Read at the Annual Conference of the Ussher Society, January 1998

THE TECTONIC EVOLUTION OF PERIDOTITES IN THE LIZARD OPHIOLITE COMPLEX, SOUTH-WEST ENGLAND

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Cook, C.A., Holdsworth, R.E. and Styles, M.T. 1988. The tectonic evolution of peridotites in the Lizard Ophiolite Complex, south-west England. *Geoscience in south-west England,* **9,** 182-187.

The mantle peridotites of the Lizard Complex, south-west England, preserve direct and indirect evidence for several deformation episodes : 1) Extensional uplift of mantle prior to the formation of oceanic crust in an incipient ocean basin; 2) Their subsequent emplacement by thrusting in an intra-oceanic setting at the onset of obduction; 3) Extensional reactivation of the intra-oceanic thrust contacts in response to late stage collapse of a nappe pile (Jones, 1997).

An early fabric is characterised by a sub-vertical foliation and a steeply plunging mineral lineation. This fabric pre-dates the formation of oceanic crust as it is cross-cut by MORB-type gabbro intrusions and dykes. Among the least deformed peridotites are spinel- and plagioclase-lherzolites with a coarse to medium-grained porphyroclastic texture. With increasing deformation, these pass transitionally into mylonitic plagioclase-bearing peridotites and mylonitic amphibole-bearing peridotites which have a medium to fine-grained porphyroclastic textures. The presence of 'fertile' spinel lherzolite and the orientation of the peridotite fabric is not typical of emplacement of peridotites at an oceanic spreading centre. Alternatively it is proposed that systematic changes in microstructure, mineral chemistry and geothermometry of the different peridotite types are related to changing conditions of P and T during tectonically controlled uplift of mantle. Changes in the whole-rock compositions of the deformed peridotites are thought to be related to syntectonic metasomatism by hydrous melts. The subsolidus trajectory of the peridotites suggests deformation in the footwall of an extensional shear zone or in the margins of a upwelling mantle diapir.

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INTRODUCTION

The Lizard Complex (Figure 1) forms the highest structural level exposed in the Variscan nappe stack of south-west England (Holder and Leveridge, 1986). The Lizard Complex has previously been interpreted as a peridotite diapir with a dynamothermal aureole overprinted on regionally metamorphosed amphibolites (Green, 1964). More recently, the Lizard Complex has been considered as a highly deformed and dismembered Devonian ophiolite assemblage (Bromley, 1979; Styles and Kirby, 1980). In the ophiolite models, the mantle section of the Lizard consists of variably deformed peridotites (Flett and Hill, 1912; Green, 1964; Rothstein, 1977, 1981, 1988, 1994; Davies, 1984). A detailed discussion of the ophiolite model and a summary of the different lithologies represented in the Lizard complex is presented in a review by Floyd *et al.* (1993).

The Lizard complex of high-grade metamorphic rocks is separated from the low-grade, Gramscatho group Devonian metasediments to the north by a high-angle extensional fault, related to reactivation of earlier thrust faults (Power *et al.,* 1996). This paper describes fabrics which predate the main magmatic events related to the formation of oceanic crust. These fabrics are related to deformation of a high pressure and high-temperature spinel lherzolite protolith and its subsequent evolution to lower P and T assemblages during uplift of the mantle. Details are provided about the nature of fabrics related to this deformation and the subsequent changes in peridotite microstructure, mineral and whole-rock geochemistry. These observations are consistent with other examples of deformed mantle, and provide important new constraints on the tectonic evolution of the Lizard peridotites.

FIELD OBSERVATIONS

Field evidence suggests that the peridotites are one of the earliest rock types formed in the ophiolite part of the Lizard complex. Borehole evidence (Leake and Styles, 1984) suggests that the peridotites are the substrate on/in which the highly deformed ultramafic/mafic rocks of the Traboe cumulate complex were formed. Controversial contacts between peridotite and amphibolite in the Ogo Dour cove area, on the west coast, suggest that some amphibolites at this locality are intrusive into peridotite. The peridotites are clearly intruded by the Crousa gabbro, MORB-type basaltic dykes and the Kennack Gneiss (Figure 1 for locations).

