

# Clinopyroxene microtextures reveal incompletely extracted melts in abyssal peridotites

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## ABSTRACT

**Textural evidence is interpreted to suggest that in regions where upwelling rates of the mantle are slow to very slow, a small amount (~2%) of melt was present when plagioclase-free abyssal peridotites entered the conductive regime at the base of the oceanic lithosphere. Upon crystallization, this melt appears to have been undersaturated in orthopyroxene, but precipitated clinopyroxene, Al-rich and Ti-poor spinel, and sulfides. Furthermore, the primary clinopyroxene grains have rare earth element patterns typical of residues of fractional melting, suggesting that the interstitial liquids were incremental partial melts rather than having mid-oceanic-ridge basalt compositions.**

**Keywords:** texture, oceanic ridge, peridotite, melt extraction.

## INTRODUCTION

Theoretical models, geophysical observations, and trace element geochemistry of clinopyroxenes from abyssal peridotites have been used to infer that melt extraction from the upwelling mantle beneath mid-ocean ridges is extremely efficient, and leaves almost no trapped melt in the residues (Ahern and Turcotte, 1979; McKenzie and Bickle, 1988; Johnson et al., 1990). Chemical interaction between migrating melts and the lithospheric mantle can easily be identified by the presence of veined peridotites and by Ti enrichment of spinels (Dick, 1989). However, compositional heterogeneities that might have been caused by melt transport through the partially molten mantle (asthenosphere) and the deep lithosphere are more difficult to identify. Early structures generated by deep-seated interactions between melt and rock are unlikely to be preserved during slow cooling and lower temperature solid-state deformation. Any partial melts that have been trapped in the residual solid at the end of partial melting should equilibrate with the mantle minerals upon crystallization. However, certain observations suggest that small amounts of melt have reacted with, or been trapped within, the res-

idues. For example, (1) whole-rock Na concentration in plagioclase-free abyssal peridotites is considerably higher than that expected for residues of near-fractional melting (Elthon, 1992; Niu, 1997; Baker and Beckett, 1999); (2) where analyses are available, platinum-group element patterns are positively trending and sulfide modal abundances are unusually high, inconsistent with a purely residual origin (Rehkämper et al., 1999; Luguët and Lorand, 1999); and (3) late interstitial clinopyroxene and pyroxenite veins have been described in some abyssal peridotites (Cannat et al., 1990; Ceuleneer and Cannat, 1997; Kempton and Stephens, 1997). In this paper we present the results of a systematic investigation of disseminated clinopyroxene textures in a suite of 135 abyssal peridotites representative of ridges having slow and very slow spreading rates. Our results suggest that (partial) melt was present during the high-temperature, plastic deformation of the peridotite and that this liquid crystallized in situ to form at least 2 vol% of magmatic clinopyroxene and Ti-poor spinel.

