Upper mantle anisotropy beneath central and southwest Japan: An insight into subduction-induced mantle flow

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\textbf{A B S T R A C T}

Analysis of seismic anisotropy in the crust and mantle wedge above subduction zones gives much information about the dynamic processes inside the Earth. For this reason, we measure shear wave polarization anisotropy in the crust and upper mantle beneath central and southwestern Japan from local shallow, intermediate, and deep earthquakes occurring in the subducting Pacific slab. We analyze 5 phases from 198 earthquakes recorded at 42 Japanese F-net broadband seismic stations. This data set yields a total of 980 splitting parameter pairs for central and southwestern Japan. Dominant fast polarization directions of shear waves obtained at most stations in the Kanto–Izu–Tokai areas are oriented WNW–ESE, which are sub-parallel to the subduction direction of the Pacific plate. However, minor fast polarization directions are oriented in NNE–SSW directions being parallel to the strike of the Japan Trench, especially in the north of Izu Peninsula and the northern Tokai district. Generally, fast directions obtained at stations located in Kii Peninsula and the Chubu district are oriented ENE–WSW, almost parallel to the Nankai Trough, although some fast directions have NW–SE trends. The fast directions obtained at stations in northern central Honshu are oriented N–S. Delay times vary considerably and range from 0.1 to 1.25 s depending on the source depth and the degree of anisotropy along the ray path. These lateral variations in splitting character suggest that the nature of anisotropy is quite different between the studied areas. Beneath Kanto–Tokai, the observed WNW–ESE fast directions are probably caused by the olivine A-fabric induced by the corner flow. However, the slab morphology in this region is relatively complicated as the Philippine Sea slab is overriding the Pacific slab. This complex tectonic setting may induce lateral heterogeneity in the flow and stress state of the mantle wedge, and may have produced NNE–SSW orientations of fast directions. The ENE–WSW fast directions in Kii Peninsula and the Chubu district are more coherent and may be partly induced by the subduction of the Philippine Sea plate. The N–S fast directions in northern central Honshu might be produced by the trench-parallel stretching of the wedge due to the curved slab at the arc–arc junction.

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\section{1. Introduction}

Seismic anisotropy within the crust and upper mantle has been documented in a number of different tectonic settings worldwide, including subduction zones, spreading centers and stable cratons. Crustal anisotropy is caused mainly by the preferred alignment of stress-induced microcracks (e.g. Kaneshima, 1990), while mantle anisotropy is generally attributed to deformation or stress, which results in a lattice-preferred orientation (LPO) of anisotropic mantle minerals, primarily olivine (e.g., Karato, 1987; Nicolas and Christensen, 1987; Silver and Chan, 1991; Zhang and Karato, 1995). Laboratory studies show that under moderate to large strains, the $a$-axis of olivine becomes aligned in the shear direction of the mantle flow (Nicolas and Christensen, 1987; Zhang and Karato, 1995). This alignment is only produced when dislocation creep is the dominant deformation mechanism and is called “A-type” olivine fabric (Zhang and Karato, 1995). However, new laboratory results have shown that when olivine aggregates are deformed under high-stress, low-temperature, and water-rich conditions, the fast axes of individual olivine crystals tend to align 90° from the flow direction (Jung and Karato, 2001), producing what is called “B-type” olivine fabric. These B-type olivine fabrics, in conjunction with trench-normal flow in the mantle wedge, may explain the trench-parallel fast directions in some regions (Karato, 2003; Kneller et al., 2005). It is not clear, however, if the stresses, temperatures, and volatile concentrations needed to produce B-type olivine fabrics are relevant to a large volume of the mantle wedge.
One of the key factors controlling the development of LPO is temperature (see Savage, 1999 and references therein). At temperatures greater than 900 °C, mantle minerals will develop a LPO under moderate shear strain, and thus anisotropy can be actively produced by present-day mantle deformation. If the temperature is then decreased to less than 900 °C causing little or no deformation, anisotropy may become ‘frozen in’, leading to fossil anisotropy (Currie et al., 2004). Present-day mantle deformation has been invoked to explain anisotropy in tectonically active regions, such as subduction zones and spreading centers (e.g. Vinnik et al., 1992). On the other hand, anisotropy over stable cratons has been explained by fossil anisotropy within the lithosphere produced by the most recent tectonic event (Silver and Chan, 1991), sublithospheric mantle flow (Fouch et al., 2000), or a combination of both (Vinnik et al., 1992; Levin et al., 1999; Fouch et al., 2000).

