Seismic anisotropy in the uppermost mantle, back-arc region of the northeast Japan arc: petrophysical analyses of Ichinomegata peridotite xenoliths

メタデータ	言語: en 出版者: American Geophysical Union 公開日: 2008-01-30 キーワード (Ja): キーワード (En): 作成者: Michibayashi, Katsuyoshi, Abe, Natsue, Okamoto, Atsushi, Satsukawa, Takako, Michikura, Kenta メールアドレス: 所属:
URL	http://hdl.handle.net/10297/509

Seismic anisotropy in the uppermost mantle, back-arc region of the northeast Japan arc: petrophysical analyses of Ichinomegata peridotite xenoliths

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Abstract A dense network of seismic stations has been deployed across the northeast Japan arc to investigate mantle wedge structures. To attain independent petrophysical constraints, we determined the seismic properties of Ichinomegata mantle xenoliths from the back-arc region that were brought to the surface from the mantle lithosphere by volcanic eruptions. We calculated the seismic properties of the xenoliths from olivine and pyroxene crystal-preferred orientations and single crystal elastic constants. The small magnitude of measured S-wave splitting (delay time of 0.22s in the area where the xenoliths were entrained) can be explained by the average seismic properties of mantle xenoliths for an approximately 20-km thick horizontal anisotropic layer, indicating that the mantle lithosphere could be one of the dominant sources of seismic anisotropy; this layer is possibly related to deformation in the uppermost mantle lithosphere due to back-arc spreading along the northeast Japan arc.

1. Introduction

Subduction zones are regions where large chemical exchanges between the interior and surface of the Earth dominantly occur. Tectonic plate motion causes solid-state plastic corner flow between the subducting slab and the overriding plate and subsequently leads to the development of crystal-preferred orientation (CPO) of constituent olivine crystals within the mantle. The seismic anisotropy resulting from olivine CPO tends to produce a maximum seismic wave velocity parallel to the direction of plastic flow within the upper mantle [*Nicolas and Christensen*, 1987].

Measurements of shear-wave splitting play a crucial role in imaging flow patterns within mantle wedges [e.g., *Nakajima and Hasegawa*, 2004; *Audoine et al.*, 2004]; however, observed shear-wave splitting from earthquakes of intermediate depth may be affected by anisotropy in the mantle wedge, the crust, and the slab. If shear-wave splitting occurs due to mineral CPO, it is necessary to understand the strength of strain in the mantle wedge and the elastic coefficients of minerals to evaluate the delay time along ray paths.

The northeast Japan arc is a typical subduction zone, where the Pacific plate subducts beneath the land area at a rate of ~10cm/year and is one of the most seismologically studied arcs. Shear-wave polarization anisotropy has been systematically investigated in the mantle wedge of the northeast Japan arc; Fast directions in the back-arc side are oriented nearly E-W, whereas fast directions in the fore-arc side are oriented approximately N-S [Fig. 1; *Nakajima and Hasegawa*, 2004]. Although seismic anisotropy observations from the back-arc side of the northeast Japan arc are generally interpreted in terms of the CPO of mantle minerals arising from present-day mantle process such as mantle wedge convection and plate motion [*Nakajima and Hasegawa*, 2004; *Ishise and Oda*, 2005], we show in this paper that peridotite xenoliths from the uppermost mantle lithosphere entrained by Ichinomegata Volcano in the back-arc region of northeast Japan at ca. 10,000 yr in age preserve strong asymmetric fabrics with intermediate seismic anisotropy. This anisotropy could be one of the dominant sources in explaining the observed delay times of shear-wave velocity in this region. Furthermore, we argue that such seismic anisotropy in the uppermost mantle lithosphere could have been induced by back-arc spreading along the northeast Japan arc related to the opening of the Japan Sea.

2. Geological setting and sample selection

Ichinomegata Volcano, located on Oga Peninsula, northeast Japan (Fig. 1), is one of the few places on Earth where deep-level xenoliths occur in the back-arc region of an island arc. The host magma is calc-alkali andesite to dacite in composition and is ca. 10,000 yr in age. The Ichinomegata xenolith suite is composed of peridotites, websterites, clinopyroxenites, gabbros, amphibolites, and other shallow-level rocks such as granitic and metavolcanic rocks and sediments [e.g., *Abe et al.*, 1998]. The peridotite xenoliths are up to 30 cm in diameter, but usually less than 10 cm. The xenoliths are generally lherzolite with some hartzburgite that have secondary pargasite and rare phlogopite of mantle metasomatic origin due to the addition of hydrous melt/fluid to dry peridotite [e.g., *Abe et al.*, 1998].

