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THE STUDY OF ANISOTROPY IN THE SUBDUCTION ZONES AROUND JAPAN

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Seismic anisotropy is one of the most important keys to understand the interior of the Earth. Most of the minerals constituting the Earth show the elastic anisotropy in those stiffness tensors. Each of the major minerals in the upper mantle, especially olivine, has specified crystal structures inherent of it. The velocity of seismic waves, therefore, is anisotropic. Seismic anisotropy is also induced by aligned cracks in originally isotropic media. The orientation is mainly controlled by stress. The preferred orientation of the anisotropic minerals and cracks in an elastic body generates the anisotropic component of the stiffness tensor of an elastic body. Seismic anisotropy tells us the important fact on the dynamics on the deformation or stress state and the tectonics related on the plate motion.

Plastic and viscous flow is the dominant mechanism orienting minerals systematically and cause the velocity anisotropy of their aggregates. In a plastic field, crystals are deformed principally by the dislocation slip. For olivine simple slip systems occur and allow significant preferred orientations to be developed. Seismic anisotropy in the upper mantle is generally considered due primary to the deformation-induced lattice preferred orientation of olivine crystals. The dislocation creeps seem to play the most important role under the upper mantle condition, at the high strains associated with the flow near ridges and subduction zones [Ribe, 1989]. The dynamic recrystallization is also important together with intracrystalline slip, in generating preferred orientation in the mantle. In plastically deformed aggregates olivine tends to be oriented with the [010] direction parallel to the flow plane and with [100] parallel to the flow line. The preferred orientation of olivine can be extremely strong due to enhanced diffusion and grain boundary mobility selecting the favorably oriented grains at very high temperatures [Nicolas and Christensen, 1987]. Such favorable conditions and the existence of a simple slip system in olivine cause a significant elastic anisotropy of olivine-rich ultramafic rocks.

Kumazawa and Anderson [1969] reported stiffness tensor components of olivine. A single crystal olivine shows a large anisotropy of 25% and 22% for P and S velocities, respectively. The P wave with maximum velocity propagates along a-axis or [100] of the crystallographic axes. The anisotropy of S waves propagating along b- and c-axes, say [010] and [001], reaches 10% whereas along a-axis it is practically zero. The transformation to the β-phase under conditions of 400-km discontinuity, approximately at 13 GPa and 1400°C [Jeanloz and Thompson, 1983], lets a density and average velocities of P and S waves increase. While the velocity anisotropy of S waves does not virtually change after the transformation, the anisotropy of P wave velocity drops from 24% to 17% [Weidner et al., 1984]. The β-phase to γ-phase transformation only leads to an insignificant change of density and velocities of P and S waves, while the anisotropy drops about 4% to 8%, respectively [Weidner et al., 1984].

Hess [1964] firstly pointed out the existence of anisotropy, about 7%, in the uppermost mantle in the northeastern Pacific from the observations of azimuthal variation in Pn velocity. The fastest direction of Pn velocities was parallel to trends of fracture zones and the slowest direction was parallel to magnetic lineation. He suggested that the preferred orientation of olivine crystals caused anisotropy. Morris et al. [1969] showed clear evidence of azimuthal dependence of Pn-wave velocities in the upermost mantle near Hawaii. Similar observations were compiled by Christensen [1984]. The azimuthal anisotropy of Pn velocities in the oceanic lithosphere ranges from 3% to 10% with the direction of the fastest velocity oriented parallel to the fossil plate motion. He showed the dominant preferred orientation occurs for olivine and pyroxene with the orthorhombic symmetry in ophiolite. That is, a-axis of olivine and c-axis of pyroxene are oriented along the spreading direction and b-axis of olivine and a-axis of pyroxene are oriented vertically. The overall property of ophiolite, therefore, shows that the fastest velocity of P wave is along the spreading direction.

In surface waves the same results are obtained. For example, Montagner and Tanimoto [1990] showed the three-dimensional variations of anisotropic parameters inverting a large set of Love and Rayleigh wave dispersion curves using fundamental mode data in the period range 70 to 250 s. The fast direction of Rayleigh waves coincides well with the direction of the absolute plate motion, which is interpreted that the preferred orientation of olivine crystals causes the observed anisotropy in the upper mantle.

Nishimura and Forsyth [1989] showed the depth variation of the 2ϕ azimuthal anisotropic term $G_c=(C_{55}-C_{44})$ for two regions in the Pacific. They found that the fast direction was parallel to the direction of the current plate motion for the younger regions (< 80 Ma) and parallel to that of the fossil plate motion for the older regions (≥ 80 Ma).

Strong trade off exists between anisotropy and heterogeneity. Travel time analyses get into this danger. For example, Beghoul and Barazangi [1990] reported the azimuthal anisotropy beneath Basin and Range province using Pn waves. Zhao [1993] analyzed travel time data of Pn waves in the same area. He, however, concluded that the azimuthal variations in Pn velocities are apparent due to the lateral heterogeneities and mantle velocity gradient and that the mantle beneath this region is isotropic.