Seismic anisotropy can be observed through the splitting of various S-wave phases including direct S waves. When a shear wave passes through an anisotropic medium, it splits into two orthogonal components which travel at different speeds. Shear wave splitting is characterized by two parameters: the polarization direction of the first arriving shear wave at the Earth’s surface (ψ, the fast direction, in degrees), and the time lag between the two shear waves (τ, the delay time, in seconds). Basically, the fast direction of shear wave splitting in the mantle is generally assumed to be the horizontal projection of the olivine a-axis. Thus, observations of seismic anisotropy can be used to constrain the orientation of the local strain field within the mantle. The delay time depends on the thickness of the anisotropic layer and the magnitude of anisotropy within the layer.

There are many processes that can contribute to subduction zone anisotropy, including corner flow in the mantle wedge, flow beneath the slab of subducted lithosphere, flow around the slab edge, the generation and migration of melt, and anisotropic structure in the slab itself or in the overriding plate (for a review, see Park and Levin, 2002). Because of the ambiguity of which processes are contributing to the observed anisotropy, and because shear wave splitting is a path-integrated measurement with generally poor depth resolution, interpretation of shear wave splitting measurements in subduction zones is still under controversy. In particular, the interpretation of fast splitting directions that are parallel to the trench (that is, perpendicular or at a large angle to the convergence direction) is a matter of debate.

The shear wave polarization anisotropy in the mantle wedge pore water has been investigated by many researchers in various subduction zones worldwide (e.g. Nakajima and Hasegawa, 2004). The leading shear wave polarization direction varies among different subduction zones. Fast directions that are oriented nearly normal to the trench have been reported, for example, in subduction zones of Tonga (Fischer and Wiens, 1996), Izu–Bonin (Fouch and Fischer, 1996) and Marianas (Fouch and Fischer, 1998). Those that are sub-parallel to the trench have also been reported in New Zealand (Audoine et al., 2000) and the Shumagin Island section of the Aleutian (Yang et al., 1995). In addition, complex patterns of fast directions have been observed in northeastern (NE) Japan (Okada et al., 1995; Nakajima and Hasegawa, 2004), central Japan and the Kanto area (Fouch and Fischer, 1996; Hiramatsu et al., 1998; Salah et al., 2008), central South America (Polet et al., 2000), south central Alaska (Wiemer et al., 1999), the Lau backarc (Smith et al., 2001), Kamchatka (Levin et al., 2004) and in the north of New Zealand (Morley et al., 2006).

Many researchers studied the seismic anisotropy structure beneath central-southwest Japan and found different orientations of the fast polarization directions (e.g. Ando et al., 1983; Idaka and Obara, 1994, 1995; Fouch and Fischer, 1996; Hiramatsu et al., 1998; Long and van der Hilst, 2005). Major features of these previous studies will be briefly explained in Section 4.3 to compare them with the main findings in this study. Recently, Salah et al. (2008) conducted shear wave splitting measurements beneath central and southwest Japan from local shallow- and intermediate-depth earthquakes occurring in the subducting Philippine Sea (PHS) slab. The study also includes shallow events in the Pacific slab beneath Kanto. The crustal anisotropy from the shallow events in their study shows fast directions which are more or less aligned in the σ3max directions, implying that the anisotropy is produced by the alignment of the vertical cracks in the crust induced by the compressive stresses. Results from the intermediate-depth events, on the other hand, show a noticeable contribution from the upper mantle anisotropy and are characterized by a complex pattern having NW, NE and EW fast directions beneath Kanto, which might be produced by complex corner flows induced by both the NNW Pacific plate subduction and the oblique NNW PHS slab subduction, with the associated olivine LPO. These various results encourage us to re-examine the seismic anisotropy structure beneath the central and southwestern Japan subduction zone from local earthquakes occurring in the Pacific slab.

In this study, we use direct S-wave splitting observations from earthquakes that originate in the subducting Pacific plate to constrain crustal and upper mantle anisotropy beneath central and southwest Japan (Fig. 1). The Pacific plate is subducting beneath central and northeastern Japan along the Japan–Izu–Bonin trenches, while the young PHS plate is subducting to the northwest beneath southwest Japan along the Nankai Trough (Seno et al., 1993, 1996). The Izu Peninsula on the PHS plate is colliding with central Japan (Matsuda, 1978). Active arc volcanoes form a distinct volcanic front in Hokkaido–northern Honshu and Kyushu, and are associated with the subduction of the Pacific and the PHS plates (Fig. 1). Quaternary volcanoes also exist along the coast of the Sea of Japan of southwest Honshu (Yokoyama et al., 1987). This region offers a good opportunity to investigate seismic anisotropy within an active convergent margin, upon which patterns of mantle strain can be inferred and constraints on mantle dynamics can be placed.