In the field two main types of peridotite can be identified: coarse-grained lherzolites in low-strain areas, and mylonitic peridotites in high-strain zones. The coarse-grained lherzolites are exposed in the central, southern and eastern parts of the Lizard (Figure 1), whilst the mylonitic peridotites are predominant in the northern and western areas. In most areas, the different peridotite types are juxtaposed by later brittle faults, although gradational contacts are preserved near Kynance Cove (Figure 1).

In the field, coarse-grained lherzolites have a fabric defined by slightly stretched orthopyroxene porphyroclasts, spinel, olivine and recrystallised clinopyroxene. Pyroxene-rich layers

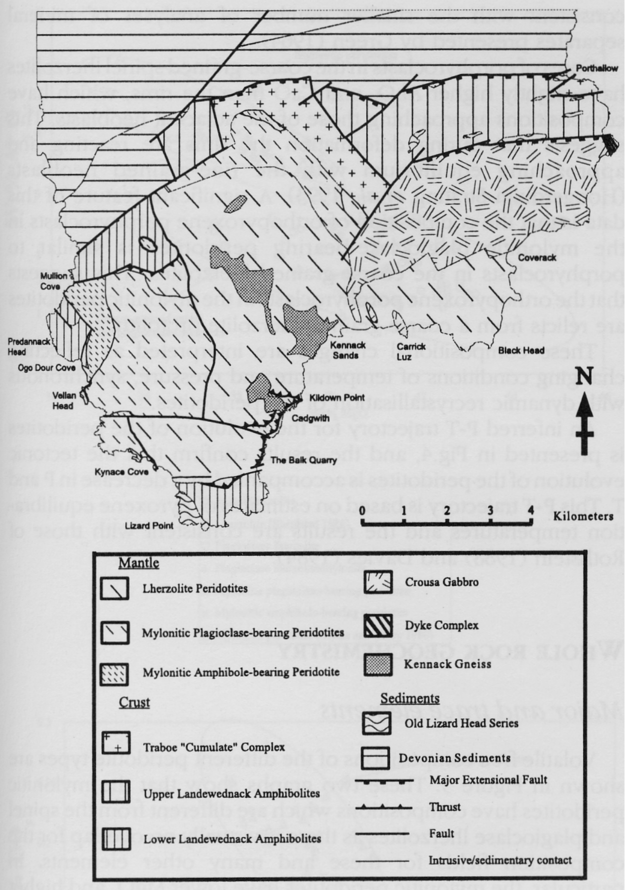


Figure 1. Geological Map of the Lizard Complex. Modified after (Flett 1912; Green, 1964; Floyd et al., 1993).

may occur parallel to this fabric. In comparison, the mylonitic peridotites have a much stronger fabric, also defined by elongate orthopyroxene porphyroclasts and more extensively recrystallised olivine, pyroxene, spinel, plagioclase and/or prominent amphibole.

The characteristic fabric of the coarse-grained lherzolites is a north-north-west to north-east orientated sub-vertical foliation with mineral stretching lineations plunging down-dip (Figure 2). In the high-strain zones, the mylonitic peridotites show a north-north-west orientated foliation which dips steeply to the east-north-east, whilst mineral lineations again plunge down-dip. The similarity in the orientation of fabrics in the different peridotite types, and the presence of gradational contacts near Kynance Cove suggests that these fabrics where produced by heterogeneous strain during the same deformation event.

MICROSTRUCTURES

A detailed study of peridotite microstructure has been conducted on samples of coarse-grained lherzolite and mylonitic peridotite. This has allowed further sub-division of the peridotites using microstructural characteristics.