## SAMPLE SELECTION

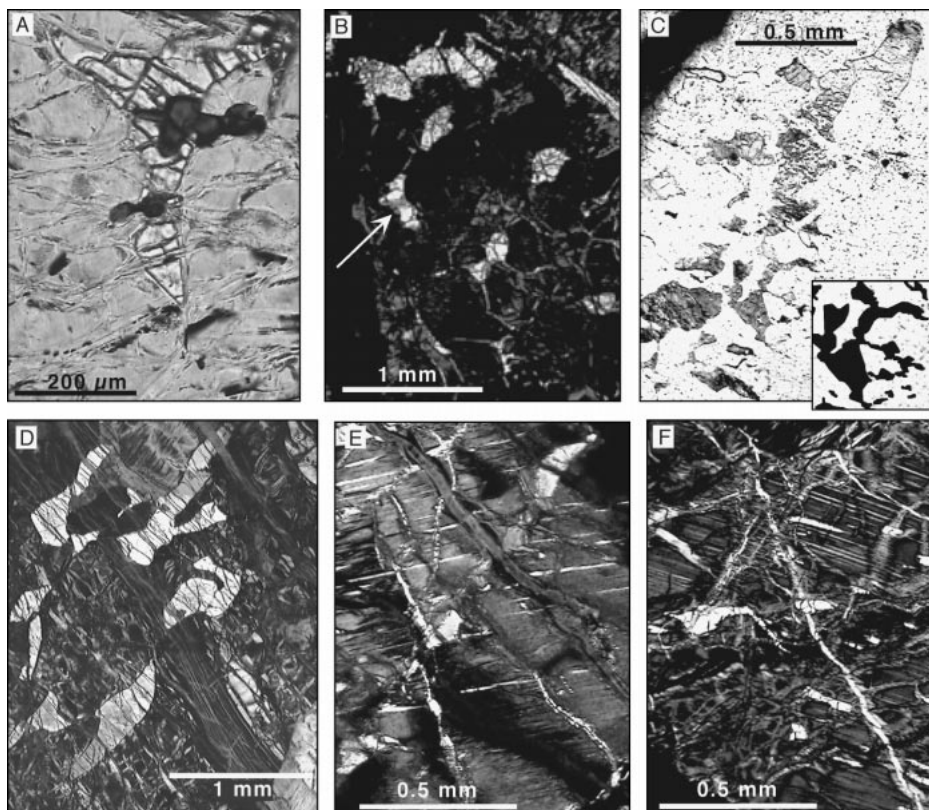
We considered 270 ultramafic rocks recovered from the Southwest Indian Ridge (Mével et al., 1998) and from several sites in the North Atlantic Ocean. The Atlantic samples come from different sites along the south wall of the Kane transform valley (Auzende et al.,

1994), Ocean Drilling Program Sites 670 (Bryan et al., 1990) and 920 (Karson et al., 1997), the 15°N region (Cannat et al., 1992), and the central Atlantic (Bonatti et al., 1992). We chose decimeter- to meter-sized samples that had no evidence of pyroxenite, gabbro, or dunite veins. Strongly foliated and mylonitic rocks were also discarded. In order to avoid rocks affected by metasomatism (Dick, 1989), only plagioclase-free lherzolites and harzburgites characterized by spinels with  $\text{TiO}_2 < 0.2$  wt% and low to moderate  $\text{Cr}/(\text{Cr} + \text{Al})$  ratios (from 0.1 to 0.5) were selected. Textures are protogranular to slightly porphyroclastic with a small amount of recrystallized grains. The remaining selection represents about half of the initial number of samples considered for each site.

## TEXTURES

Although all samples are 70%–80% serpentinized at present, the primary, coarse-grained assemblage was made of millimeter- to centimeter-sized olivine and orthopyroxene and clinopyroxene crystals showing plastic deformation indicated by lattice bending, the presence of subgrains, and recrystallization into fine-grained textures ( $\leq 0.1$  mm) with straight grain boundaries. Primary spinels are 0.5–3 mm long and have elongated or vermicular shapes. In addition to the large grains involved in the granular assemblage, almost all the 135

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**Figure 1.** A: Interstitial clinopyroxene and spinel at junction of three large (now serpentinized) olivine crystals. Note low dihedral angles of clinopyroxene. Southwest Indian Ridge. B: Disseminated intergranular clinopyroxene crystals at boundaries of (now serpentinized) olivine neoblasts. Several crystals are in optical continuity, and one grain shows magmatic twins (arrow). Kane Fracture Zone, Atlantic Ocean. C: Olivine-clinopyroxene schlieren showing clinopyroxene patches in optical continuity within mosaic of corroded (now serpentinized) olivine grains. Inset: Image analysis showing enlarged area of schlieren. Southwest Indian Ridge. D: Clinopyroxene-filled en echelon veinlets within serpentinized peridotite. Note optical continuity of clinopyroxenes. Southwest Indian Ridge. E: Clinopyroxene veinlet filling brittle microfracture in orthopyroxene, discordant to clinopyroxene exsolution lamellae. Kane Fracture Zone, Atlantic Ocean. F: Clinopyroxene veinlet merging with clinopyroxene blebs that crystallized on clinopyroxene exsolution lamellae within orthopyroxene. Diagonal white line is serpentine. Kane Fracture Zone, Atlantic Ocean.