2. Data and methods

We utilize data from the F-net (Fig. 2); a network of 82 broadband seismic stations that is administered by the Japanese National Research Institute for Earth Sciences and Disaster Prevention (NIED). This seismic network was installed in or before 2001 and was collectively known as the FREESIA array (e.g., Fukuyama et al., 1998; Okada et al., 2004). We have processed data for a subset of 42 stations of the F-net array which are located in the present study area. F-net data are made available at the website by NIED (www.fnet.bosaisi.go.jp). Despite relatively high levels of cultural noise in Japan and the proximity of many F-net stations to the ocean, the data quality of F-net stations is generally very high. Coverage of F-net seismic stations is particularly good in Kanto, Izu–Tokai, and Kii Peninsula regions, but relatively sparse near the Japan Sea coast and in the westernmost part of the study area (Fig. 2). We analyze local S phases from shallow, intermediate, and deep slab earthquakes with M > 3.0 that occurred from January 2000 to September 2006 in the subducting Pacific plate beneath central and southwest Japan. A map of the 198 events used in this study both in plan view and in a cross-section is shown in Fig. 3. There is abundant intermediate-depth seismicity beneath the Kanto–Izu, and the Tokai–Kii Peninsula regions. Because both the Pacific and PHS plates subduct underneath the Kanto region, causing complex seismic activities in the upper mantle (e.g., Noguchi, 1998; Hori, 2006), some shallow events in this region might also occur in the subducting PHS slab (Hori, 2006; see also Salah et al., 2008). These possible events are excluded from the present analysis.
Fig. 1. (a) Distribution of the active and Quaternary volcanoes (solid and open triangles, respectively) on the Japan islands. Curved lines show the trenches, which represent the major plate boundaries around the Japanese region with triangles in the side of the subducting plate. Names of major districts are shown. (b) Index map of the Japanese islands showing the relative plate motions (Seno et al., 1993, 1996).

We apply a four-pole Butterworth band-pass filter with corner frequencies at 0.01 and 1.00 Hz to the waveform data, and window around the direct S phase. Records were visually inspected for high signal/noise ratio and waveform clarity. We restrict our analysis to ray paths with free surface incident angles of 35° or less to avoid contamination of particle motions by converted phases (Nuttli, 1961; Evans, 1984). This is a serious restriction in obtaining a complete coverage for the shear wave analysis. Nevertheless, we could obtain quite good data coverage in many regions such as Kanto, Izu, Tokai, and Kii Peninsula owing to the presence of many seismic stations and the intense seismic activity. Throughout the analysis scheme, we examine more than 6000 seismograms, and exclude those which do not meet the above criteria. This process limits the number of measurements to 980 good-quality splitting parameter pairs (fast polarization direction and delay time).

In order to determine the shear wave splitting parameters $\varphi$ and $\tau$ (the polarization direction of the fast shear wave arrival in degrees and the time separation between the two orthogonal components in seconds, respectively), we use the cross-correlation method (e.g.,

Fig. 2. Geographical distribution of the 42 F-net seismic stations (solid circles) used in the present study. Three capital letters beside each symbol denote the station code.

Fig. 3. (a) Epicentral distribution of the 198 events used in this study shown as circles. Event symbols vary in color according to focal depth and in size according to magnitude. (b) Cross-sectional view of the used events along the longitude direction.
Fig. 4. An example of seismograms of a deep earthquake observed at station SGN in the north of Izu Peninsula. Hypocentral parameters are shown above the seismograms. (a) and (b) are the observed NS and EW components, respectively. (c) and (d) are the N115°E slow component and the N205°E fast components, respectively. Note how this rotation angle along with a time shift of 0.25 s (delay time) produces similar waveforms in (c) and (d) compared to those at (a) and (b). (e) Original particle motion for the time window shown in (a) and (b). (f) Particle motion for the time window in (c) and (d) corrected by removing the splitting effects. Obtained fast direction and delay time in this example are N25°E and 0.25 s, respectively.

