich peridotite is separated by a shallow east-dipping fault plane from olivine-pargasite peridotite to the west. The fault was located again in a trench between Teneriffe and Isle of Wight farms and can be traced around the hill slope north of Wheal Unity. The former copper mine at Wheal Unity appears to be approximately astride the fault. The northerly limit of the fault is uncertain but is probably cut off by the W.S.W.—E.N.E. reverse fault at Porth Mellin. In this northern area the north-south fault brings a belt of primary assemblage peridotite with slight augen recrystallization over recrystallized hydrous and anhydrous assemblages with strikes of foliation swinging from N.N.W. to N.E.—S.W.

Two other faults in Georges Cove appear to be cut by the reverse fault. One of these strikes N.N.E. and dips steeply E.S.E. and possibly is downthrowing to the E.S.E. The other is a sheared north-south contact between peridotite and granulite.

At Ogo Dour Cove a N.E.—S.W. striking fault dips at 35° S.E. and shows pyroxene and hornblende granulites with lenses of peridotite thrust north-westwards over the green-brown hornblende amphibolites.

The major fault forming the south-west margin of the peridotite at Ryniau has a N.N.W.—S.S.E. strike and dips steeply (75°) to the N.E. On general structural grounds the Predannack area of amphibolites is interpreted as a roof area and the movement on the fault is probably north-east side upthrown i.e. a reverse fault. The age of this fault is unknown.

The general pattern of these faults is that of moderately dipping reverse faults (or steep thrusts) with east over west movement. They post-date the emplacement of the peridotite and act as channels or favourable localities for Kennack Gneiss minor intrusions. The fault near Kynance, as well as a microgranite vein, has several dykes of amphibolite along and near the fault plane — these are sheared and show drag effects consistent with east over west movement. This may be interpreted as later movement on an established fault plane which also acted as a favourable channel for the intrusion of the basaltic dykes. On the other hand the evidence may be interpreted as showing that these north-south faults post-date or are synchronous with the basaltic intrusions. The first alternative seems the more probable since the sense of movement on the faults is generally consistent with the regional stress field and the upward movement of the peridotite at the time of the peridotite intrusion. The absence of deflection of foliation in the peridotite near the fault zones and the

presence of much sheared serpentinite within them indicates that the faulting occurred after the main cooling and intrusion of the peridotite, possibly during the waning phase of the regional metamorphism and stress field that accompanied the peridotite intrusion.

(b) **TRANSCURRENT FAULTING.** At Gew Graze on the west coast of the Lizard there is a major fault zone associated with minor acid intrusion and with hydrothermal alteration to talcose and kaolinitic rocks. The fault has an east-west strike and steep (75°) southerly dip. Well-developed slickensides on a number of major movement faces are horizontal or plunge at 10° E. or W. Other slickenside surfaces within the fault breccia plunge more steeply to the south. On the east coast, south of Carn Barrow and almost directly on strike from this fault, there is a major fault zone striking at 100° E. of N. and dipping at $70-80^\circ$ S. This fault zone also has sub-horizontal slickensides indicating transcurrent movement and also has a strongly developed drag dip of 60° S.S.W. in the Landewednack Hornblende Schist (normal strike and dip 80° E. of N./ 15° N.).

An attempt to prove the continuity of these faults fails through lack of outcrop between Gwavas and Grochall farms. However on the sides of the small gully running from Grochall to Kynance Cove there is an area of variable foliation strikes at about the place where the postulated fault might cross the gully. North and north-east of this the peridotite is of the strongly foliated, recrystallized type with N.N.W. foliation. South and south-west the peridotite is of the primary assemblage with poorly defined foliation striking east-west. A further important feature is that the north-south trending thrust at Kynance Cove cannot be traced north across Predannack Downs but the same type of fault is present to the north-east near Mt. Carlees. The similarity of the character of the faults at the exposures at Carn Barrow and Gew Graze and the independent evidence of the displacement of the north-south thrust are considered to justify the hypothesis that there is one major fault extending right across the peninsula. The movement on this fault is mainly transcurrent with dextral displacement (north side east movement) but also in part a normal fault movement of south side down in the eastern part of the peninsula accounting for the $200+$ displacement of the base of the peridotite at Carn Barrow. It is possible that the normal fault movement is later than the transcurrent movement.