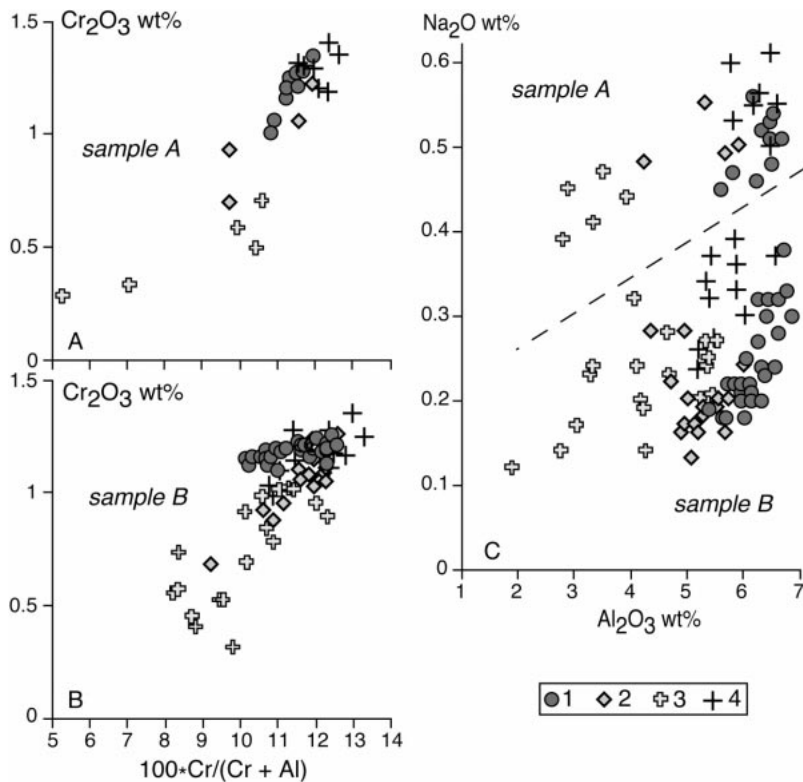
samples selected for this study also contain smaller grains of clinopyroxene, which constitute the object of this study. In thin section, several distinct textural environments may be distinguished. (1) Discrete, interstitial clinopyroxene grains are associated with tiny grains of spinel at the triple junctions of serpentinized olivine grains (Fig. 1A). (2) Disseminated clinopyroxenes in optical continuity, with curvilinear boundaries, occur at the multiple junctions of recrystallized, polygonal, serpentinized olivine grains (Fig. 1B). These clinopyroxenes are commonly associated with tiny grains of spinel and sulfides, and some display vein-like projections that infiltrate olivine and orthopyroxene grain boundaries. (3) Intergranular clinopyroxene patches in optical continuity define schlieren to several millimeters long (Fig. 1C). Aggregates of corroded olivine neoblasts, mantled by spinel  $\pm$  sulfides and containing intergranular clinopyroxenes, are concentrated around the large or-

thopyroxene and clinopyroxene grains. Toward the olivine matrix, these aggregates often grade into veinlets. (4) En echelon microfractures filled with clinopyroxene crosscut the serpentinized olivine matrix in discontinuous parallel veinlets extending over several millimeters (Fig. 1D), often linked by spinel veinlets. A network of linear microfractures, 1–5  $\mu\text{m}$  wide, filled by clinopyroxene and spinel, also transects olivines and orthopyroxenes (Fig. 1E). (5) Small prisms or spindle-shaped grains of clinopyroxene have apparently grown on, or replaced, the thin and regular clinopyroxene exsolution lamellae within orthopyroxene. Detailed observation shows that these blebs are often discordant to the thin exsolution lamellae and that they are located at the intersections of, or merge with, the tips of clinopyroxene veinlets that crosscut the orthopyroxene host (Fig. 1F). In the vicinity of these microfractures, orthopyroxene is commonly replaced by clinopyroxene lamellae

oriented along the crystallographic directions of the mineral host. Resorbed orthopyroxene grain boundaries, with embayments filled by a fine-grained aggregate of secondary olivine (Plate 1.7 of Ceuleneer and Cannat, 1997), typically rimmed by clinopyroxene, are also a common feature. Modal proportions of the intergranular and vein clinopyroxenes, estimated by point counting a selection of 20 thin sections, are in the range 0%–3%; the average is  $\sim$ 2%.

