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Lattice-preferred orientation and microstructure of peridotites from ODP Hole 1274A (15°39′N), Mid-Atlantic Ridge: Testing models of mantle upwelling and tectonic exhumation

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ABSTRACT

Eleven harzburgites and one dunite from Ocean Drilling Program Leg 209 Hole 1274A preserve high-temperature mantle textures. Electron backscatter diffraction (EBSD) analysis shows moderately developed crystal lattice preferred orientations (LPOs) in olivine and orthopyroxene (M-indices ≈ 0.1) indicative of crystal-plastic deformation at ~1250 °C. These rocks preserve a protogranular texture with a weak olivine foliation, a very weak or absent orthopyroxene foliation that may be decoupled from the orthopyroxene LPO, and minor interstitial clinopyroxene and spinel. Olivine grain size distributions, along with melt-related microstructures in orthopyroxene, clinopyroxene and spinel suggest that high-temperature deformation textures have been overprinted by pervasive post-deformation melt-rock interaction. Paleomagnetic data constrain the olivine [100] axes to be subhorizontal and oriented at low angle ($\leq 28.6° \pm 10.6°$) to the ridge axis at the onset of serpentinization. This orientation is consistent with either complex 3-D mantle upwelling or 2-D mantle upwelling coupled with complex 3-D tectonic emplacement to the seafloor.

1. Introduction

A fundamental characteristic of mid-ocean ridges is the behaviour of the mantle as it upwells beneath the ridge axis. Two end-member models of mantle upwelling geometry have emerged. The first, a two-dimensional (2-D) model, involves a mantle which upwells passively in response to plate separation. Upwelling is uniform along the ridge axis. Subsequent to corner flow (the transition from vertical upwelling to horizontal spreading), the mantle flows perpendicularly away from the ridge axis. The alternative model is three-dimensional (3-D), involving mantle upwelling that may be actively driven by buoyancy. Along the ridge axis, upwelling is focused at ridge segment centers. Subsequent to corner flow the mantle flows away from ridge segment centers in a radial pattern before transitioning to a passive 2-D geometry at some distance from the ridge axis. 3-D upwelling has been invoked at slow-spreading ridges to explain seismic (Tolstoy et al., 1993; Tucholke et al., 1997), gravity (e.g., Kuo and Forsyth, 1988; Lin et al., 1990) and geological (Dick, 1989; Whitehead et al., 1984) observations suggestive of thicker crust and abundant basalt at ridge segment centers and thinner crust with exposed peridotite and gabbro near ridge segment ends. At fast-spreading ridges, recent seismic tomography experiments have observed low-velocity zones beneath the East Pacific Rise (Toomey et al., 2007) and the Gulf of California (Wang et al., 2009) thought to be regions of 3-D upwelling and melting, and the mantle section of the Oman Ophiolite preserves structures indicative of mantle diapirs or 3-D flow (Ceuleneer et al., 1988; Jousselin et al., 1998; Nicolas and Rabinowicz, 1984; Nicolas and Violette, 1982). Some seismic anisotropy observations have implied that mantle flow directions may be skewed from ridge-perpendicular, by ~9° at the East Pacific Rise (Toomey et al., 2007) and by ~38° at the Mid-Atlantic Ridge (Dunn et al., 2005). The cause of this apparent skew is not certain, though it may due to ridge migration relative to the hotspot frame (Dunn et al., 2005) or changing patterns of global mantle flow (Toomey et al., 2007). Both of these hypotheses essentially invoke a 2-D mantle pattern that has been rotated with respect to the surface tectonics, although both Dunn et al. (2005) and Toomey et al. (2007) report segment-center enhanced melt delivery, and thus do not preclude the possibility of a superimposed 3-D pattern with ridge-parallel flow below the resolution of the anisotropy observations.

