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Shear-wave splitting beneath the southwestern Kurile arc and northeastern Japan arc: A new insight into mantle return flow

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[1] Shear-wave splitting in the southwestern part of the Kurile arc and the northeastern (NE) Japan arc is investigated using the waveforms from local earthquakes. For both arcs observed shear-wave splitting shows clear evidence for a striking rotation of fast direction across the arc, suggesting the different feature of anisotropy between the fore-arc and back-arc sides. Trench-parallel fast directions are observed in the fore-arc side, which is consistent with the anisotropy expected from the deformation of the B-type olivine fabric as well as the anisotropy in the slab. Fast directions observed in the back-arc side show approximately E-W and ESE-WNW in the NE Japan arc and N-S in the southwestern Kurile arc, which are characterized by the local maximum-dip direction of the subducted Pacific plate not by the direction of plate convergence. This relationship suggests that the direction of the mantle return flow is governed by the local slab geometry. **Citation:** Nakajima, J., J. Shimizu, S. Hori, and A. Hasegawa (2006), Shear-wave splitting beneath the southwestern Kurile arc and northeastern Japan arc: A new insight into mantle return flow, *Geophys. Res. Lett.*, *33*, L05305, doi:10.1029/2005GL025053.

1. Introduction

[2] Seismic anisotropy around the Japanese Islands has been studied mainly by shear-wave splitting measurements, and the understanding of mantle dynamics has been enhanced through obtained splitting parameters [e.g., *Ando et al.*, 1983; *Okada et al.*, 1995; *Hiramatsu et al.*, 1997; *Long and van der Hilst*, 2005; *Anglin and Fouch*, 2005]. Recently, *Nakajima and Hasegawa* [2004] revealed a striking rotation of fast directions from trench-parallel closer to the trench to trench-perpendicular far from the trench in the central part of northeastern (NE) Japan, and interpreted it in terms of mantle flow. Their study area is, however, too confined to discuss the regional mantle flow, which is very important to constrain the mantle dynamic associated with the Pacific plate.

[3] This study is the first attempt to investigate a detailed shear-wave splitting beneath the area covering the southwestern Kurile arc and the NE Japan arc. If shear-wave splitting is responsible for mantle flow associated with the subducted Pacific plate, a systematic spatial variation of shear-wave splitting will be observed for both arcs. The study area includes the arc-arc junction, where the direction of plate motion changes relative to the trench axis. As a consequence, oblique subduction takes place beneath the southwestern Kurile arc with the fore-arc sliver [*Kimura*, 1986] (Figure 1). This area is, therefore, an excellent natural laboratory for studying the effects of oblique subduction and local slab geometry on mantle flow. We focus on the regional-scale variation in splitting parameter to understand tectonic deformation and dynamic processes in the mantle.

2. Data and Results

[4] We utilized the cross-correlation method [e.g., *Ando et al.*, 1983] on S arrivals from local earthquakes to constrain fast polarization directions and delay time between fast- and slow-shear waves. Hypocenter distribution of the 1,047 earthquakes used in this study is shown in Figure 1. We used 281 nation-wide seismic stations. All the stations have three-component seismometers with a sampling rate of 100 Hz. We restrict our analysis to ray paths with incident angles to free surface of 35 degrees or less to avoid contamination of particle motions by converted phases. Our analysis obtained 3,021 pairs of splitting parameters. See auxiliary materials[1] for details on station distribution, waveform analysis, and resulting measurements.

[5] Figure 2a shows the distribution of average fast direction and delay time for each station. Results reported by *Nakajima and Hasegawa* [2004] are shown for the central part of NE Japan (38.5°N–40.0°N), which are also included in the discussion below. Rose diagrams of station-average fast directions for six regions (Figure 2b) and the distribution of fast directions after performing spatial averages (Figure 2c) indicate that the across-arc rotation of fast directions is apparent not only in the NE Japan arc but also in the southwestern Kurile arc. Fast directions observed in the fore-arc side appear to be sub-parallel to the strike of the trench axis for both arcs, while those in the back-arc side vary from arc to arc, approximately ESE-WNW in the south of NE Japan, E-W in the north of NE Japan, and N-S in southwestern Kurile, where an identical plate convergence takes place but an obliquity of the subduction changes slightly corresponding to the change of the strike of the trench (Figure 1). In particular, the N-S polarized fast directions in southwestern Kurile are significantly oblique to the relative plate motion (N65°W) beyond the typical estimation error of ±30° (see auxiliary materials). These observations indicate that anisotropy in the back-arc side is not characterized by either the strike of the trench or the direction of plate convergence. The N-S polarized fast

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[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005GL025053.