In this study, we selected nine peridotite xenoliths from twenty lherzolite samples for detailed petrophysical analyses to evaluate the effect of rock seismic properties on seismic-wave properties. We focused on olivine crystals, as olivine is the most common mineral in the upper mantle. In addition, we obtained two samples that had previously been studied petrologically and geochemically by *Abe et al.* [1998] and analyzed their seismic properties in terms of three common minerals: olivine, orthopyroxene, and clinopyroxene.

3. Microstructural analyses

Most of the peridotite xenoliths have a pervasive main foliation composed of compositional banding defined by pyroxene-rich and pyroxene-poor layers and a lineation defined by elongate pyroxene grains. We analyzed microstructures from XZ thin sections cut perpendicular to the foliation and parallel to the lineation. Most of the peridotite xenoliths have medium- (<5 mm) to fine-grained (<1 mm) granular texture, whereas only two of the peridotite xenoliths have porphyroclastic textures.

The peridotite xenoliths with granular texture have shape-preferred orientations (SPOs) of olivine that are oriented oblique to the main foliation (Fig. 2). Although the oblique foliation tends to weaken as olivine grain size decreases, the angle between the two foliations is constantly around 20°, indicating that these are steady-state microstructures. So-called 'oblique foliation' is a typical microstructure resulting from shear deformation [e.g., *Nicolas and Christensen*, 1987]. The similar nature of the oblique foliations within all the peridotite xenoliths indicates that their origins are related to a pervasive event in the uppermost mantle lithosphere beneath the northeast Japan arc.

We estimated temperature conditions in the range 850 to 1000 °C based on orthopyroxene thermometers after *Witt-Eichkshen and Seck* [1991] and *Kohler and Brey* [1990]. This estimate is in good agreement with previous studies, which could represent a cooling event in the mantle lithosphere [*Takahashi*, 1986]. It appears that the peridotite xenoliths are derived from relatively shallow levels in mantle, at 30 to 40 km depth [*Takahashi*, 1986], where the depth of the Moho is estimated to be approximately 28 km [*Zhao et al.*, 1990].

4. Fabric analyses

To examine deformation conditions in more detail, we measured the CPO of olivine from highly polished thin sections using a scanning electron microscope equipped with an electron-backscatter diffraction system, housed at the Center for Instrumental Analysis, Shizuoka University, Japan. We determined 150 to 250 olivine crystal orientations per sample, and visually checked the computerized indexation of the diffraction pattern for each crystal orientation. Olivine CPO data show {0kl}[100] patterns, with the [100] axis slightly oblique to the main foliation (Fig. 3a).

As we are unable to measure strain from naturally deformed samples, the fabric strength (*J*-index) is used to evaluate the influence of the CPO on seismic properties [e.g., *Ben Ismail and Mainprice*, 1998]. The fabric strength varies between 4.2 and 11.95 for all analyzed olivine aggregates, with a mean value of 6.98 and a standard deviation of 2.85 (Fig.4).

5. Rock seismic properties

We calculated the seismic properties of the peridotite xenoliths from single crystal elastic constants, crystal density, and the CPO of olivine, enstatite, and diopside, assuming two different scenarios: either a composition of 100 % olivine, or the actual modal composition of the rock. The elastic constants used in our calculations are those of *Abramson et al.* [1997] for olivine, *Chai et al.* [1997] for enstatite, and *Collins and Brown* [1998] for diopside; we also used the Voigt Reuss Hill averaging scheme [*Mainprice et al.*, 2000].

For the analyzed olivine aggregates consisting of 70 to 90 % modal compositions, the seismic anisotropy of P-waves varies between 4.8 and 14.7%, with a mean value of 8.66% and a standard deviation of 3.0. The seismic anisotropy of S-waves varies between 3.73 and 8.99%, with a mean value of 6.04% and a standard deviation of 1.75. Figure 5 shows the seismic properties as a function of fabric strength; the results are similar to those of *Ben Ismail and Mainprice* [1998] determined for subduction zone peridotites.

The addition of enstatite and diopside to the actual modal compositions reported by *Abe et al.* [1998] results in P-wave and S-wave anisotropies that are decreased by approximately 20% compared to those for a pure olivine aggregate. Maximum P-wave anisotropy is reduced from 14.7 to 11.4 % and from 7.7 to 6.3% for samples I708 (Ol, 0.75; Opx, 0.19; Cpx, 0.06) and I702 (Ol, 0.82; Opx, 0.14; Cpx, 0.04), respectively, while maximum S-wave anisotropy is reduced from 8.99 to 7.35 % and 5.43 to 4.6%, respectively (Fig. 4). These reduced anisotropies are, however, within the range of anisotropies for a composition of 100 % olivine (Fig. 4).

