Localization of deformation and melt flow in the shallow oceanic mantle: constraints from combined microstructural and geochemical studies of mantle peridotites in the Josephine ophiolite (S. Oregon)

C. J. Garrido
P. Kelemen
G. Hirth
H. J. B. Dick

Woods Hole Oceanographic Institution, Geology & Geophysics, Woods Hole, MA 02543, USA

Several studies have demonstrated that the extraction of Mid-Ocean Ridge Basalts (MORB) needs focused melt flow in high permeability conduits. Different mechanisms for focused extraction of MORB have been proposed: (a) hydrofractures from the bottom of the melting region to the ridge axis; and (b) high-permeability channels by dissolution of solid phases during focused porous flow of adiabatically ascending mantle. Kelemen *et al.* (1995)[1] have proposed that dunites in the mantle section of ophiolite may represent high permeability porous flow channels for melt segregation and extraction of MORB from the upwelling mantle.

In the mantle section of the Josephine ophiolite (S. Oregon) occur different structural types of dunites that provide a good opportunity to investigate the role of dunites on the localization of melt flow in the shallow mantle. Three structural types of dunites can be identified [2]: (a) sub-horizontal dunites parallel to the foliation of the enclosed harzburgites; (b) narrow tabular dunites cross-cutting the subhorizontal foliation; and (c) dunites associated with broad shear zones.

Constraints on the magmatic melt/rock ratio

The melt/rock reaction origin of dunites in the Josephine ophiolite is supported by several geochemical observations. For example, comparing Ti-content in olivine versus Cr# content in spinel, harzburgites follow a trend consistent with different degrees of melting. Most dunites, however, diverge from this trend by having higher Ti-content in olivine for a given Cr# content in spinel. This divergence is in agreement with a melt/rock reaction origin of dunites.

To constrain the melt/rock ratio of dunites during the magmatic event, we use the Ti content in olivine (an incompatible element in olivine), since in dunites it is sensitive to variations in melt/rock ratio. Assuming that the Ti content in olivine is proportional to changes in melt composition and to instantaneous melt/rock ratio, high Ti contents in olivine would be indicative of high permeabilites during the magmatic event. In our study the Ti content in olivine is considered as a proxy for melt/rock ratio and permeability, and it is used to assess the relative permeabilities of dunites during the magmatic event. We are aware, however, that other magmatic processes, such as different amounts of trapped melt, might also increase the Ti content in olivine. The different structural types of dunites display contrasted Ti variation (Fig. 1) (by about a factor of four), with the highest Ti content in the dunites within the shear zone. This observation suggest that shear zone dunites were more permeable than nearby dunites, and thereby, melt was localized trough these high strain regions.

Correlation between microstructure and composition of dunites

The different structural types of dunites display contrasted microstructures; horizontal and tabular

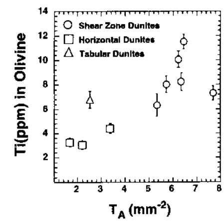

FIG. 1. Ti content in olivine (measured by ion probe) versus the number of triple junction per area in dunites (T_A).

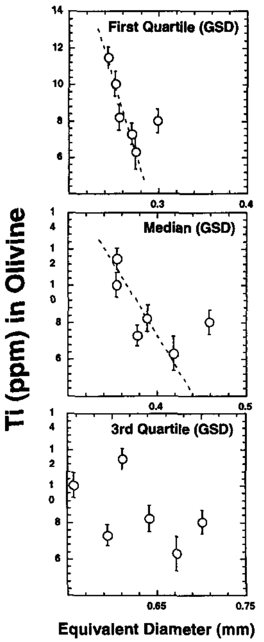

FIG. 2. Equivalent diameter of olivine versus Ti content in olivine (only sheared dunites).

dunites have relatively coarse grained microstructures, while sheared dunites have smaller and variable grain sizes, with some samples showing S-C fabric and strong lattice preferred orientations.

In order to quantify the microstructure of dunite, we have developed an image processing procedure for tracing grain boundaries in digital images of peridotites. These images are used to compute quantitative mean microstructural parameters (L3) and the rock grain size distribution.

There are significant correlations between the Ti-content in olivine in dunites and microstructural parameters. Except for the tabular dunites, the Ti content in olivine is negatively correlated with the mean intercept length of olivine (L3). Similarly, there is a positive correlation between the number of olivine-olivine-olivine triple junctions per area (TA) and the Ti-content of olivine in dunites (Fig.1). These correlations, which are especially well-defined if one considers only sheared dunites, indicate a negative dependence between the Ti-content in olivine and the olivine grain size. In terms of geochemically inferred permeabilities, we interpret these correlations as the result of an increase in permeability of dunite related to the reduction of the mean grain size of olivine during the magmatic event.

All the dunites have a log-normal grain size distribution (GSD). If one considers only the smaller grain sizes of the GSD (first quartile; Fig. 2) the negative correlation between olivine grain size and olivine Ti-content is still present. This negative dependence remains in the higher class of the GSD (Median; Fig. 2). However, this correlation disappear when the highest class of the distribution are considered (third quartile; Fig. 2). Therefore the negative correlation between grain size and Ti-content in olivine is controlled by the smaller grains in a given dunite. In addition, the perseverance of the negative correlation up to at least the median of the distribution indicates that this negative correlation is of magmatic in origin and has not been substantially modified by lithospheric recrystallization after the magmatic event.

Discussion and conclusion

In the Josephine ophiolite, the different structural types of dunites display different Ti-content in olivine, with the highest contents in dunites associated with shear zones. This observation suggests that shear zone dunites were more permeable than other dunites. Quantitative microstructural study of dunites reveals a negative correlation between grain size and the Ti-content in olivine (Fig. 2). This negative correlation suggests that permeability differences among dunites were related to changes in grain size. This observation seems to be in disagreement with formulations for permeability in partially molten peridotites that predict a positive correlation between permeability and grain size. Two possible explanations might account for this correlation. The higher permeability in the fine-grained dunites can arise by increasing the porosity of the shear zones due to gradients in melt pressure induced by deformation[3]. Therefore, deformation will simultaneously increase the permeability and decrease the grain size of dunite. However, the fact that the observed negative grain size dependence of the melt/rock ratio is also present in dunites away from the shear zone, suggests that the decrease in permeability was microstructurally controlled. An alternative explanation would be that, in partially molten mantle rocks, the pore size is weakly dependent on grain size. In this scenario, a grain size reduction would increase the permeability of molten peridotites due to an increase in the total number of triple junctions per unit volume (Fig. 1). In both cases, strain localization, coupled with the dissolution of pyroxenes, would create highly permeable dunite channels in deforming partially molten mantle. These dunite channels in the shallow mantle might provide a locus for melt flow and strain localization.