#### GEOCHEMICAL DATA

In order to further our understanding of these different textural environments, we have also determined the compositions of several clinopyroxene types. Electron-microprobe analyses show that the different clinopyroxenes in each sample show well-defined compositional trends characterized by simultaneous decreases of the Al, Cr, and Na contents, with generally scattered Ti contents. The clinopyroxene blebs within orthopyroxene define the most Al- and Cr-rich end member, whereas intergranular and vein clinopyroxenes are poorer in Al and Cr, and have lower Cr/(Cr + Al) ratios (Cr#). In some samples the compositions of the two end members overlap in the middle part of the trend with core and rim compositions of the coarse clinopyroxenes involved in the primary granular textures (Fig. 2A). In other samples the large clinopyroxenes plot off this trend, their cores being richer in Al and Cr (Fig. 2B). Large clinopyroxene cores are poorer in Na, relative to the blebs within orthopyroxene and to the interstitial and vein-related grains, for similar Cr# (Fig. 2C). Rim compositions either plot on the main compositional trend, or define, with the cores, another trend as shown in Figure 2. In individual thin sections, primary and late spinels have the same compositions (i.e., with  $\text{TiO}_2$  content  $<0.2$  wt%), and their Cr# correlates with that of the average clinopyroxene. It is also of note that the compositions of the late clinopyroxenes are too rich in Na and Ti to be simple remobilization of orthopyroxene exsolutions. This fact is particularly evident when the peridotites are, like those in the Atlantic 15°N region, strongly refractory harzburgites (Cannat and Casey, 1995); although devoid of coarse clinopyroxene grains, these rocks show intergranular and vein clinopyroxenes with as much as 0.5 wt%  $\text{Na}_2\text{O}$ . Trace element data for a few Atlantic peridotites have also been collected. Figure 3 shows that the large clinopyroxenes have rare earth element patterns similar to those calculated for near-fractional melting residues (Johnson et al., 1990), suggesting that they have not re-equilibrated with mid-oceanic-ridge basalt (MORB) compositions.

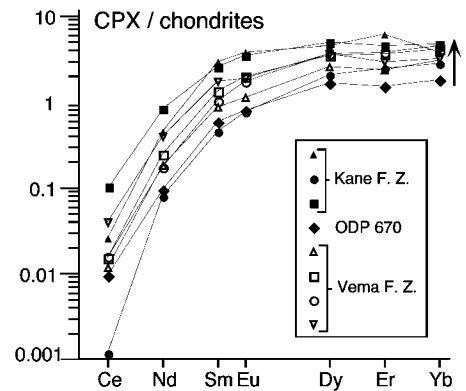


**Figure 2. Compositional variations of clinopyroxenes in two abyssal peridotite samples. Sample A: dredge 25/2, Southwest Indian Ridge. Sample B: site KN15, Kane Fracture Zone, Atlantic Ocean. Symbols: 1—coarse-grained cores, 2—coarse grained rims, 3—interstitial and vein-forming grains, 4—grains within orthopyroxene.**

## DISCUSSION AND CONCLUSIONS

The similarity of the clinopyroxene textures described here to melt geometries produced experimentally during deformation of mantle rocks (Bussod and Christie, 1991; Kohlstedt and Zimmerman, 1997; Daines and Kohlstedt, 1997) leads us to the conclusion that these clinopyroxenes have crystallized from interstitial melt. Clinopyroxene grains such as those shown in Figure 1A have a shape consistent with dihedral angles of melt in olivine aggregates (Waff and Bulau, 1979, 1982; and review in Laporte and Provost, 2000), although in most cases this feature would appear to have been modified by crystal growth. Furthermore, textures 1 to 3 are almost identical to the equilibrium melt distribution in deformed, partially molten rocks (e.g., Fig. 3 of Kohlstedt, 1992; Fig. 6 of Hirth and Kohlstedt, 1995; and Fig. 13 of Watson, 1999). The geometry of these disseminated clinopyroxenes also resembles that of "impregnation" clinopyroxenes described in ophiolitic dunites, where such clinopyroxenes are interpreted to have crystallized from a liquid (Nicolas and Prinzhofer, 1983; Kelemen et al., 1995). We interpret schlieren textures (Fig. 1C) to have been more extensive zones of melt accumulation that corroded the recrystallizing olivine matrix, whereas the veinlets of texture 4 are