Figure 3b presents the seismic properties of the peridotite xenoliths shown in Fig. 3a; these are the seismic properties most similar to the mean properties shown in Fig. 4. The P-wave velocity is fastest subparallel to the lineation, which is closely related to the CPO maximum of olivine [100]. The P-wave velocity is slow for waves propagating in a plane normal to the [100] maximum, resulting in an axial symmetry with the [100] maximum as the symmetry axis. Polarization anisotropies of most samples have two maxima girdles on each side of a plane normal to the [100] maximum, whereas the minimum birefringence occurs for propagation directions close to the [100] maximum, subparallel to the lineation. The orientation of the polarization plane of the fastest S-wave systematically marks the orientation of the great circle that contains the maximum concentration of [100]. These anisotropic patterns are quite common as previously reported elsewhere [e.g., *Mainprice et al.*, 2000].

6. Discussion and conclusions

Although the original orientations of the Ichinomegata peridotite xenoliths were lost during their volcanic transport to the surface, we are able to derive quantitative constraints on the intrinsic anisotropy within the lithospheric mantle but not constrain the trend of the fast split shear waves [*Ben Ismail and Mainprice*, 2001]. If the structures within the uppermost mantle lithosphere were randomly oriented, the peridotite xenoliths analyzed in the current study would make no contribution to the observed shear-wave splitting; however, it is likely that regional-scale structures within the uppermost mantle lithosphere are oriented horizontally, as described below.

The opening of the Japan Sea is thought to have occurred over the period 25 to 13 Ma as a consequence of back-arc spreading within the northeast Japan arc; most of the basic geologic structure of the present Japanese Islands was accomplished during this time [Fig. 5; e.g., *Sato*, 1994]. The depth of the Moho beneath the Ichinomegata crater is approximately 28 km near the coast of the Japan Sea [*Zhao et al.*, 1990], while the temperature of the Moho is thought to be about 850 °C [*Kushiro*, 1987]. The depth of the Moho becomes deeper, up to 38 km in depth, towards the northeast Japan arc [*Zhao et al.*, 1990], where temperatures are 950 to 1000 °C [*Kushiro*, 1987]. As described above, the peridotite xenoliths analyzed in the present study came from relatively shallow levels in the mantle of 30 to 40 km depth at temperatures in the range 850 to 1000 °C [*Takahashi*, 1986]. Therefore, we consider it is likely that the Ichinomegata peridotite xenoliths are derived from the uppermost mantle lithosphere in the region dominated by horizontal extension and back-arc spreading (Fig. 5).

The thickness (T) of an anisotropic layer is given by $T=(100dt<Vs>)/AVs$, where dt is the delay time of S-waves, <Vs> is the average velocity of the fast and slow velocities, and AVs is the anisotropy for a specific propagation direction expressed as a percentage [e.g., *Pera et al.*, 2004]. Accordingly, the observed delay times (e.g., 0.22 s at Oga Peninsula where Ichinomegata Volcano is located) can be explained by the seismic properties of our average peridotite xenolith shown in Fig. 3b for an approximately 20-km thick anisotropic layer with a horizontal foliation and lineation (Fig. 5). It is noted that the bulk anisotropy should be less than that in each individual sample due to destructive interferences [e.g., *Ben Ismail and Mainprice*, 2001], so that it might be necessary to have a thicker anisotropic layer.

As Ichinomegata Crater is one of just a few localities where deep-level inclusions can be found in an island arc setting, the peridotite xenoliths demonstrate the possible occurrence of an anisotropic layer in the uppermost mantle lithosphere that might be related to ‘frozen’ deformation during back-arc spreading along the northeast Japan arc (Fig. 5). S-wave seismograms of intermediate-depth earthquakes show small delay times but regionally coherent polarizations, where the E-W fast anisotropy occurs from the back-arc region to the volcanic front above the low velocity zones [*Nakajima and Hasegawa*, 2004]. Although the low velocity zones are commonly attributed to the zones of partially melted mantle [*Kushiro*, 1987], the propagation of a partial-melting front across the lithosphere would not erase the pre-existing CPO and related seismic anisotropy, even if it does modify the microstructure [*Vauchez and Garrido*, 2001]. Consequently, mantle lithosphere in the back-arc region is possibly one of the dominant sources of seismic anisotropy, which is presently commonly attributed to corner flow.