Coarse grained lherzolites : The coarse-grained lherzolites are predominantly spinel lherzolites being composed of coarse-grained orthopyroxene porphyroclasts surrounded by a matrix of olivine, clinopyroxene and spinel, all showing varied degrees of recrystallisation. They typically show medium to coarse-grained porphyroclastic microstructures (Mercier and Nicolas, 1975). In some outcrops coarse-grained lherzolites with identical microstructures occur, but these differ due to the occurrence of interstitial patches of saussurite and spinels with saussurite rims. The saussurite appears to be an alteration product of plagioclase. This observation suggests that although the original 'primary' assemblage was a coarse-grained spinel lherzolite (Green, 1964), some of these rocks have undergone incipient metamorphic re-equilibration as a result of passing from the spinel to the plagioclase stability field, and are now plagioclase lherzolites.

Mylonitic peridotites: In the high-strain zones, two types of mylonitic peridotite occur - mylonitic plagioclase-bearing peridotite and mylonitic amphibole-bearing peridotite. These two peridotite types are often interbanded at a mm scale (Green, 1964; Davies, 1984). The mylonitic plagioclase-bearing peridotites have a fine to medium-grained porphyroclastic microstructure (Mercier and Nicolas, 1975). They are characterised by an assemblage of olivine, relict orthopyroxene porphyroclasts, clinopyroxene, and plagioclase, the latter occurs as interstitial crystals and rims around spinel. Small brown Ti-pargasite amphiboles (amphibole names are according to the IMA classification, Leake, 1978) occur as a minor component in some samples. Microstructures suggest that the mylonitic plagioclase-bearing peridotites are transitional with the coarse-grained lherzolites through a process of increasing deformation, dynamic recrystallisation and grain size reduction.

The mylonitic amphibole-bearing peridotites are transitional in microstructure from the mylonitic plagioclase-bearing peridotites (Green, 1964). This assemblage is characterised by the presence of up to 30% pargasitic hornblende, which has replaced pyroxene and plagioclase (Green, 1964).

MINERAL COMPOSITIONS

In order to establish the relationships between the different peridotite types defined using microstructural criteria, selected samples have been analysed to determine mineral compositions.

Figure 3 shows wt% Al_2O_3 versus wt% CaO in orthopyroxene, these compositions are selected as representative data. Figure 3 reveals that the composition of orthopyroxene varies with microstructure. There is a systematic decrease of Al_2O_3 and CaO from porphyroclasts in spinel lherzolite to neoblasts in The mylonitic amphibole-bearing peridotite. This observation is consistent with the

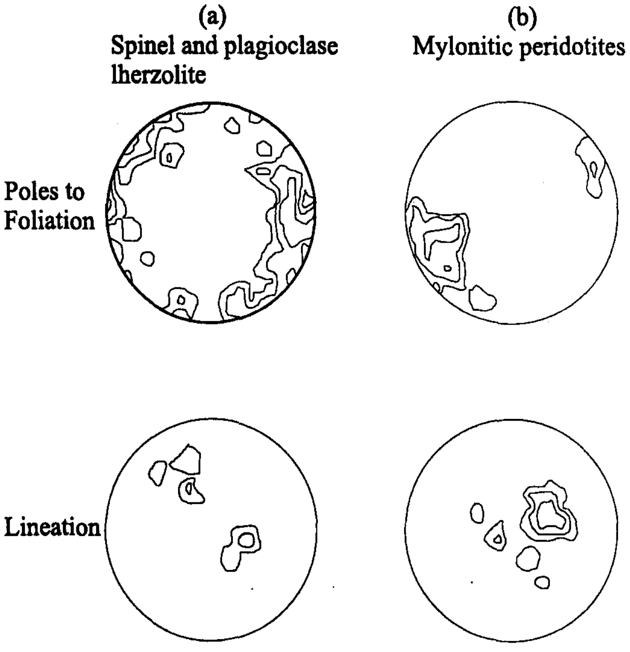


Figure 2. Peridotite fabric orientations (a) Coarse-grained lherzolites (n=150); (b) Mylonitic peridotites (n=75): data presented as contoured stereographic plots.

