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Direct evidence for upper mantle structure in the NW Pacific Plate: Microstructural analysis of a petit-spot peridotite xenolith

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ABSTRACT

Petit-spots, the late Miocene alkali basaltic volcanoes on the Early Cretaceous NW Pacific Plate, originate at the base of the lithosphere. The petit-spot volcanic rocks enclose fragments of tholeiitic basalt, dolerite, gabbro, and mantle peridotite, providing a unique window into the entire section of subducting oceanic lithosphere. We provide here the first direct observations on the deep structure of the Pacific lithosphere using microstructural analyses of a petit-spot peridotite xenolith. The xenolith is a lherzolite that consists mainly of coarse- and medium-grained olivine, orthopyroxene, and clinopyroxene, as well as fine-grained aggregates of spinel and orthopyroxene that probably represent replaced pyrope-rich garnet. A strong deformational fabric is marked by a parallel alignment of millimeter-sized elongate minerals and their crystallographic preferred orientation. The olivine displays a [010] fiber pattern with a girdle of [100] axes and a maximum of [010] perpendicular to the foliation, a pattern which is consistent with a transpressional deformation in high temperature conditions at the base of oceanic lithosphere. Our microstructural observations and seismic data indicate that the lower part of the NW Pacific lithosphere possess an early stage structure of mantle flow at the asthenosphere. This interpretation is compatible with a conventional model in which oceanic lithosphere is thickened during cooling and plate convection. A discrepancy between the weak anisotropy in the petit-spot peridotite and the strong azimuthal anisotropy from the seismic data in the NW Pacific plate implies the existence of a highly anisotropic component in the deep oceanic lithosphere.

1. Introduction

Oceanic plates cover about 70% of the earth's surface, and exert a major control on the thermal evolution, material circulation, and dynamics of our planet (Turcotte and Schubert, 1982). Reaching an understanding of the visco-elastic and petrological structures of oceanic plates is one of the most fundamental aims of earth science (Faccenda et al., 2008; Kawakatsu et al., 2009; McKenzie, 1967; Parsons and Sclater, 1977; Stein and Stein, 1992). Tectonic structures in the lithosphere develop progressively from mid-oceanic ridges to convergent margins, eventually influencing the processes of subduction.

A conventional semi-infinite half-space model of heat conduction for the growth of an oceanic plate provides a beautiful explanation for the observed depth profiles of ocean floors and heat flow measurements (e.g., Davies, 1980; Davis and Lister, 1974; Stein and Stein, 1992; Turcotte and Schubert, 1982). Seismic observations have verified the predicted depths of the lithosphere–asthenosphere boundary (LAB), which increase with increasing age of the oceanic plate (Kawakatsu et al., 2009; Turcotte and Schubert, 1982). The results of a recent seismic analysis using a receiver function suggest the existence of a layered melt-rock structure at the top of the asthenosphere (Kawakatsu et al., 2009). These studies indicate that the upper part of an oceanic plate thickens downwards at the LAB as it moves away from a ridge, and that anisotropic structures develop in response to interactions between lithosphere and asthenosphere.

Deformational structures in oceanic lithosphere are important because they enable interpretations of the observed seismic anisotropy in terms of flow directions or plate motions (Long and Silver, 2009; Nicolas and Christensen, 1987; Park and Levin, 2002; Savage, 1999). Based on experiments and geological observations of plastically deformed peridotites, it is generally accepted that the fastest direction of seismic wave propagation represents the direction of mantle flow (Mainprice et al., 2000; Nicolas, 1989; Nicolas and

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Christensen, 1987). However, geological observations on upper mantle structures in oceanic plates have been restricted to the shallowest part of the mantle, in the spinel-lherzolite facies, corresponding to depths in the upper half of the plates, and it is not known whether the shallow structures are comparable to those in the lower half. Although hotspot xenoliths are potentially derived from deep levels of the sub-oceanic mantle, they are part of a hybrid mantle significantly modified by intra-oceanic plume-related processes, such as those underlying Hawaii (Sen et al., 2005), French Polynesia (Tommasi et al., 2004), the Canaries (Vonlanthen et al., 2006), and Kerguelen (Bascou et al., 2008).

Recently, a new window into oceanic lithosphere has been discovered on the seafloor of the NW Pacific. It is called a petit-spot, a new type of intra-plate volcanism caused by the flexing of an oceanic plate upon entering the Japanese subduction zone (Hirano et al., 2006). Petrological studies reveal that the alkali basaltic volcanoes have their roots at the base of the NW Pacific lithosphere (Hirano et al., 2006, 2008), and that essentially unaltered pieces of oceanic lithosphere were caught up in the ascending magma as mafic and ultramafic xenoliths (Abe et al., 2006; Hirano et al., 2004; Yamamoto et al., 2009).

During focused and exhaustive investigations of the NW Pacific petit-spot knolls, Abe et al. (2006) reported the discovery of a centimeter-sized peridotite fragment that had originated in the garnet-stability field. Here, we report the results of a microstructural analysis of this petit-spot xenolith; based on the results of the analysis, we go on to infer the structure and evolution of the Pacific Plate. Even though the sample is small, containing a limited number of grains, it has great importance as a natural sample of the widespread deeper parts of the Pacific lithosphere.

2. Sample locality and petrological background

The petit-spot volcanoes are located on the seaward slope of the northern Japan Trench (Fig. 1). The NW Pacific Plate is Early Cretaceous in age (150–120 Ma), making it the oldest oceanic plate in the world. However, geochronological data reveal that the petit-spot alkali basaltic volcanism occurred during the late Miocene to the present (Hirano et al., 2001, 2006, 2008). Reconstructions of recent plate motion show that the locus of volcanism was on the seaward slope of the outer rise, indicating that the young basalts were erupted along lithospheric fractures in response to plate flexure during subduction (Hirano et al., 2006). The silica-undersaturated nature and LREE-enriched geochemical signature of the alkali basalts are compatible with a small degree of partial melting of mantle beneath the LAB (Hirano et al., 2001, 2006).