Acknowledgements. We greatly thank David Mainprice for his support during this study. Aaron

Stallard, Martha Savage and an anonymous reviewer provided valuable suggestions that greatly improved the paper. This work was supported by research grants from the Japan Society for the Promotion of Science.

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Figure captions

Figure 1: Japanese Island arcs. Abbreviations: VF, volcanic front; AF, aseismic front; I, Ichinomegata. The peridotite xenoliths are from Ichinomegata Volcano, Oga Peninsula, northeast Japan (Star symbol). The fast directions in the back-arc side are oriented nearly E-W (arrow at the west side of VF), whereas those in the fore-arc side are approximately N-S [arrow at the east side of VF; *Nakajima and Hasegawa*, 2004].

Figure 2: Photomicrographs of a peridotite xenolith with oblique foliations, as defined by the shape-preferred orientation (SPO) of olivine grains. The SPO indicates a sinistral sense of shear. The main foliation (X) is defined by compositional banding and oriented horizontally. The white arrows show the orientation of the olivine SPO, oriented 20° from the main foliation. (b) Orientation distributions of olivine grains with respect to the main foliation (X). The angles between the SPO and the main foliation are approximately 10–20°. The mean aspect ratio is 2.2.

Figure 3: (a) Crystal-preferred orientations (CPO) of olivine. Foliation is vertical (XY plane, solid line) and lineation (X) is horizontal within the plane of the foliation. Equal area projection, lower hemisphere. (b) Seismic properties calculated from CPO data shown in (a). Contours for Vp are in km/s, while those for dVs are in % anisotropy and trace of the Vs1 polarization plane.

Figure 4: Relationships between seismic anisotropy and fabric strength (*J*-index) for Vp and Vs anisotropy. Solid and dashed lines represent average values and standard deviation,

respectively, for Vp and Vs anisotropy. Large symbols indicate seismic anisotropies assuming a composition of 100% olivine, while two small symbols connected to the large symbols are those calculated from the CPO of olivine, enstatite, and diopside and the actual modal composition of the rock.

Figure 5: Schematic diagrams showing the tectonic evolution of the northeast Japan arc between ca 20 Ma and 10 Ka. Star symbols indicate possible locations of the Ichinomegata peridotite xenoliths within the mantle. The shaded area in the vicinity of the star symbol at 10 Ka shows the possible thickness of the seismically anisotropic layer, from which the measured delay times of S-waves occurs. Dashed lines beneath the northeast Japan arc show low velocity zones, after *Nakajima and Hasegawa* [2004].

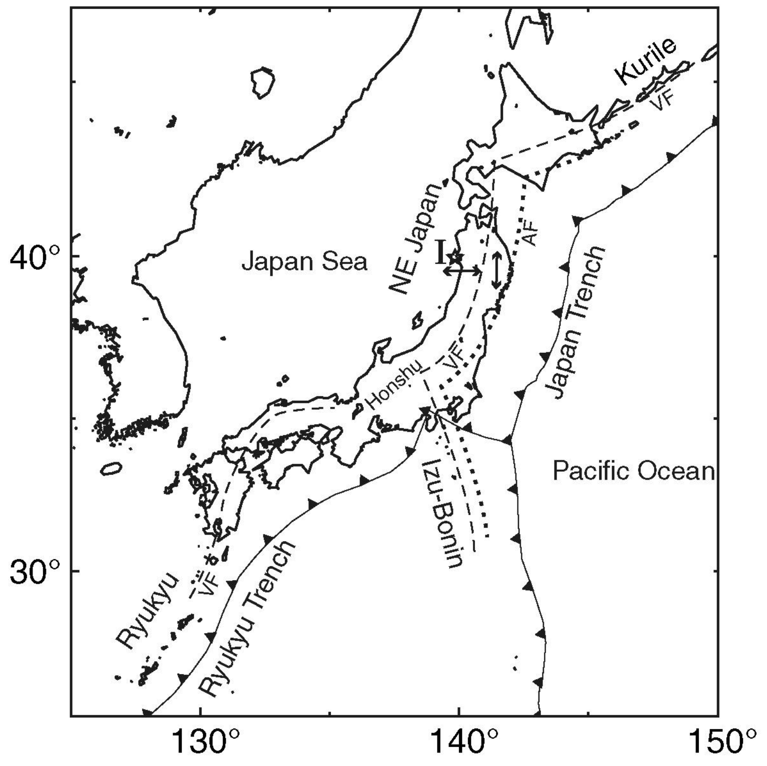
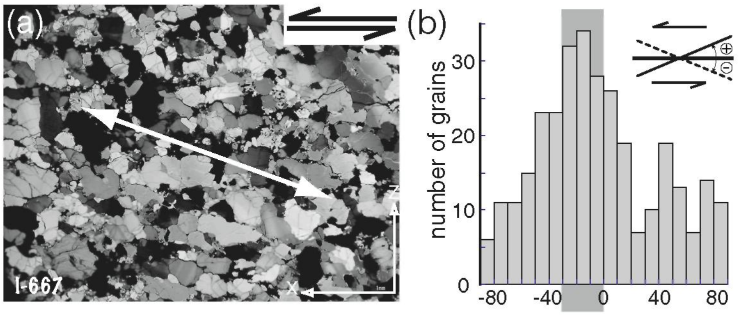