(c) **THE W.S.W.—E.N.E. THRUSTS.** There are in the area a group of reverse faults or thrusts striking approximately W.S.W.—E.N.E., dipping at 30° or thereabouts to the south and with the southern block over-riding the northern block. These have the same attitude and sense of movement as that postulated for the Meneage Breccia. These faults could have developed in a Hercynian movement of northward thrusting (Hendriks 1959). The two most clearly demonstrable of these faults occur east of Porthallow (Fig. 5). One, at the centre of Pol Lawrance, carries undulating amphibolite and granulite, developed around the margin of a larger peridotite body, over a smaller peridotite-granulite complex. The other, at the west of Pol Lawrance, carries the peridotite-granulite complex over mica and actinolite schists of the Old Lizard Head Series. Both faults die out to the west against a north-south vertical fault.

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A much larger fault with parallel strike, the same sense of movement and a 45° southerly dip occurs on the south side of Mullion Cove. In this case the peridotite is thrust north over granulite and peridotite of the peridotite roof zone and this fault also probably ends against the N.N.W. sub-vertical fault at Ryniau.

The contact north of Burnoon, between the roof area of the peridotite to the south and Landewednack Hornblende Schists and Old Lizard Head Series rocks (unaffected by the dynamothermal aureole of the peridotite) to the north, is probably also a gently dipping reverse fault of south over north movement and W.S.W.—E.N.E. strike. The western limit of the Meneage Breccia and of the Landewednack Hornblende Schist near Bonython, shown as a fault on Pls. 1 and 2, is of uncertain character and may be a sub-horizontal thrust or an intersection of fault and thrust (Flett 1946, p.151).

The main Lizard Boundary running from north of Trelowarren Lodge, by Lower Relowas and Rosemorder to Porthallow is poorly exposed and was not examined in detail in the present study. If the evidence from the coastal exposures and from the Burnoon area is generally valid then the Lizard Boundary in these areas is likely to be a mixture of gently-dipping roughly east-west reverse faults with south over north movement and a series of east-west normal faults downfaulting the over-riding thrust slices of metamorphics against the over-ridden Palaeozoic sediments.

(d) THE EAST-WEST NORMAL FAULTS. The most obvious faults in the Lizard area are the most recent, a series of east-west normal faults downthrowing to both north and south, post-dating the thrusting of the Lizard block over the Palaeozoic sediments to the north. These normal faults are most clearly seen in the cliffs near Lizard and from Lizard to Kennack Sands.

The southern boundary of the peridotite at The Balk is a fault striking E.S.E.—W.N.W. and dipping at 45° to the north. Drag effects in the Landewednack Hornblende Schists immediately to the south indicate a north side down movement and smaller parallel faults, clearly with north side down movement, occur in the cliffs to the south at Kilcobben Point, Church Cove and between Church Cove and The Balk. This boundary fault has been regarded as a thrust by Flett (1946, p.45) on which the peridotite thrust up and southwards over the Landewednack Hornblende Schist. Sanders (1955, p.237) considered the fault to be a normal one and this conclusion is supported by the evidence described above.

The base of the peridotite sheet with its characteristic zone of olivine-pargasite peridotite can be roughly traced from west of The Balk near the 200 ft. contour to near the Methodist Chapel in Lizard. In this area it is cut off by another east-west normal fault, also dipping at $40-50^{\circ}$ N. and emerging on the west coast at Pentreath Beach. The vertical displacement on the fault at The Balk is of the order of 200 ft. since the displacement of the base of the peridotite sheet is from a sea-level exposure of olivine-pargasite peridotite, on the north side of the fault, to near the 200 ft. contour. The vertical displacement at Pentreath Beach is probably slightly greater than this.

In the cliff sections from The Balk to Carn Barrow, east-west striking faults of unknown displacement are common and the vertical component of movement on the Carn Barrow transcurrent fault has already been described. The complexity of the Devil's Frying Pan exposures is due to the presence along the southern wall of the 'blow-hole' of a W.N.W.—E.S.E. fault downthrowing to the north and displacing the base of the peridotite sheet with its sills of Kennack Gneiss. There is a major fault at Cadgwith striking N.W.—S.E. along the strike of a microgranite dyke, which has a vertical displacement of about 250 ft. downthrowing to the south. South of Kildown Point a well exposed fault with angular fault breccia dipping at 75° N.N.E. and downthrowing to the north, brings the base of the peridotite sheet from near the 150 ft. contour down to sea-level. North of Enys Head a south-dipping E.-W. fault with a prominent breccia zone, downthrows to the south and on the shore platform on its northern side is olivine-pargasite peridotite overlying amphibolite giving a contact probably of the same character as that at Kildown Point.