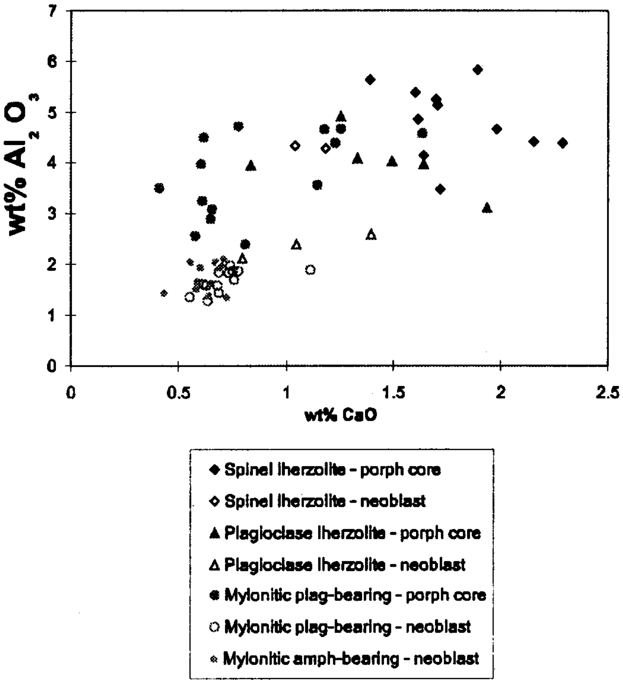


Figure 3. *Plot of Al_2O_3 vs CaO for orthopyroxenes from spinel lherzolite, plagioclase lherzolite, mylonitic plagioclase-bearing peridotite, and mylonitic amphibole-bearing peridotite. Major element analysis of orthopyroxenes were performed at the British Geological Survey, Keyworth, by Wavelength-dispersive spectrometry using a Cameca SX50 electron microprobe and at the Research School of Earth Sciences, the Australian National University, Canberra, by energy-dispersive spectrometry using a fully automated Cameca Camebax electron microprobe using the methods of Ware (1991).*

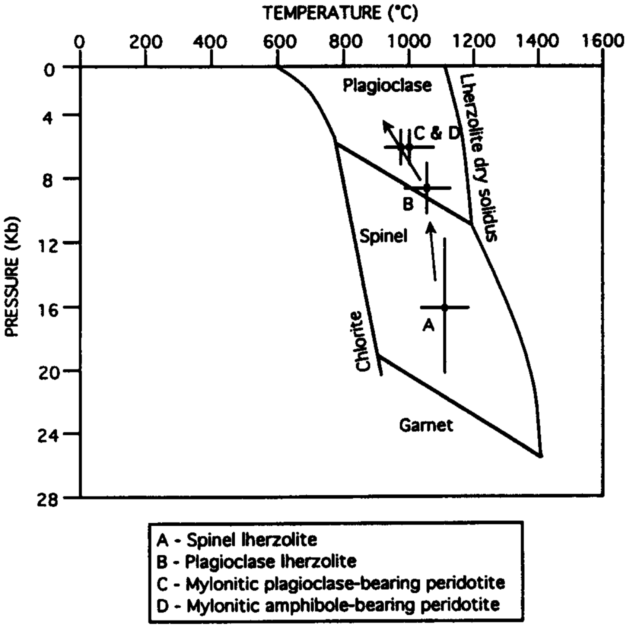


Figure 4. *The inferred P-T path for the Lizard peridotites, based upon data obtained from the thermometer of Wells (1977) and Witt-Eikschen and Seck (1991), and data presented in Rothstein (1988) and Davies (1984).*

smaller number of analyses of mineral separates presented by Green (1964).

Cores of porphyroclasts in the coarse-grained spinel lherzolites have slightly higher Al_2O_3 and CaO than the rims, which have compositions approaching those of the adjacent neoblasts. This suggests that during deformation the rims are reacting and approaching equilibrium with the fine-grained neoblasts (Hoogerduijn Strating *et al.,* 1993). A significant feature of this data is that the composition of orthopyroxene porphyroclasts in the mylonitic plagioclase-bearing peridotites is similar to porphyroclasts in the coarse-grained lherzolites. This suggests that the orthopyroxene porphyroclasts in the mylonitic peridotites are relicts from a coarse-grained lherzolite protolith.