Figure 1. Michibayashi et al.



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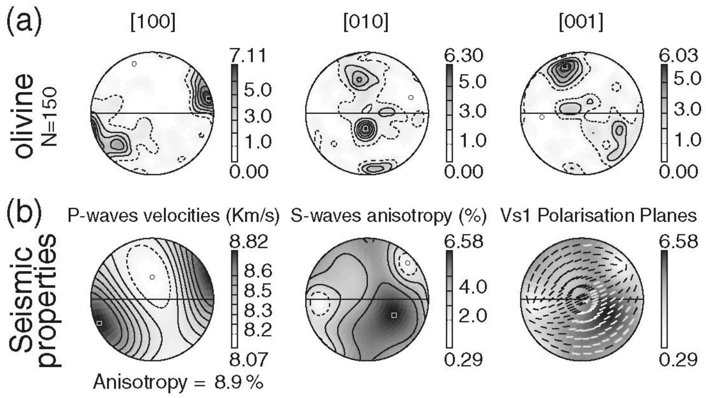

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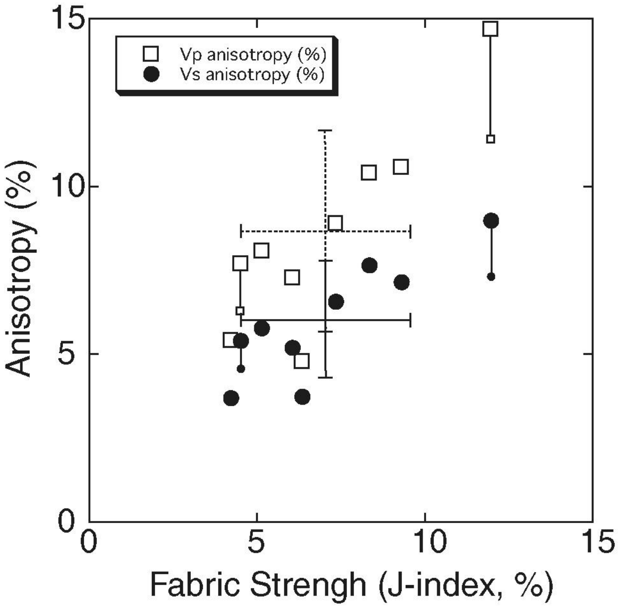

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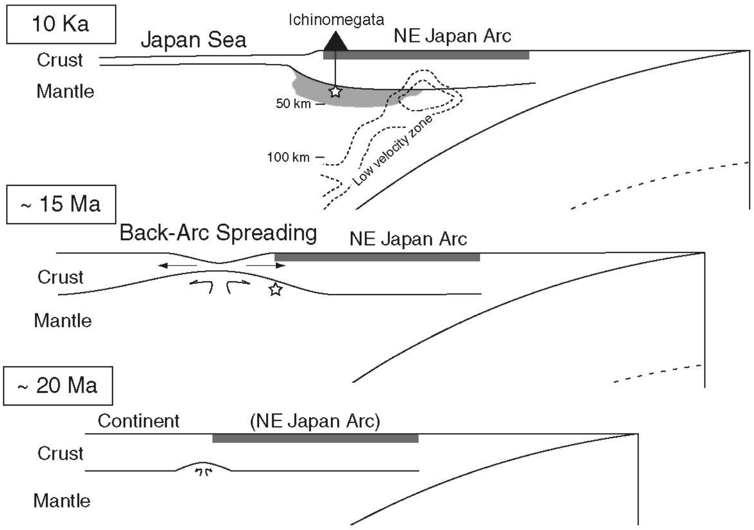

Figure 5: Michibayashi et al.