Fučko, 1984; Okada et al., 1995; Nakajima and Hasegawa, 2004, and others). This simple method yields an estimate of $\phi$ and $\tau$ from the two horizontal components of a single seismogram. Two horizontal components of observed seismograms of shear wave arrivals are rotated stepwise in a horizontal plane with angles from 1° to 178° with an interval of 3° for a specific time window centered on the S-wave arrival. The time window selected is taken to be nearly equal to 1–2 cycles of the wave (Okada et al., 1995). The delay time $\tau$ and the fast polarization azimuth $\phi$ which yield the maximum correlation are taken to be the best measurements of the time delay and the axis of symmetry (fast axis) of the anisotropic medium, respectively. The obtained polarization direction and delay time for each seismogram are checked as follow. Anisotropy-corrected seismograms are obtained by a clockwise rotation $\phi$ and a relative time shift $\tau$. In the absence of anisotropy the particle orbit is expected to be linear. After passing through an anisotropic medium, the particle motion would start with a movement along the polarization azimuth of the maximum velocity phase and end with a movement along the azimuth of the minimum velocity phase. The particle motion in that case is expected to be approximately elliptical for a long-lasting signal. Appropriate rotation and time shift will resolve the S-wave into two orthogonally polarized phases whose waveforms are similar to each other, and hence would show a linear orbit, which is expected from the source mechanism, in the resultant particle motion diagram (Figs. 4 and 5). The data showing linear orbits obtained from anisotropy-corrected seismograms are used to exclude artificial results of waveforms contaminated by noise.

3. Splitting results
3.1. Splitting patterns at selected stations

In Fig. 6, in an attempt to detect any tendency for events from a specific region around each station to have particular fast directions, we plot the splitting data (the fast polarization directions and delay times) against the backazimuth (the horizontal direction measured from north from a receiver to the epicenter of an earthquake) for 21 representative seismic stations in Kanto, Izu Peninsula, Tokai, Chubu, Kii Peninsula, and the eastern part of Shikoku. Fig. 7 shows the rose diagrams of the data obtained at 24
Fig. 6. (a–u) Plots of fast polarization directions (left) and delay times (right) vs. backazimuth for data observed at some F-net seismic stations. At some stations (such as ABU, KIS, and ISI) a characteristic pattern is observed; while at others (such as NAA, TTO, and WTR), a wide range of fast polarization directions is seen. Delay times have also a wide range of variations.
stations. Because of the intense seismic activity in Kanto–Izu and in Tokai–Kii Peninsula as well as the relatively dense seismic stations in these areas, we are able to characterize the splitting pattern in good detail. It is obvious from a visual inspection of Figs. 6 and 7, that a wide range of splitting behavior is observed at F-net stations.

At stations TYM, ONS, and ASI which are located in the Kanto district (inset maps in Fig. 6), there is no clear systematic pattern in the fast polarization directions with respect to the backazimuth. However, the dominant direction is NW–SE especially from events located to the south and the southwest. NNE–SSW fast polarization directions are also observed at station ONS which are located in the center of the land area near the volcanic front. Delay times at these stations are intermediate and do not exceed 0.7 s for the majority of the data.

In Izu Peninsula, the dominant fast directions at station FUJ are NW–SE, although minor NE–SW fast directions are also seen (Figs. 6 and 7). At JIZ, fast directions are diverse from E–W to N–S, with some NE–SW fast directions. Further inland, station SGN also shows dominantly NW–SE fast polarization directions. Delay times are generally variable and sometimes reach more than 1.0 s, especially for the data from events located to the southwest (Fig. 6). In the Tokai region, we see a predominance of the NW–SE fast polarization directions at stations located in the southern part (OHS, KNY, and TNR) for data from events located to the south and southwest.
Fig. 6. On the other hand, WNW–ESE to E–W fast directions are seen at stations located landward in Tokai (NAA, KNM, TTO, and KFU). Stations WJM and SRN on the coast of the Sea of Japan show predominantly N–S fast polarization directions. Delay times vary considerably and sometimes reach 1.4 s for some data.

In the Chubu district, the prominent fast polarization directions near Lake Biwa are NE–SW (stations ABU and TGA). Some WNW–ESE fast directions are also seen for data from events located to the south and northwest for TGA (Fig. 6). The latter direction is more visible at station YAS along the coast of the Sea of Japan (Fig. 7). Delay times are generally variable except for YAS (Fig. 6).