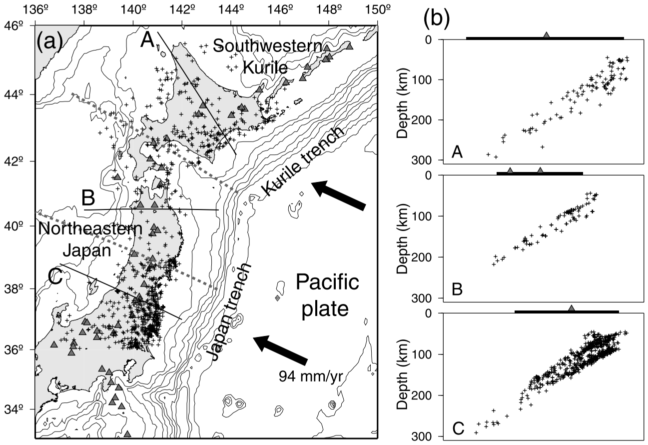

Figure 1. (a) Tectonic setting of the study area and distribution of hypocenters used in this study. Black arrows show the direction of the relative plate motion (N65°W) between the Pacific and North American plates [*DeMets et al.*, 1994]. Crosses and gray triangles represent hypocenters and active volcanoes, respectively. We selected 1047 earthquakes with M > 2.5 and the depth shallower than 300 km that occurred from 2001 to 2004. (b) Cross-sectional view of hypocenters for three regions divided by gray dashed lines in (a). Bars and gray triangles on the top of each cross section represent the land area and active volcanoes, respectively.

directions have also been observed in previous studies [e.g., *Fouch and Fischer*, 1996; *Long and van der Hilst*, 2005], and we consider them as robust results. Averaged delay times tend to increase toward the back-arc side, and are generally 0.2–0.4 sec and 0.05–0.15 sec in the back-arc and fore-arc sides, respectively.

3. Mantle Return Flow and Oblique Subduction

[6] The systematic spatial variation in splitting parameters would be consistent with the large-scale deformation expected by subduction processes, rather than the small-scale deformation in the crust. Furthermore, the contribution from crustal anisotropy would be much smaller than that from upper mantle anisotropy because of shorter path length in the crust and smaller delay time (<0.1 s) [*Kaneshima*, 1990]. Slab anisotropy may partly contribute to the observed shear-wave splitting, but the effect would be smaller at least for shear-wave splitting in the back-arc side since it could produce a trench-parallel fast direction [*Ishise and Oda*, 2005] and the path length in the slab is generally much smaller than that in the mantle wedge [*Nakajima and Hasegawa*, 2004]. Hence we assume that shear-wave splitting observed in the back-arc side is attributable to anisotropy in the mantle wedge.

[7] An inclined low-velocity zone is imaged in the back-arc mantle wedge of NE Japan and southwestern Kurile, sub-parallel to the down-dip direction of the slab [*Nakajima et al.*, 2001; *Wang and Zhao*, 2005], and is interpreted as the