Some mafic xenocrysts and xenoliths of tholeiitic basalt, dolerite, gabbro and mantle peridotite were obtained from the petit-spot volcanoes, which are typically monogenetic alkali basalt volcanoes (Abe et al., 2006). The mantle peridotite xenoliths consist of lherzolite and olivine orthopyroxenite. The major element data for the constituent minerals in the petit-spot peridotite xenoliths are presented by Abe et al. (2006) and Yamamoto et al. (2009). The Fo (forsterite) values [Mg/(Mg + Fe) × 100] of olivine are 89.8–92.7, slightly higher than those of typical mantle (e.g., Arai, 1994; Takahashi, 1986). The Cr# [Cr/(Cr + Al)] of spinel in the petit-spot peridotite xenoliths varies from 0.08 to 0.38 (Abe et al., 2006; Yamamoto et al., 2009). These values suggest that the source mantle had already been molten to some degree. Using a two-pyroxene geothermometer (Wells, 1977) and CO_2 Raman densimeter (Yamamoto and Kagi, 2006), equilibrium conditions of spinel and garnet peridotites were determined to be 800–1100 °C at a minimum pressure of 13–16 kbar, corresponding to a depth of >40–50 km below the seafloor (Abe et al., 2006; Yamamoto et al., 2009). Generation of mid-ocean ridge basalt (MORB) could be considered as a possible depletion event in sub-oceanic mantle. Noble gas isotopic data for three spinel–lherzolite xenoliths and two sets of olivine xenocrysts in three submarine volcanoes indicate that the xenoliths resemble MORB (Yamamoto et al., 2009).

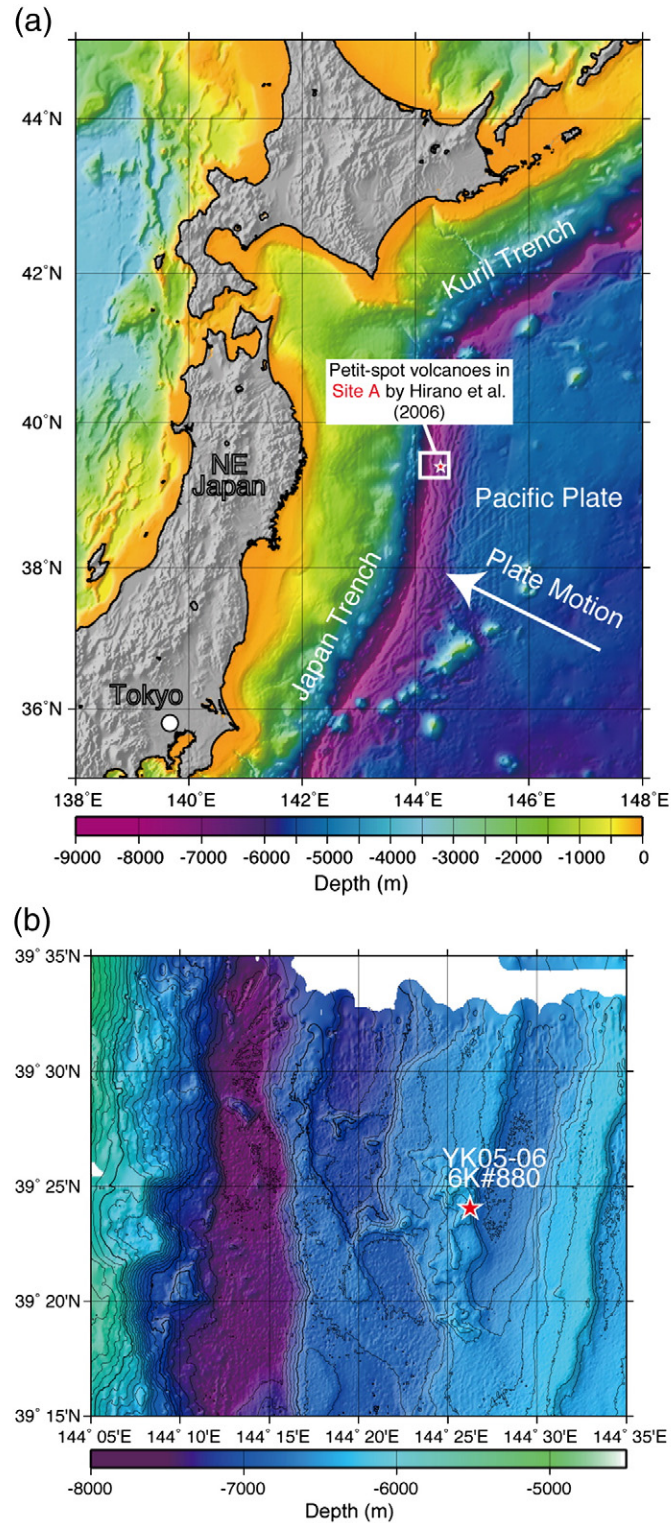

Fig. 1. (a) Bathymetric map of the NW Pacific Ocean, showing the surveyed area (white rectangle; Site A of Hirano et al., 2006) and the sampling point at dive site 6K#880 (star). The sample was dredged from the eastern fault escarpment of petit-spot volcanoes in the Japan Trench. (b) Enlargement of Site A. The red star indicates the site where sample 6K#880R2O was obtained during a dive as part of the cruise YK05-06 (R/V *Yokosuka* and the submersible *Shinkai 6500*; dive site 6K#880). Topographic data are from Amante and Eakins (2008).