Fast polarization directions in Kii Peninsula and eastern Shikoku are generally variable. However, it is easy to see that the NE–SW and NW–SE fast directions at stations KIS and ISI are dominant in Kii peninsula and eastern Shikoku and Chugoku (Fig. 7). Although the data in this region is generated by deep events in the Pacific plate, most delay times are generally small.

It is clear from the above description that at most stations anisotropy does exist, although the backazimuths are sometimes limited to definite directions due to the event-station geometry. It seems, at this point, that the anisotropy observed beneath central and southwestern Japan has significant spatial variations owing to various factors that affect the shear wave splitting in subduction zones.

3.2. Spatial variations in splitting results

We plot the geographical distributions of shear wave splitting in map view in Fig. 8a and b. The fast polarization directions are plotted at the station locations as bars whose lengths are scaled by
the delay time. In these maps, we notice significant variations in the character of splitting behavior from station to station implying that at least some of the observed splitting has a shallow origin.

The stations in Kanto, Izu, and eastern Tokai show prominently two fast polarization directions: NW–SE and NE–SW. The former is, however, more developed than the latter especially in Izu Peninsula and Tokai regions (Fig. 8a). Moving westward to Kii Peninsula and Lake Biwa regions, the predominant fast polarization direction is NE–SW (Fig. 8b). In Shikoku and Chugoku regions, the number of stations having reliable observations is too few to judge any major orientation of the fast polarization directions. This larger variation in splitting behavior in Kanto–Tokai regions could be due to the complex tectonic setting in these regions as both the Pacific and PHS plates overlap each other and subduct beneath this region (e.g., Noguchi, 1998; Hori, 2006).

In order to get more consistent fast polarization directions for a proper interpretation, we define the main- and sub-fast directions (MFD) and (SFD) for each rose diagram (like those of Fig. 7) in the same way as Nakajima and Hasegawa (2004). A window with an angle of $30^\circ$ is set in a rose diagram and is gradually shifted by an interval of $15^\circ$. The frequency of fast directions in each window is calculated, and the central direction of the window with the maximum frequency of fast directions is selected as an MFD at the station. An SFD at each station is also calculated in the same manner, but a central direction of the window with the second maximum frequency of fast directions is selected. The obtained MFD and SFD are, respectively, indicated by thick and thin black lines in Fig. 9.
Except at a few locations near the volcanic front and in Shikoku, the MFD and SFD for the majority of stations show approximately similar trends. In the Kanto–Izu–Tokai area, the major fast polarization direction is NW–SE with some scatters in the central part of the land area. In the southwestern part of Japan, the distribution of MFD and SFD, however, shows less scatter and mainly have NE–SW fast directions. A striking feature in Fig. 9 is the consistent NW–SE fast polarization direction in the Tokai area along the coast of the Pacific Ocean. In general, these results are consistent with those obtained by Long and van der Hilst (2005), although they used different data sets such as the teleseismic S, SKS, and SKKS phases.

4. Discussion

4.1. Observed splitting in the Kanto area

The majority of the selected events in the Kanto area east of longitude ~139.5–140° E are shallower than 70 km. Therefore, paths from events in this region travel primarily through the subducting slabs and the overlying crust and largely miss the mantle wedge (Fig. 3b). Observed splitting times are generally low, being around 0.1–0.2 s. Consequently, the observed weak splitting in this region is mainly of crustal origin with probably minor contributions from slab anisotropy.
Many fast polarization directions in the Kanto area are oriented more or less WNW–ESE which are sub-parallel to the subduction direction of the Pacific plate. In addition, some fast directions are oriented NNE–SSW, which are parallel to the Japan Trench. Hence, both convergence-parallel and convergence-perpendicular fast directions are simultaneously observed. Iidaka and Obara (1995) detected a weak seismic anisotropy in this region (east of the volcanic front) from a large deep earthquake beneath Sakhalin Island with NE–SW and NW–SE main fast directions.

Salah et al. (2008) in their study of the mantle wedge anisotropy above the subducting PHS slab, observed NE–SW, NW–SE, and E–W fast polarization directions from shallow and intermediate-depth events occurring in the PHS and Pacific slabs in the Kanto area recorded at the Hi-net seismic stations. The area they studied corresponds to the shallower portion of the wedge above the PHS and Pacific slabs. The pattern of the fast polarization directions is similar, however, to that shown in Fig. 8a. On the other hand, the splitting times they obtained fall in the range 0.1–0.3 s, which are small compared to those observed in this study.