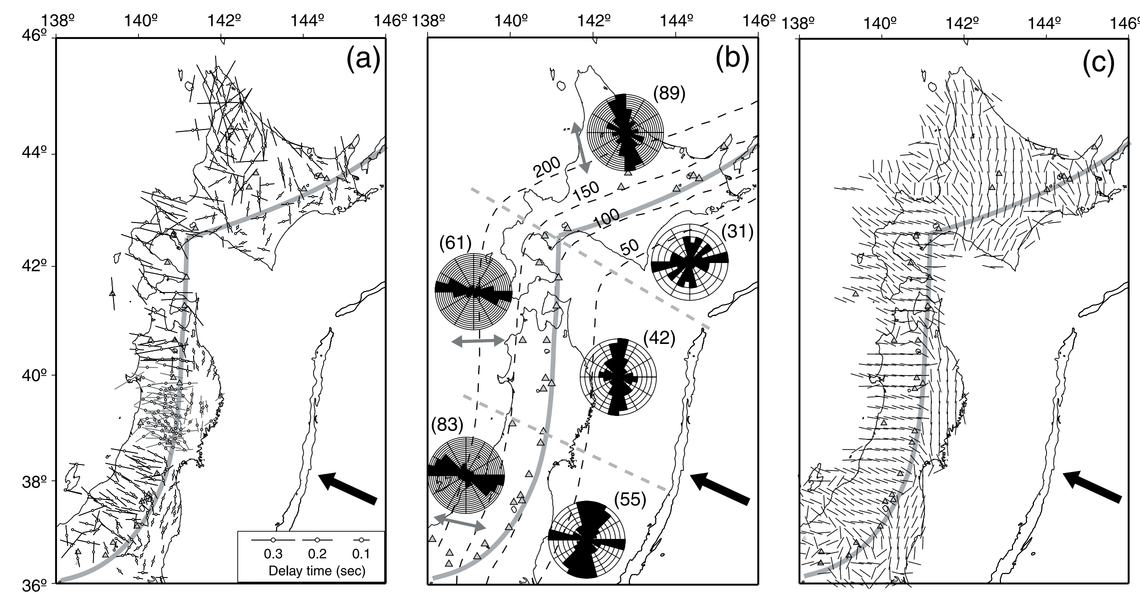

Figure 2. Distribution of the average fast direction and delay time for each station plotted on the station location as black bars. Length of the bar is normalized to the averaged delay time. Gray bars in the central part of NE Japan (38.5–40°N) are the results by *Nakajima and Hasegawa* [2004]. The gray curve indicates the volcanic front. (b) Rose diagrams of the average fast direction for six regions. The study area is divided into three regions according to the strike of the trench axis and each region is further divided into two regions, the fore-arc and back-arc sides of the volcanic front. Gray dashed lines show the boundary of the regions. The number in parentheses represents the number of stations in each region. Dashed contours indicate the upper boundary of the Pacific plate with an interval of 50 km. Gray arrows next to the rose diagrams in the back-arc side represent the maximum-dip direction of the subducted slab for each region [*Hasegawa et al.*, 1994; *Umino et al.*, 1995; *Katsumata et al.*, 2003]. (c) Distribution of fast directions after performing spatial averages [*Audoine et al.*, 2004]. Bars show the average fast direction obtained at each grid point. The grid spacing for the calculation is 0.2 degrees.

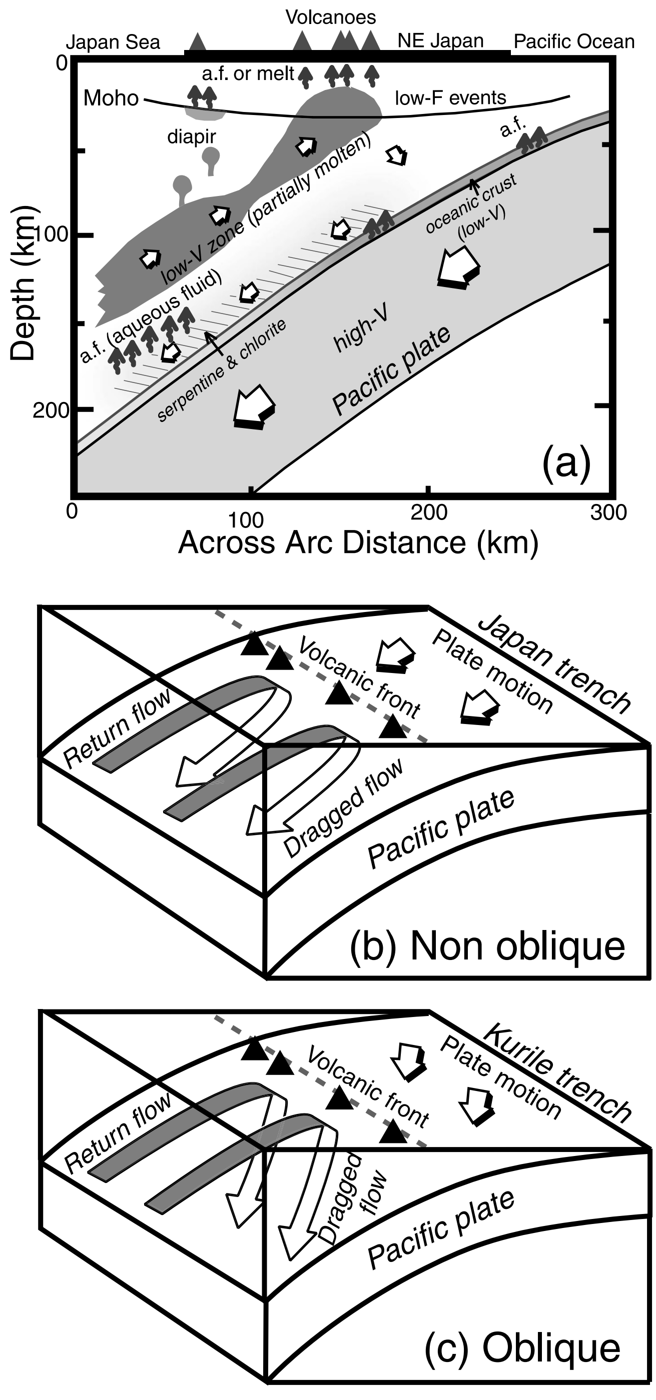

Figure 3. (a) A 2-D schematic figure of vertical cross-section in NE Japan, showing the flow model with inferred transportation paths of fluids [after *Hasegawa and Nakajima*, 2004]. Schematic representations of mantle flow for (b) non-oblique and (c) oblique subduction.