The applicability of the 3-D upwelling model to slow-spreading mid-ocean ridges has yet to be shown conclusively. Ceuleneer and Cannat (1997) found azimuthally heterogeneous olivine [100] axes oriented at an oblique angle to the ridge axis in peridotites drilled at Ocean Drilling

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Program (ODP) Site 920 in the MARK area. This study was limited by the technical difficulty of measuring olivine and orthopyroxene crystal orientations prior to the advent of the electron backscatter diffraction (EBSD) technique and by structural reorientations that later paleomagnetic work (Lawrence et al., 2002) suggested may not have accounted for *in situ* deflections of the paleomagnetic vector from true north.

ODP Leg 209 (Kelemen et al., 2004) identified the Fifteen-Twenty Fracture Zone (FTFZ) area of the Mid-Atlantic Ridge (MAR) as an ideal location for testing models of mantle upwelling. The MAR from 14°–16°N to the north and south of the FTFZ has extensive outcrops of peridotites and gabbros on both sides of the axial valley (Kelemen et al., 2004 and references therein). Two "bull's-eye" gravity lows centered at ~14°20′N and 16°00′N may be magmatic centers of ridge segments, zones at which melt delivery and/or mantle upwelling may be focused in three dimensions (Escartin and Cannat, 1999; Fujiwara et al., 2003). The full spreading rate of the ridge is ~25 mm/year, and the FTFZ offsets the ridge by ~200 km (Fujiwara et al., 2003).

ODP Leg 209 drilled 8 sites to the north and south of the FTFZ. Hole 1274A (Fig. 1) was the only hole that recovered peridotites with a sufficient quantity of unserpentinized olivine to assess mantle deformation. Located at 15°39′ ~31 km north of the fracture zone, Hole 1274A was drilled in the western flank of the rift valley wall, and is ~6 km north of a non-transform discontinuity (Fujiwara et al., 2003). Hole 1274A penetrated to a total depth of 155.8 m below seafloor (mbsf) with ~22% total recovery (Kelemen et al., 2004). Of the total rock recovered from Hole12274A, ~77% was harzburgite, ~20% dunite, and ~3% gabbro (Fig. 1). Additionally, from ~95–145 mbsf the recovered cores contained some intervals of serpentine mud and breccia that were interpreted to be fault gouge; rock recovered from this portion of the core is highly to completely altered. On the thin-section scale some peridotite samples contain over 50% of the unaltered, original mantle mineralogy with some unaltered patches up to a few mm in diameter, making these among the freshest oriented peridotites ever recovered from *in situ* ocean crust. Shipboard analysis revealed that the peridotites of Hole 1274A are highly depleted harzburgites that preserve weakly deformed (protogranular) mantle textures (Kelemen et al., 2004).

Subsequent studies confirm the depleted nature of the peridotites; this composition is the result of considerable melting, either related to the present-day upwelling (Godard et al., 2008) or resulting from an ancient depletion event (Harvey et al., 2006; Seyler et al., 2007; Suhr et al., 2008). Textural analysis of the Hole