The nature of the southern contact of the gabbro at Coverack is not clear but there is no evidence of a major fault. The northern contact at Porthoustock is certainly a major fault striking east-west and curving through a smooth arc to the west to strike north-south. The fault is nowhere exposed but from the distribution of the rock types it is clear that the north and west side is the downthrown side. The problematical relationships of the Treleague Quartzite have already been discussed and Carr (1960) gives evidence for the southern margin of the Quartzite being a normal fault downthrowing to the north.

The fault at East Beach, Porthallow, which brings the Old Lizard Head Series to the south into contact with very sheared sediments of the Palaeozoic sequence, strikes E.N.E.—W.S.W. at the coast and probably swings nearer to E.S.E.—W.N.W. to the west. The fault dips south at 60° and the sediments immediately to the north are dragged from a 15° S.E. to a 60° S.E. dip. The drag effects indicate that this fault also is a normal fault.

The fault at Polurrian Cove on the west coast which forms the northern limit of the peridotite and Traboe type of hornblende schist, strikes N.E.—S.W. and dips at 50° to the south-east. Drag effects on the Palaeozoic sediments are not strongly developed but do indicate a south side down movement. There is a distinct zone of angular fault breccia in this fault zone which suggests a normal fault rather than a steep reverse fault although both alternative explanations are given in the Memoir (1946, p.134). The minor faulting on Mullion Island described previously is consistent with a major fault striking nearly north-south between Mullion Island and the mainland and this is either the continuation of or intersects the Polurrian Fault. Whittard (1961) has reported the coring of 'Devonian slates' 7½ miles south-west of Mullion Cove. This is further evidence that the Lizard Boundary does not continue on the strike of the boundary fault at Polurrian but a continuation of a fault on the trend defined between Mullion Island and the mainland would place this coring on the western side of the Lizard Boundary fault. It is probable that further coring in

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the area would reveal as complex a boundary to the Lizard Complex as is present in the land areas.

(e) SUMMARY OF FAULTING. Apart from the faults described and grouped together in the previous sections there are innumerable minor movement planes and faults exposed in the Lizard cliffs. Many of the contacts of contrasted rock types are sheared and the shearing and associated hydrothermal effects result in retrogressive alteration that does much to obscure the primary features of the contacts. In the serpentinized peridotite particularly, practically every joint plane is a movement plane and this 'brecciation' in apparently random manner is largely responsible for the foliation induced in the post-peridotite minor intrusions.

In summary it is possible to recognize in the Lizard three distinct faulting patterns. The earliest pattern is of approximately north-south striking, easterly dipping reverse faults in which the central and more easterly parts of the peridotite complex moved westward over the marginal part of the peridotite and the western metamorphic aureole. These are consistent with late-stage movements in the stress-field of the orientation present during regional metamorphism and peridotite intrusion. A later distinctive series of thrusts or moderately dipping reverse faults strikes roughly E.N.E.—W.S.W. and has a south over-riding north movement—these could be part of a Hercynian system of east-west thrusts and northward thrusting movement. These reverse faults were followed, probably in the Hercynian late orogenic or post-orogenic period by a series of east-west normal faults, downthrowing to both north and south.

IV. THE AGES OF THE LIZARD ROCKS

The palaeontological evidence for the age of the rocks in the Meneage Breccia north of the Lizard Boundary has been summarized by Flett (1946, pp.120-136). An Ordovician age for the Meneage Quartzite remains in dispute and a Lower Devonian age is given as an alternative (Flett 1946, p. 126). The suggested Silurian age for limestone lenses in the Meneage Breccia also needs confirmation and an age of Middle Devonian for plant remains is the only other palaeontological evidence from this sequence.

Flett (1946, p.24) regarded the movements giving rise to the Meneage Breccia as Hercynian (Carboniferous) in age and causing the thrusting of the *Archaean* Lizard Complex over the lower Palaeozoic rocks. Flett separated the history of the Lizard Complex into two distinct phases — the first a period of high grade regional metamorphism accompanied by the intrusion of the Man of War Gneiss. He regarded the deposition of the Treleague Quartzite as preceding the second phase which was the sequence of genetically related intrusives ranging from the Traboe Hornblende Schist and peridotite to the acid Kennack Gneiss.

Scrivenor in 1949 regarded the Old Lizard Head Series as metamorphosed Lower Palaeozoic and by implication would regard the whole sequence of intrusion and metamorphism in the Lizard as post-Devonian events. Similarly Hendriks (1959, p.255) supported the conclusion that the Old Lizard Head Series were metamor-

phosed Lower Devonian sediments and placed the intrusion of the 'serpentine', as the metamorphosing body, as Upper Devonian or Lower Carboniferous in age.

It is considered that the present study of the Lizard has either confirmed or established the following sequence and relative timing of events.