Even in the case of weak anisotropy, very drastic changes in the basic properties of the seismic wavefield can appear. The most obvious phenomena is the behavior of shear wave polarization in anisotropic media. In an anisotropic medium shear waves split into the two orthogonal waves, quasi-sear waves, with different velocities.
The anisotropic effect is also found in waveforms of surface waves. The significant waveform anomalies in long period surface waves, $f < 15$ mHz, are caused by lateral variations in azimuthal anisotropy, as a result of coupling between fundamental branch Rayleigh and Love waves.

The detection of Shear wave splitting however, was about 15 years late in comparison with P wave azimuthal anisotropy. Ando et al. [1980] firstly reported shear wave splitting using S waves from intermediate and deep earthquakes beneath volcanic area in central Japan. Since then many researchers have reported shear wave splitting using S, ScS and SKS waves. S wave polarization is strongly distorted only if the incidence angle is larger than the critical angle at the free surface [e.g. Evans, 1984]. This critical angle is close to 35° for a normal Poisson ratio of 0.25. Sear waves with nearly vertical incident angle are generally analyzed for shear wave splitting study. Restricting combination of sources and receivers allows us to analyze S and ScS wave splitting in subduction zones and SKS waves in continents.

In continental regions SKS waves of teleseismic events arrive at nearly vertical incidence and are useful to detect shear wave splitting. Silver and Chang [1991] measured shear wave splitting in the phases SKS and SKKS at 21 broadband stations in North America, South America, Europe, Asia, and Africa. They found the most recent significant episode of internal deformation of the subcontinental upper mantle appears to be the best predictor of the direction of fast polarized wave and a good correlation between delay time and lithospheric thickness. From these observations they concluded that anisotropy is caused by deformation and frozen in the lithosphere of subcontinental upper mantle. On the other hand Vinnik et al. [1992] compiled the observations of SKS wave splitting globally. They pointed that the global distribution of the direction of fast polarized waves has the peak which is parallel to the current absolute plate motion. They concluded that anisotropy is formed by the present mantle flow in asthenosphere due to current plate motion. This trend, however, concentrated in small region, especially in North America and the number of observation is relatively large in this region. Further researches are needed to resolve the location and cause of anisotropy beneath continents.

In subduction zones direct S waves of nearby intermediate or deep event are useful for shear wave splitting study. Ando et al. [1983] revealed two anisotropic regions beneath central Honshu, Japan and suggested that the cause of anisotropy was the preferred alignment of cracks or the preferred orientation of olivine in the mantle wedge from the observations of S wave splitting of 26 intermediate and deep earthquakes at local 14 stations. Bowman and Ando [1987] revealed S wave splitting in Fiji. The direction of the fast polarized waves is consistent with the extension direction of Lau Basin and South Fiji Basin. Xie [1992] observed S wave splitting with faster arriving of E-W and time delays of 0.1 to 0.4 s from intermediate events underneath Guam. ScS waves are S waves reflected at core-mantle boundary. Fukao [1984] observed a uniform NNW-SSE direction of the fast polarized waves with the average arrival time difference 0.8±0.4 s between the two polarized waves at 20 stations of the Japan meteorological agency using ScS wave splitting from a deep earthquake beneath the sea of Okhotsk. He proposed that anisotropy resides in the descending slab of lithosphere with olivine crystals whose a-axes are aligned in the NNW-SSE direction. Ando [1984] analyzed short period seismograms of intermediate and deep earthquakes recorded at 24 stations of WWSSN (World-Wide Standardized Seismograph Network) around the Pacific ocean. The direction of fast polarized waves is generally parallel to the plate motion near the station. The average arrival time difference is 1.0±0.4 s. Assuming 4% velocity difference, the thickness of anisotropic layer is estimated to be 100 km.

Recently combining the results of SKS, SKKS and direct S of teleseismic events, it has become possible to investigate anisotropy not only beneath receivers but also around sources. Kaneshima and Silver [1992] reported anisotropy occupying the source side in the subduction zones of the Nazca plate beneath South America and the Pacific plate beneath Kamchatka assuming S waves pass through two anisotropic layers in the upper mantle, one is around source and another beneath receiver. Removing anisotropy beneath receivers reported by Silver and Chan [1991] they found the time delays between the two splitted waves are 1.0 s to 1.5 s in each region, where the polarization direction of the fast wave is perpendicular to the trench. Russo and Silver [1994] observed the trench parallel fast polarization in South America and proposed the trench parallel flow attributed by retrograde motion of the subducting slab exists beneath the Nazca plate.

The formation of anisotropy is usually discussed in the view of global plate tectonics from the consistency between the fast direction and the direction of the plate motion. Is global modeling for the formation of anisotropy valid for all situations? The answer is "No". Our detail mapping of shear wave splitting shows the regional variation of anisotropy in lateral and vertical in subduction zones around Japan and fails to be interpreted in terms of "global anisotropy".