These compositional changes are interpreted as reflecting changing conditions of temperature and pressure, synchronous with dynamic recrystallisation of the peridotites.

An inferred P-T trajectory for the evolution of the peridotites is presented in Fig.4, and the results confirm that the tectonic evolution of the peridotites is accompanied by a decrease in P and T. This P-T trajectory is based on estimates of pyroxene equilibration temperatures and the results are consistent with those of Rothstein (1988) and Davies (1984).

WHOLE ROCK GEOCHEMISTRY

Major and trace elements

Volatile free compositions of the different peridotite types are shown in Figure 5. These two graphs show that the mylonitic peridotites have compositions which are different from the spinel and plagioclase lherzolites as there is virtually no overlap for the composition fields for these and many other elements. In particular, the mylonitic peridotites have lower MgO, and higher TiO_2 and Al_2O_3 than the coarse-grained lherzolites.

Rare Earth Elements

The chondrite normalised compositions for the Lizard peridotites analysed in this study (Figure 6) are comparable with the analyses from the Lizard published by Frey (1969), although there are subtle differences which may be due to different analytical techniques used.

The spinel lherzolites and plagioclase lherzolites have identical REE compositions, characterised by extreme depletion of LREE relative to chondrite (LREE close to detection limits) and they possess (Ce/Yb) normalised ratios of (average = 0.03). The REE compositions of the mylonitic plagioclase bearing-peridotite and mylonitic amphibole-bearing peridotites are identical, but contrast markedly with the spinel and plagioclase lherzolites. The mylonitic peridotites show similar HREE to the spinel and plagioclase lherzolites, but they are much less depleted in LREE, approaching chondritic values, and possess (Ce/Yb) normalised ratios of (average 0.35) for the mylonitic plagioclase bearing peridotite and (average 0.44) for mylonitic amphibole-bearing peridotites.

INTERPRETATION OF GEOCHEMICAL DATA

The geochemical compositions of the Lizard peridotites shown in Figures 5 and 6 reveal that peridotites vary in composition, between the coarse-grained lherzolites and the mylonitic peridotites. If the mylonitic peridotites were simply the products of deformation and re-equilibration of a coarse-grained Ilierzolite protolith, as suggested by field, microstructural and mineral compositions above, they would be expected to show a similar whole rock composition. The observed changes in geochemistry suggest, however, that during deformation, the mylonitic peridotites were enriched in major, trace and rare earth