interpreted as former melt-filled microfractures associated with shear deformation. Schlieren and veinlets are generally oriented in the high-temperature foliation of the peridotite (Cannat et al., 1990; Ceuleneer and Cannat, 1997), a feature that indicates the presence of melt during plastic deformation of the rocks. Other veinlets and linear microfractures, also filled with clinopyroxene and spinel, show random orientations. Such microfractures resemble melt-filled microfractures that form at the end of the crystallization of plutonic rocks when the rheology is principally controlled by the interconnected framework of crystals rather than by interconnected, residual melt (e.g., Bouchez et al., 1992; Büttner, 1999). These textures are not present everywhere in individual thin sections, suggesting that the former melt was inhomogeneously distributed and that a number of deformation mechanisms operated simultaneously during the final stages of crystallization of the studied abyssal peridotites. Furthermore, on the scale of a single thin section, some parts of the rock appear to have been devoid of melt, because they show the classic fabric of plastic deformation dominated by a dislocation-creep mechanism that characterizes sublithospheric deformation (Nicolas and Poirier, 1976; Mercier, 1985). This hypothesis is supported by



**Figure 3. Representative rare earth element patterns of studied abyssal peridotites. Arrow indicates modal clinopyroxene (CPX) increasing from 3% to 6.5%. Kane Fracture Zone (F.Z.): inductively coupled plasma emission mass spectrometry analyses on hand-picked minerals. Vema Fracture Zone and Ocean Drilling Program (ODP) Site 670: ion microprobe analyses of large clinopyroxene cores.**

the fact that the combination of plastic deformation, cataclastic granulation, and microfracturing has been reproduced by the experimental deformation of coarse-grained rocks with inhomogeneous melt distribution (Dell'Angelo and Tullis, 1988). Association of textures 3 and 4, in particular, can be understood in the light of experiments that show that greater abundance of melt in some regions of the rock during syntectonic recrystallization results in pervasive fragmentation and corrosion of the primary grains while melt is driven out to accumulate in extension cracks (Rutter and Neumann, 1995). These textures therefore point to synchronous crystallization and deformation. Furthermore, that precipitation of clinopyroxene from the interstitial liquids is associated with that of Al-rich spinel rather than plagioclase indicates that this process occurred at relatively high pressure (>0.9 GPa). These observations and the preservation of different clinopyroxene microtextures associated with different compositions at thin-section scale are therefore interpreted to be the result of crystallization induced by a temperature decrease as the upwelling mantle entered the conductive thermal regime at the base of the lithosphere.

In addition to describing the presence of crystallized melt in these rocks, it is also important to determine the chemical nature of this melt. The lack of Ti enrichment in spinel and lack of light rare earth element re-enrichment in the primary clinopyroxene grains suggest that the composition of this liquid was not simply that of MORB. Furthermore, the cusp-shaped orthopyroxene boundaries and replacement of this mineral phase by clinopyroxene and spinel  $\pm$  olivine (texture 5) sug-

gest that the liquid present was undersaturated in orthopyroxene but saturated in clinopyroxene and spinel. In the light of experimental studies that show that at pressures above ~1.7 GPa, the melting reaction for spinel and garnet lherzolite produces liquids saturated in clinopyroxene and spinel ( $\pm$ olivine) but not in orthopyroxene (Walter et al., 1995; Kinzler, 1997), we conclude that the interstitial liquid present in these rocks was most likely an incremental partial melt produced within the upper pressure range of the spinel stability field or above. Identification and further characterization of these interstitial liquids are essential for understanding the dynamics of the suboceanic mantle and for interpreting the geophysical and geochemical characteristics of abyssal peridotites.

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