1. Deposition of a sequence of pelitic sediments, tuffaceous sediments and basalt flows.

2. Local intrusion of acid sills (the Man of War Gneiss).

3. Regional metamorphism of 1 and 2 in a stress field with maximum compression directed E.N.E.—W.S.W. and with intrusion of diapiric peridotite bodies during the regional metamorphism.

4. Intrusion of gabbro — of uncertain time relationship or genetic relationship to either the preceding peridotite or the following basaltic dykes.

5. Intrusion of basaltic dykes and sills with chilled margins and in a stress environment of E.N.E.—W.S.W. relative tension. This implies a large change in stress and temperature environment from stage 3 and thus probably a major time break.

6. Intrusion of acid microgranite probably very closely following stage 5, in a similar stress field and with relationships of basic and acid rocks suggesting incomplete cooling of the former before intrusion by and reaction with the latter.

7. Northward thrusting or reverse faulting of the igneous metamorphic block over Palaeozoic (including Devonian) sediments to the north. This is the Carboniferous (Hercynian) event of previous authors.

8. Post-orogenic normal faulting giving faults of east-west strike and probably occurring in the waning or relaxing phase of stage 7.

With this geologically established sequence in mind, a series of absolute age determinations by the potassium-argon method was undertaken in collaboration with J. A. Miller at the Department of Geodesy and Geophysics, Cambridge. The results of these determinations are summarized in Table 1 in which are also included the measurements by Dodson (1961) on the Lizard rocks.

From the Table the striking feature is the grouping of most of the ages in the 350-390 million years range. In detail it is apparent that both the Oxford and Cambridge results show a slightly younger age for the muscovite from the Old Lizard Head Series than the biotite from the Kennack Gneiss. The total volume technique of argon measurement used at Cambridge gives a slightly greater age than the isotope dilution method used at Oxford — this consistent difference is also apparent in comparative measurements undertaken at Oxford and Cambridge on the Shap granite (Dodson *et al.* 1961). It is particularly encouraging that the hornblendes, containing about one twentieth of the potassium present in the micas, give in three cases ages that are quite closely agreeing with the ages from micas. In particular hornblende and biotite from the same hand-specimen 96392 gave ages of 366 ± 20 and 397 million years respectively for the Kennack Gneiss.

From these results it can be definitely stated that a 370-390 million year age marks an 'event' in the crystallization history of the Lizard rocks. The Hercynian granites of south-western England have been dated as about 265 million

TABLE 1: Age Determinations in the Lizard Area

Rock Unit	Mineral	% K ₂ O	No. of deter- mina- tions	Age (millions of years)	* δ t	Method	Determined at	Specimen No. and Rock Type
Old Lizard Head Series	Muscovite (coarse)	9.03	: 5	357	3.25	KA, Total Volume	Cambridge	96388 Muscovite chlorite schist
" " " "	Muscovite (fine)	9.01	: 5	352	3.21	KA, Total Volume	Cambridge	96388 " " "
" " " "	Muscovite (coarse)	9.17	: 5	355	3.20	KA, Total Volume	Cambridge	96391 " " "
" " " "	Muscovite (fine)	9.11	: 5	359	3.27	KA, Total Volume	Cambridge	96391 " " "
" " " "	Muscovite	7.68	: 3-4	349	—	KA, Isotope Dilution	Oxford	9372 Muscovite Schist
" " " "	Muscovite I	9.49	: 3-4	348	—	KA, Isotope Dilution	Oxford	20557 Muscovite Schist
" " " "	Muscovite II	8.58	: 3-4	352	—	KA, Isotope Dilution	Oxford	20557 Muscovite Schist
Landewednack	Hornblende	0.375	: 8	371	3.37	KA, Isotope Dilution	Cambridge	96396 Blue-green hornblende, plagioclase, sphene amphibolite
Hornblende Schist			:					
" " "	Hornblende	0.425	: 6	442	3.94	KA, Isotope Dilution	Cambridge	96389 Blue-green hornblende, plagioclase, sphene amphibolite
" " "	Biotite	6.4	: 3-4	369	—	KA, Isotope Dilution	Oxford	9380 Hornblende, Biotite schist
Traboe Hornblende Schist	Hornblende	0.211	: 7	357	3.25	KA, Isotope Dilution	Cambridge	96395 Brown-green hornblende, plagioclase, diopside amphibolite
" " "	Hornblende	0.242	: 7	492	4.43	KA, Isotope Dilution	Cambridge	96394 Brown hornblende, augite, hypersthene granulite
Kennack Gneiss	Hornblende	0.577	: 7	366	3.33	KA, Isotope Dilution	Cambridge	96392 Biotite, hornblende amphibolite
" "	Biotite	6.97	: 5	397	3.58	KA, Total Volume	Cambridge	96392 Biotite, hornblende amphibolite
" "	Biotite	5.98	: 5	384	3.47	KA, Total Volume	Cambridge	96393 Biotite, hornblende amphibolite
" "	Biotite	7.39	: 3-4	368 (av.)	—	KA, Isotope Dilution	Oxford	9406 Granite gneiss
" "	Biotite	(—)	: —	352 $\pm$ 10	—	Rb-Sr, Isotope Dilution	Oxford	—) Granite gneiss
" "		(—)	: —	353 $\pm$ 13	—	Rb-Sr, Isotope Dilution	Oxford	—)