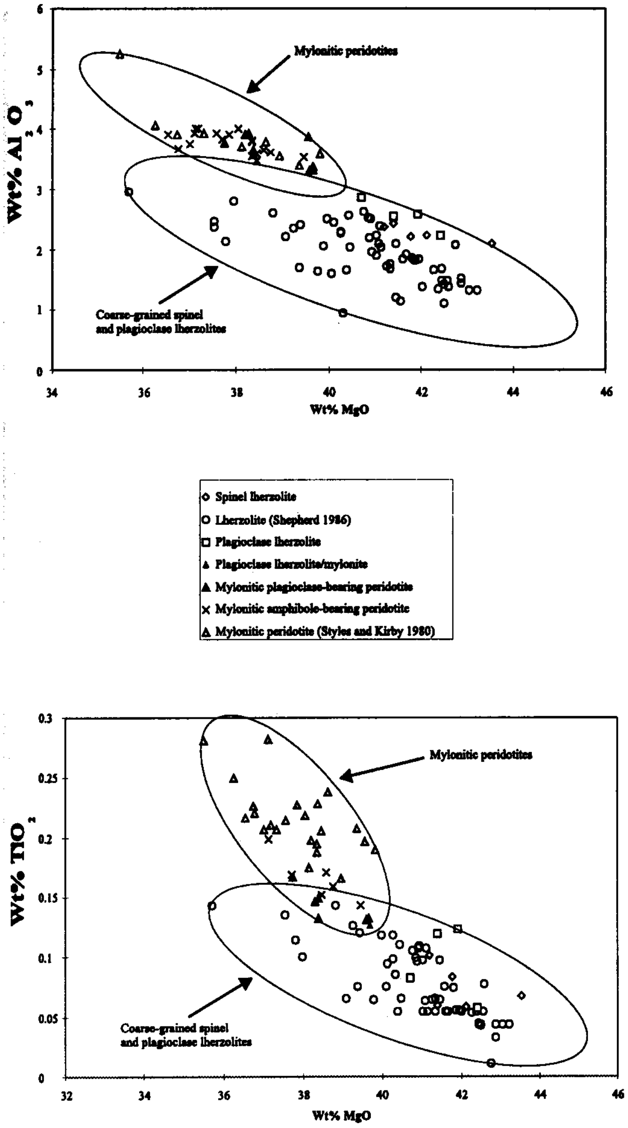


Figure 5. Plot of Al_2O_3, and TiO_2 against MgO for whole-rock samples of Lizard peridotite. Peridotite samples were analysed by XRF at the University of Durham. Includes data from Shepherd (1986), Styles and Kirby (1980) and D.H. Green (pers comm). All major element compositions are reported as volatile-free.

elements. A process that causes the geochemical enrichment of a rock is metasomatism, related to the interaction between a rock, and a melt and/or a hydrous fluid resulting in a change of the bulk composition. The increase of TiO_2 in the whole-rock composition of the mylonitic peridotites relative to the coarse-grained lherzolites suggests that the metasomatism was related to the infiltration of a melt. Eggler (1987) suggests that Ti is relatively insoluble in H_2O and CO_2 rich fluids and hence a magmatic component, rather than a fluid alone, is likely to be important. Using petrological, whole-rock REE and isotopic studies, Davies (1984) concluded that the composition of the mylonitic peridotites is related to a melt infiltration event. The presence of amphibole, a hydrous phase, in the mylonitic peridotites shows that hydrous fluids must also have been associated with the melt responsible for the metasomatism of the peridotites.

DISCUSSION

The data presented in the preceding sections suggest that mylonitic plagioclase-bearing peridotites were formed by syntectonic

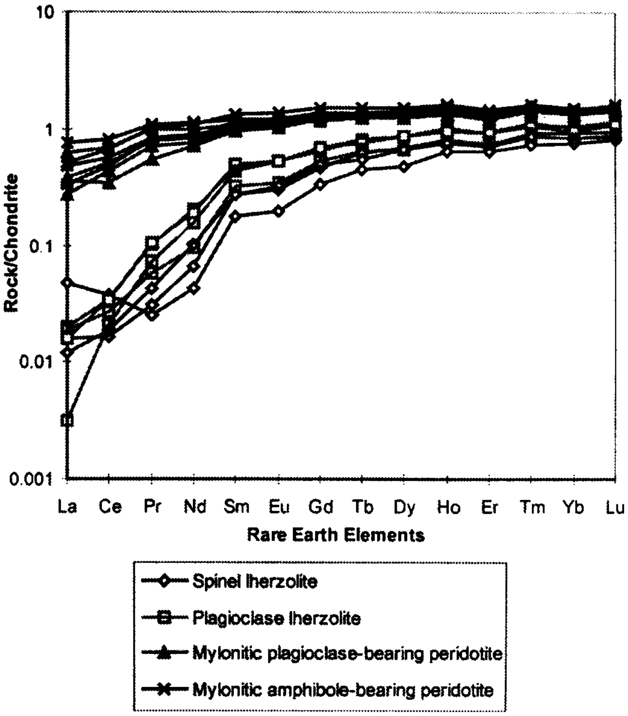
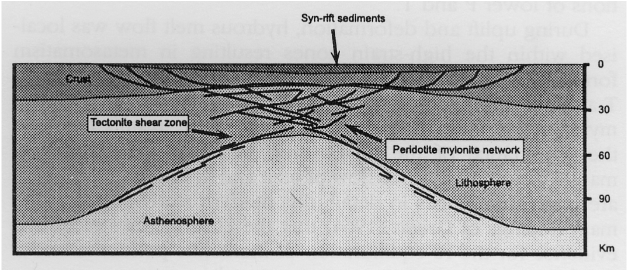
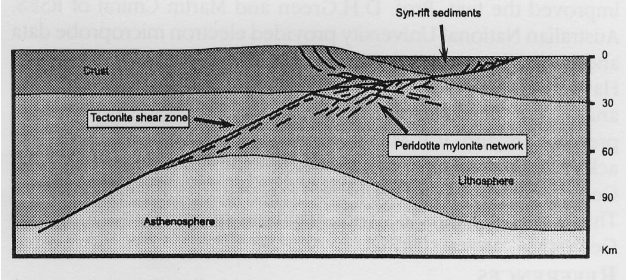