4.2. Observed splitting in southwest Japan

Fast polarization directions in southwest Japan are mainly oriented NW–SE in Izu–Tokai and ENE–WSW in the Kii Peninsula and the Chubu districts. The former is sub-parallel to the subduction direction of the Pacific plate, whereas the latter is oblique to the subduction direction and may even be closer to the direction perpendicular to the subduction direction. Moreover, it is rather
close to the strike of the Nankai Trough. Fouch and Fischer (1996) detected a similar pattern in central Honshu, where WNW–ESE fast polarization directions in the Tokai region are clearly recognized (Fig. 10). Similar splitting patterns in southwest Japan have also been reported by Long and van der Hilst (2005) using teleseismic data. Salah et al. (2008) observed NW–SE and NE–SW fast directions in the wedge above the PHS slab. The splitting times are less than 0.4 s, which are smaller than those observed in this study.

### 4.3. Interpretation

In subduction zones, anisotropy may occur in the crust, the down-going slab, or the region between the upper slab surface and the Moho, which is called the mantle wedge. Fig. 11 illustrates the relation between splitting times and focal depths of the studied events. There is a slight tendency of increased splitting times for the deep (350–400-km depth) events. However, the correlation...
Fig. 7. Examples of rose diagrams of the observed fast polarization directions at some selected F-net seismic stations in central and southwest Japan. Three capital letters above each rose diagram denote the station code. Two digits to the lower right indicate the number of observations, and the average delay time in seconds, respectively.
Fig. 7. (Continued).
Fig. 8. Splitting vectors for all observed data plotted at the station locations (small open circles) in Kanto–Izu-E. Tokai (a) and in W. Tokai and SW Japan (b). The major plate boundaries and the distribution of active and Quaternary volcanoes are shown. The direction of a bar indicates the fast polarization direction and its length is scaled to the delay time. A bar with a delay time of 0.50 s is shown to the upper right in (a) and in the lower right in (b).

Fig. 9. Distribution of main- and sub-fast directions (MFD and SFD) at each station shown by thick and thin black bars, respectively (see text for details). Length of each thin bar is normalized relative to the frequency of MFD. Solid and open triangles denote active and Quaternary volcanoes. Thin and thick curved lines show major plate boundaries around Japan, and the volcanic front, respectively.

Fig. 10. Observed fast directions ($\phi$) and splitting times ($\tau$) of Fouch and Fischer (1996) around Japan from local S phases generated by events with focal depths of 150–430 km plotted at the midpoint of the source-receiver path. Dark and light lines bisected by arrows represent the 95% confidence limits for both $\phi$ and $\tau$. Crosses show hypocenters and the black symbols denote station locations. Large vector denotes the direction of absolute Pacific plate motion (Gripp and Jordon, 1990). Note that some fast directions are parallel to the Japan Trench, while others are parallel to the Pacific plate subduction direction.
The present study shows the N–S, E–W and NW fast directions in the northern, central and Tokai regions of central Honshu. Ando et al. (1983), using data from intermediate-depth and deep earthquakes, detected north and east fast polarization directions in the wedge portion of the upper mantle in the northern and central parts of central Honshu, respectively. A similar pattern of ~N–S fast directions in the northern region and ~E–W fast directions in the central region of central Honshu, have also been detected by Hiramatsu et al. (1998) using waveforms generated from local deep earthquakes in the region. Fouch and Fischer (1996) also found a similar pattern in central Honshu. Moreover, they found WNW–ESE fast polarization directions in the Tokai region (Fig. 10). We found many similarities between these studies and our results. The pattern of the fast directions in Tokai in central Honshu is more or less parallel to the Pacific plate subduction direction (Fig. 1b). On the other hand, the N–S fast direction in the northern part of central Honshu is perpendicular to this direction. Even if the NW–SE fast directions in Tokai are consistent with the Olivine A-fabric associated with the flow induced by the Pacific plate subduction, it is obviously difficult to interpret the N–S fast directions by the Olivine B-fabric because in such a deep portion of the mantle wedge the temperature is higher and the stress is lower.