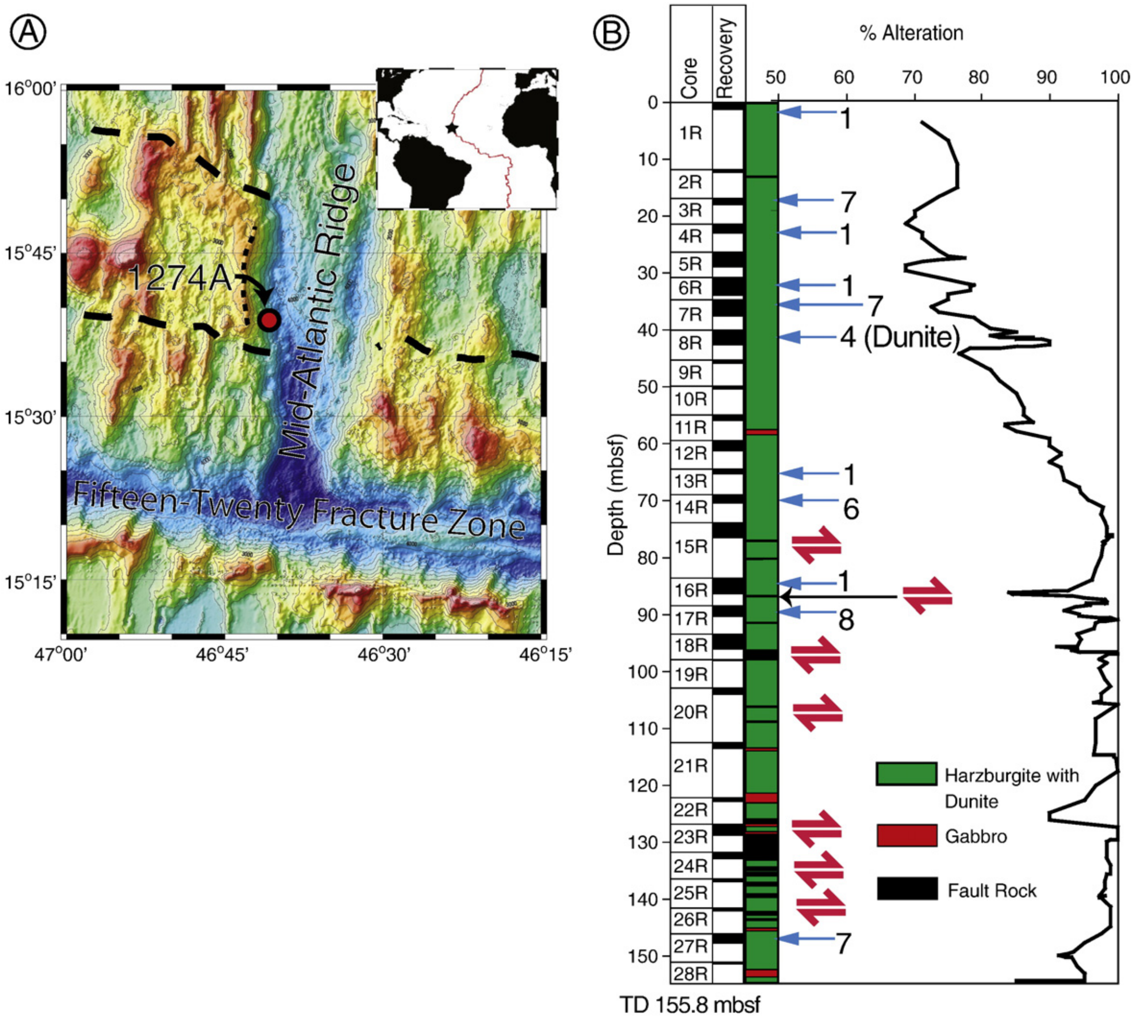

Fig. 1. A) Location of Hole 1274A, Ocean Drilling Program Leg 209. The heavy dashed lines indicate the interpreted non-transform discontinuities of Fujiwara et al. (2003). The fine dashed line indicates the fault scarp discussed in the text (Hole 1274A lies at the base of this scarp). Bathymetry is from Fujiwara et al. (2003). B) Diagram showing the lithology and recovery of ODP Hole 1274A. The column labeled "Core" indicates the core number. The column labeled "Recovery" indicates the amount of rock recovered from a given segment of core; black indicates recovered rock as a percentage of each core segment. The colored column indicates the rock type recovered from the core segment. Jagged black line indicates alteration downhole. In showing rock type and alteration in this figure, the recovered rock is scaled to the entire length of the core segment, although there is no constraint on the absolute depth of recovered rock within a given core segment (from Kelemen et al., 2004). Arrows with numbers indicate the location of samples and number of thin sections used in this study. Red arrow symbols indicate zones of interpreted faulting.