Furthermore most of the previous works conclude that seismic anisotropy in the upper mantle is caused by the preferred orientation of olivine. But this is the reflection of the restricted observation. SKS wave splitting studies in continental regions does not seem to tell us the information of anisotropy in deeper part of the upper mantle.
In subduction zones we have some merits in comparison with in continental regions: (1) large shear strain is caused by subduction to the depth of 650 km. We, therefore, expect

the preferred orientation of β- or γ-spinel besides olivine. (2) We can use various source depths. It is easy to find the difference of anisotropy with depth.

The main theme of this thesis is to acquire what occurs in subduction zones through seismic anisotropy lighted up by mainly shear wave splitting. In this thesis we perform the study of seismic anisotropy using shear wave splitting, which is the most dramatic property we can see in the waveform. Shear wave splitting has high resolution of the lateral variation of anisotropy because of the observation using rays with vertical incident angle. On the contrary it is usually difficult to estimate the vertical variation, in other words the location of an anisotropic region on a raypath. Moreover we cannot distinguish the trade off between the scale and the degree of anisotropy if the spatial coverage of raypaths is weak or we have no *a priori* information on its scale or degree. Our study is characterized by the quantity of data. To enhance the spatial resolution of the distribution of anisotropy we try to analyze as many kind of data as we can utilize now. These data are originally recorded on papers, magnet tape and MO diskettes and have been changing the recording as the time come later. We convert the analog data to the digital data by hand digitizing and using the A/D converter. The quality of hand digitized data is lower than that of A/D converted data.

We have four reports in this thesis entitled (1) Three-dimensional image of the anisotropic bodies beneath the central Japan, (2) Seismic anisotropy near source regions in subduction zones around Japan, (3) ScS wave splitting of deep earthquakes around Japan, and (4) Attenuation anisotropy beneath the subduction zones in Japan. Following is brief introduction of each paper.

In paper (1), we construct the three-dimensional image of the "historical" anisotropic bodies beneath the central Japan using a large number of data recorded at telemetering networks for micro-earthquake observation. The size of the anisotropic body is $0.75° \times 0.5° \times 75$ km in northern part and $1.25° \times 1.25° \times 100$ km in southern part and the depth of the former is shallower than that of the latter. The size of former is close to that of the mantle diapir with a diameter of 50 km predicted by petrological study. Considering the relation with the location of the volcanoes, the elevation high, the velocity and Q structure in the mantle wedge we consider the anisotropic body is the region of the preferred alignment of cracks filled with melt.

In paper (2) we remove the ambiguity of the contribution of anisotropy beneath the receiver, which makes it difficult to estimate exactly ScS data alone, using the broad-band data installed in the late 1980's at seven receivers in Honshu, Japan. Comparing S wave splitting beneath the receiver in the central Japan with ScS wave splitting of deep events around Japan, we separate the observed ScS wave splitting into the one beneath receivers and around sources. We estimate the existence of anisotropy beneath some receivers at the same time. The results are consistent with those of paper (3), giving us more detailed anisotropic structure in the subducting slab. The anisotropic regions are distributed non-uniformly in the slab, like patch with a diameter of 100 km. Furthermore we emphasize the preferred orientation of not only olivine but also spinel is the cause of seismic anisotropy below 400 km. The phase transformation olivine to β-spinel can change anisotropy in the slab.

In paper (3), we analyze ScS wave splitting of five deep events around Japan using the hand digitizing data at Japan Meteorological Agency's stations all over Japan. We observe a uniform splitting widely over Japan for an event and clearly find discrepancies of splitting parameter over Japan among each event. The change in ϕ depending on the source depth is also recognized. We suggest that there is no uniform anisotropy widely beneath Japan and the observed ScS wave splitting is dominantly caused by anisotropy within the subducting slab. The thickness of anisotropic region, therefore, is estimated about 100 km, which is large enough to generate the observed δt under the assumption 5 % anisotropy. No or less anisotropy beneath Japan revealed by both paper (2) and paper (3) is consistent with the local distribution of strong anisotropic regions in the mantle wedge reported by paper (1).

The paper (4) is somewhat strange research in comparison with the above works. Seismic anisotropy means generally "the velocity anisotropy". However we propose "the attenuation anisotropy" here. The observation of multiple ScS waves from the 1990 Sakhalin event reveals us the systematic rotation, from NW-SE to N-S, in the principle axis of those particle motion of the horizontal components. The spectral analysis of ScS_1 and ScS_2 phases clearly shows us Q_{NS} is larger than Q_{EW}, in other words, ScS waves attenuate larger in E-W direction rather than N-S direction. We suggest that the attenuation anisotropy is caused by the N-S trending upwelling flow in the mantle wedge related from the magma origin of the island arc volcanoes by petrology.

Throughout these works, we showed simple two-dimensional mantle flow accompanied with the subduction of slab, widely accepted as the cause of anisotropy, cannot explain the complex pattern of anisotropy in subduction zones. Moreover we show spinel is effective anisotropic as an origin of shear wave splitting although the preferred orientation of olivine is generally treated as a unique cause of anisotropy in the upper mantle. The upwelling fluid phase in the mantle wedge or re-orientation of mantle minerals due to phase transformation within the subducting slab is an important cause of anisotropy.

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