Another way to explain the trench-parallel fast directions in northern central Honshu might be flow in the wedge turned around from the slab edge due to slab rollback, which has been proposed in other regions and on the basis of laboratory or numerical experiments (Russo and Silver, 1994; Butterles and Olsen, 1998; Kincaid and Griffiths, 2003; Schellart, 2004; Stegman et al., 2006). However, in the Japan–Bonin trench system, the lateral length of the Pacific slab is very large and, accordingly, no flow would be expected to turn around. Furthermore, the Pacific slab is not retreating but advancing (e.g., Schellart et al., 2007). The advancing slab would produce a flow in the wedge directed SE along the Bonin Trench trend, however, which is not consistent with the N–S fast directions. Recently, it has been observed that curved 3D geometry of the slab with fixed trench shows stretching of the wedge in the direction parallel to the trench, resulting in fast polarization directions in this direction (Kneller and van Keken, 2007). Because the slab subducting beneath the junction between the Japan and Bonin Trenches has a curved shape, this could be a possible mechanism for the trench-parallel fast direction beneath northern central Honshu. However, we have to await future more detailed studies to conclude this.

5. Conclusions

We investigate shear wave splitting in direct S phases from local events recorded by the Japanese broadband F-net seismic stations. We obtain 980 splitting parameter pairs (fast polarization direction and delay time) for central and southwestern Japan. The measured splitting pattern is generally complicated beneath Kanto. However, dominant fast polarization directions of shear waves obtained at most stations in the Kanto area are oriented WNW–ESE, which are sub-parallel to the subduction direction of the Pacific plate. Fast directions are also seen in the NE–SW and E–W fast directions are simultaneously observed. This indicates that the flow beneath this region is more complex, which may be explained by the subduction of the PHS slab. These may originate from flow below the PHS slab, but the pattern of such flow induced by the WNW Pacific slab subduction would not be a simple one.

The general tendency of increasing delay times with the increase of source depth can be seen.

From the splitting maps (Figs. 8 and 9), we have seen that fast directions in Kanto area are oriented either parallel to the Pacific plate subduction direction or sub-parallel to the Japan Trench. The NW–SE fast directions seen in the Kanto region are consistent with the flow induced by the subduction of the Pacific slab, if the olivine A-fabric is aligned in the flow direction. However, the NE–SW and E–W fast directions are simultaneously observed. This indicates that the flow beneath this region is more complex, which may be explained by the oblique subduction of the PHS slab in the NNW direction, as discussed by Salah et al. (2008). For example, the corner flow predicted due to this oblique subduction is trench-normal (i.e., NE) in the shallow portion of the wedge and trench-parallel (i.e., NW) in the deeper portion.

The observed ENE fast directions beneath Kii Peninsula and southwest Japan are difficult to explain by the flow induced by the Pacific plate subduction (Fig. 1b). They are neither parallel nor perpendicular to the subduction direction. Long and van der Hilst (2005) also found similar directions in this area. They are rather parallel to the Nankai Trough, and similar to that observed in the wedge above the PHS slab (Salah et al., 2008), suggesting that this is partly caused by the B-type olivine fabric induced by the subduction of the PHS slab. However, the splitting times of Salah et al. (2008) are only around 30–50% of those observed in the present study, thus not all the anisotropy can be explained by the subduction of the PHS slab. These may originate from flow below the PHS slab, but the pattern of such flow induced by the WNW Pacific slab subduction would not be a simple one.
2008), and the remaining would be due to the flow beneath the PHS slab and above the Pacific slab. The nature of this flow might not be as simple as expected from the corner flow induced by the Pacific plate subduction.

The N-S, E-W, and NW fast directions seen in northern, central, and southern (Tokai) regions of central Honshu are consistent with the previous studies. Although the NW fast directions in Tokai might be explained by the olivine A-fabric induced by the corner flow of the Pacific plate subduction, as in Kanto, it is difficult to explain the N-S direction in central Honshu by a simple flow pattern in the mantle wedge. The lateral flow in the wedge due to slab migration (e.g., Schellart, 2004) seems unlikely to explain the observed fast directions. The effect of the curved slab to the stretching of the wedge (Kneller, 2007) is one possibility to explain the anisotropy because the slab is curved at the Japan-Bonin Trench junction. Further detailed shear wave splitting observations at much denser seismic networks beneath central and southwestern Japan are necessary for a better understanding of the anisotropy structure and its relation with tectonics and the stress state and induced mantle flow of the wedge.

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References


Hori, S., 2006. Seismic activity associated with the subducing motion of the Philippine Sea plate subside beneath the Kanto district, Japan. Tectonophysics 417, 85–100.