mantle return flow (upwelling flow) working as the main source of arc magmas. The return flow is induced by viscous coupling between the subducted slab and the mantle wedge [e.g., *Hasegawa et al.*, 1991; *Hasegawa and Nakajima*, 2004] (Figure 3a). Two plausible candidates, fluid-filled cracks aligned under the differential stress and lattice-preferred orientation (LPO) of olivine, are considered as the anisotropy associated with the return flow. Numerical simulations have shown that crack faces would be aligned normal to the plate motion [e.g., *Fischer et al.*, 2000], which results in the trench-parallel fast direction, and hence fluid-filled cracks would be ruled out as the sole explanation for the anisotropy in the back-arc mantle wedge.

[8] Deformation in the mantle wedge causes LPO of olivine, which in turn affects the directional dependence of seismic velocity. Recent experiments have yielded new insights into the diversity of olivine fabric [*Jung and Karato*, 2001; *Katayama et al.*, 2004]. Briefly, the A-type fabric, assumed in the previous interpretation of seismic anisotropy, is dominant under low stress and low-water content, whereas at higher water content other types of olivine fabric (B-, C-, and E-types) become important. It is known that the B-type, which is dominant under high stress, produces flow-normal fast direction, while the C- and E-types are dominant under lower stress than suitable for the B-type and produce flow-parallel fast direction. Numerical simulations [e.g., *Kneller et al.*, 2005] for NE Japan predict high-temperature and low-stress conditions associated with the return flow, which are suitable for A-, C-, and E-types depending on water content. As a flow-parallel fast direction is expected in every olivine fabric, we interpret that observed fast directions in the back-arc side reflect the direction of return flow in the mantle wedge.

[9] Figure 2 shows that the inferred direction of the return flow is approximately N-S in southwestern Kurile, E-W in the north of NE Japan, and ESE-WNW in the south of NE Japan, all of which are characterized by the maximum-dip direction of the subducted slab (gray arrows in Figure 2b). This relationship suggests that the return flow occurs subparallel to the local maximum-dip direction of the slab, independent of the direction of the plate convergence and the obliquity of the subduction. Mantle return flow could occur as follows. The slab subduction is responsible for dragging mantle wedge materials (downward flow), by viscous flow, along the slab surface in the direction of plate convergence. The dragged materials are passively replaced by the hot and low-viscosity mantle materials from the deep mantle wedge, resulting in an upward return flow. Materials at deeper part of the maximum-dip direction of the slab might be efficiently flowing upward and replace the material gaps, generating the return flow parallel to the maximum-dip direction of the slab. Note that the maximum-dip direction of the slab is identical with the direction of plate convergence in non-oblique subduction zones (Figure 3b) but is oblique to it in oblique subduction zones (Figure 3c). *Honda and Yoshida* [2005] demonstrates that the spatial pattern of corner flow resulting from oblique subduction is similar to that of non-oblique case, supporting our interpretation.

[10] The present observations indicate the presence of anisotropy in the fore-arc side. Recent numerical simulations [e.g., *Arcay et al.*, 2005; *Kneller et al.*, 2005] modeled high-water content and high-stress condition in the fore-arc mantle wedge, which are suitable for the B-type olivine fabric that produces a flow-normal fast direction. Then anisotropy due to the deformation of the B-type olivine fabric is one of the plausible candidates for the observed shear-wave splitting. It is known that the subducted Pacific slab shows anisotropy with the fast propagation axis of P

wave in N-S direction beneath NE Japan [*Ishise and Oda*, 2005], explaining the observed fast directions. We infer that the combined effects of anisotropy in the mantle and the slab are responsible for the observed shear-wave splitting in the fore-arc side. Note that the deformation due to the fore-arc sliver [*Kimura*, 1986] might be partly attributed to the shear-wave splitting observed in the southwestern part of Kurile arc.

4. Conclusions

[11] Our shear-wave splitting measurements reveal a striking rotation of fast directions across the arc, over a length of ~1000 km from the southern part of the NE Japan arc to the southwestern Kurile arc. Regional-scale variation in splitting parameters suggests that the cause of the anisotropy is attributed to large-scale deformation. The inferred direction of the return flow is characterized by the maximum-dip direction of the subducted slab for both arcs, which is inconsistent with the previous interpretation that the return flow is generated sub-parallel to the direction of plate convergence. Our results will provide a new insight into a better understating of mantle dynamics in subduction zones, with implications for the importance of 3D modeling of mantle flow with the local slab geometry. Further work could possibly involve inversion modeling of anisotropic bodies as well as quantitative interpretation of delay times. These are, however, beyond the scope of this paper.

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