* δ t = Error in age (millions of years) due to a 1% error in proportion of K₂O or volume of radiogenic argon.

years old (Dodson, Miller and York 1961) so that this 'event' cannot be correlated with the Hercynian orogeny. The late thrusting of the Lizard, since it involves Devonian rocks, is probably of this Hercynian phase and thus cannot have greatly modified the general Lizard mineral assemblages *except* that it is very probable that the slightly younger age given by muscovite from the Old Lizard Head Series is due to argon loss on retrogressive alteration (co-existing biotite is partially or completely altered to chlorite, cordierite is altered to secondary products) during the Hercynian thrusting. With their flat-lying foliation, micaceous character and varied lithology it is very plausible that the Old Lizard Head Series should show greater retrogressive effects during a thrusting movement than either the more massive Landewednack Hornblende Schists or the Kennack Gneiss bodies within the peridotite.

With the exception of the rubidium-strontium age of 353 million years all the determinations on the Kennack Gneiss fall in the range 366-397 million years. With the possibility of any argon loss giving a low age, it is probable that the older ages give the true age of intrusion of the Kennack Gneiss — this age of about 390 million years is compatible with the ages of Caledonian granites such as the Shap granite (397 million years) (Dodson *et al.* 1961) the Skiddaw Granite (399 million years) and the Eskdale Granite (383 million years) (Miller, 1961). From these results it is possible to attach an absolute age to events 6 and 5 and to say that the final igneous phase i.e. the acid injection gneiss, and the preceding basic dykes, are of uppermost Silurian or Lower Devonian age and are part of the Caledonian orogenic cycle. This interpretation is compatible with the geological evidence.

The problem of the age of peridotite intrusion still remains. The ages given by muscovite from the Old Lizard Head Series, biotite from the Landewednack Hornblende Schist, one hornblende from the Landewednack Hornblende Schist and one hornblende from the Traboe Hornblende Schist (in the aureole of the peridotite but 800 yards from the nearest peridotite outcrop), are close to the age of the Kennack Gneiss. This does not support the geological evidence of a probable large time break between events 3 and 5 + 6. On the other hand two ages, one of 442 million years from Landewednack Hornblende Schist at Pen Olver, and the other, giving a 492 million year age from brown hornblende in a hypersthene + augite + brown hornblende granulite immediately in contact with the peridotite, are significantly older than the Kennack Gneiss. These older ages are considered to give a 'pointer' back to the earlier, major orogenic event in the Lizard in which, on geological evidence, the regional metamorphism and peridotite intrusion occurred. The actual age of this event is unknown and it would need a concentration of ages around the 490 million year mark before this could be accepted as significant in this problem.

In summary, the interpretation placed on the evidence from age determinations and the geological study is that the Caledonian age of 370-390 million years is a true age for the injection of the Kennack Gneiss. This was also a period of partial or complete argon loss from pre-existing minerals. There was no major recrystallization of the earlier assemblages but probably a general rise in temperature during the period of basic dyke and acid gneiss injection.

A Re-study and Re-interpretation of the Geology of the Lizard Peninsula, Cornwall

The hypothesis that the Old Lizard Head Series are metamorphosed Lower Devonian sediments can no longer be considered; these rocks, the Landewednack Hornblende Schists and the peridotite are at least pre-Caledonian in age, i.e. pre-Devonian or pre-Upper Silurian. The regional metamorphism and peridotite intrusion occurred in a pre-Devonian orogenic event which has not yet been dated more accurately than probably at least 490 million years old. This event cannot as yet be adequately correlated with other early fold systems in Britain but the N.N.W.—S.S.E. direction of fold-axes during the regional metamorphism and peridotite intrusion invites comparison with other 'pre-Cambrian' areas of Britain.

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PLATE 1. Lithological map of the Lizard district, Cornwall.

PLATE 2. Locality map of the Lizard district, Cornwall.