Figure 6. Chondrite-normalised REE compositions of the Lizard peridotites. Analysis by ICP-MS at the University of Durham. Normalising values of Nakamura (1974).



a) symmetric, diapirism



b) asymmetric, detachment

Figure 7. Possible interpretations of the tectonic environment responsible for the uplift and deformation of the Lizard peridotites. After Vissers et al. (1995).

metasomatism caused by the addition of a hydrous, fluid-rich melt during the recrystallisation and re-equilibration of a coarse-grained spinel/plagioclase lherzolite host during deformation in the upper mantle.

A subsequent interaction of a hydrous fluid with the mylonitic plagioclase-bearing peridotite resulted in pyroxene being replaced by pargasitic hornblende, thus producing mylonitic amphibole-bearing peridotite. This would account for both the presence of mylonitic amphibole bearing peridotite over 100's m of outcrop, and mm scale interbanded zones within mylonitic plagioclase-bearing peridotite. This is also compatible with the very similar bulk composition.

The evidence presented here suggests that the metasomatic event and later hydrous fluid interaction seem to have preferentially occurred in the high-strain zones now composed of mylonitic peridotite. Evidence from the Lizard and other examples of deformed mantle, such as Zabargad Island (Agrinier *et al.,* 1993) and the Josephine peridotite, south-west Oregon (Keleman and Dick, 1995), suggest that melt flow is preferentially focused along actively deforming ductile shear zones. What is not clear, however, is whether the recrystallised nature of the shear zones facilitates melt infiltration, or whether the shear zone is the result of deformation enhanced by fluid flow (Keleman and Dick, 1995).

In terms of a tectonic environment these processes could occur either in the deforming margins of a peridotite diapir as proposed by Green (1964), or during footwall uplift along an extensional detachment within the mantle (Figure 7). The present-day geographic distribution of the peridotite mylonites in the Lizard complex may be consistent with either model, however, the effects of later faulting and thrusting hamper interpretation of the original geometry of these shear-zones.

CONCLUSIONS

The Lizard peridotites show a metamorphic evolution from a high-temperature and high-pressure spinel lherzolite protolith, via plagioclase lherzolite to mylonitic plagioclase-bearing peridotite during deformation related to the uplift of the mantle to conditions of lower P and T.

During uplift and deformation, hydrous melt flow was localised within the high-strain zones resulting in metasomatism forming mylonitic plagioclase-bearing peridotites. At a lower P/ T an interaction with hydrous fluid resulted in the formation of mylonitic amphibole-bearing peridotite. These results highlight the importance of the relationship between deformation in mantle rocks and focused flow of melt and fluids. Although there are many differences in detail, this modern study supports the main findings of Green (1964) that the Lizard shows extensive evidence for the re-equilibration of lherzolitic peridotite under conditions of decreasing temperature and pressure.

ACKNOWLEDGEMENTS

The authors thank Dr Julian Pearce and Prof. D.H. Green for discussions on aspects of the Lizard peridotites which have improved the text. Prof. D.H. Green and Martin Cmiral of RSES, Australian National University provided electron microprobe data and Nick Ware assisted with microprobe analysis at ANU. Ron Hardy is thanked for help with .sample preparation and XRF analyses at Durham, and Chris Ottley, for help with sample preparation and ICP-MS analyses at Durham. CAC gratefully acknowledges receipt of a PhD studentship grant from the British Geological Survey and a Durham Postgraduate Research Award. This paper is published with approval of the Director, British Geological Survey (NERC).

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