論文の内容の要旨

論文題目 Seismic anisotropy of the oceanic lithosphere/asthenosphere system elucidated by the array analysis of surface waves
（表面波アレイ解析による海洋リソスフェア/アセノスフェアの地震波速度異方性の解明）

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I propose a new multi-band method for the "broadband ocean bottom seismology". The method utilizes seismic surface waves at periods of 3-100 s recorded by arrays of seafloor instruments. The measured phase velocities are inverted for obtaining one-dimensional anisotropic structure beneath the array including its uncertainty.

The uppermost mantle structure beneath the oceanic basins is essential to discuss the oceanic lithosphere/asthenosphere system, the most simple and representative system of the theory of plate tectonics. Seismic anisotropy within the oceanic lithosphere and asthenosphere is especially important, as it reflects the flow and deformation in the uppermost mantle. Previous structural studies have been, however, limited in terms of the depth range: the top of lithosphere at depths of ~10-20 km by refraction surveys, and the structure at depths deeper than ~30 km by surface-wave tomography studies. There has been no discussion from the top of the lithosphere continuously to the asthenosphere, which needs the broadband analysis of surface waves at periods of 3-100 s. In addition, there has been limited discussion about the intensity of seismic anisotropy because of the difficulty of estimating the absolute value of seismic anisotropy by surface-wave tomography studies.

I analyzed seafloor records quantitatively to discuss the anisotropic structure in the oceanic lithosphere and asthenosphere beneath five oceanic regions: the Shikoku Basin, French Polynesia, northwest Shatsky, southeast Shatsky and southwest Shatsky regions. The datasets are those obtained by the 1-3 years deployment of the broadband ocean bottom seismometers and the differential pressure gauges at 7-11 stations in each region from 2005 to 2013.

I first developed methods to analyze broadband surface waves in seafloor records by improving existing array-analysis methods: the ambient noise cross-correlation analysis at periods of 3-30 s, and the teleseismic surface-wave array analysis at periods of 30-100 s. There were many improvements especially for the ambient noise cross-correlation analysis including the estimation of the clock delay and instrumental responses, the simultaneous estimation of the average phase velocities of multi-mode surface waves by developing a waveform fitting method, and the correction for the effects of water-depth and source heterogeneity to the phase-velocity anomalies. By the overall improvement in the study, the methods became applicable to almost all broadband array records acquired in the seafloor.

By applying the method to the datasets of five oceanic regions, I could measure phase velocities of both Rayleigh and Love waves at periods of 3-100 s, and could estimate the azimuthal anisotropy of phase velocities of Rayleigh waves at periods of 5-70 s. The period range is broad compared to previous studies, and could be used to estimate radially and azimuthally anisotropic structures beneath each region at depths of ~10-150 km except for the southwest Shatsky region, where I only analyzed surface waves at periods shorter than 30 s and could constrain structures at depths shallower than ~40 km. The errors of each estimated values were carefully discussed in each measurement procedure, and also used to estimate the uncertainty of the obtained models.

The smooth radially anisotropic models were estimated after showing the insufficiency of the isotropic model and after carefully discussing the scaling relationship between anisotropic parameters. In addition, the non-smooth radially anisotropic models were estimated to compare them with the thermal models beneath oceanic basins by focusing on parameters such as the velocity gradient in the high-velocity LID and the gradient in the transition zone between the LID and the low velocity zone (LVZ). The depth of the middle of the transition zone is estimated to be thicker for the older seafloor region in the range of 40-90 km, which indicates that the LID is corresponding to the lithosphere. The velocity gradient in the LID is zero or positive and is inconsistent with the negative velocity gradient predicted by thermal models of the oceanic uppermost mantle. The discrepancy indicates the effect of phase transition to produce the apparent positive velocity gradient in the LID. The velocity gradient in the transition zone between LID and LVZ is steeper than those given by thermal models. This result invokes mechanisms for producing the velocity reduction in the transition zone, in addition to the thermal effect, such as decreasing grain size, partial melting, or the presence of water in the LVZ.

The intensity of radial anisotropy is 3%-6% with the velocity of horizontally propagating and horizontally polarized S-wave higher than that of vertically polarized S-wave ($V_{SH}>V_{SV}$). This result indicates the presence of lattice-preferred orientation of olivine crystals and/or the presence of horizontal layers or pockets of partial melts. The depth change in radial anisotropy was not required from the data.

The azimuthally anisotropic structures of V_{SV} were estimated from the azimuthal anisotropy of Rayleigh waves. Although the intensity of anisotropy depends on the region, the intensity at depths of 10-50 km was estimated to be higher (2%-6%) than the intensity at depths of 50-100 km (0%-3%). This result indicates that the viscosity is low and the shear deformation is accumulated in the top of the asthenosphere. The fastest azimuth was estimated to be NW-SE direction in the Shikoku Basin, French Polynesia and northwest Shatsky regions, whereas it was E-W in the southeast Shatsky region and was SW-NE in the southwest Shatsky region. The S-wave splitting analysis was further applied to reveal the lateral heterogeneity of azimuthal anisotropy in the French Polynesia region. The result indicates the perturbation of mantle flow by the presence of a hot plume beneath the hotspot in the French Polynesia region.

The average fastest azimuth estimated in the French Polynesia region is not perpendicular to the magnetic lineations, but is parallel to ancient plate motion, where the rate of seafloor spreading was low. On the other hand, the fastest azimuth was estimated to be perpendicular to magnetic lineations in the southwest Shatsky region, where the rate of seafloor spreading was high. The result is same in the northwest Shatsky regions, whereas it is oblique in the southeast Shatsky region, where the rate of seafloor spreading is the middle. These results indicate that the flow in the uppermost mantle is parallel to the ancient plate motion when the plate motion is fast, whereas the flow is perpendicular to the ancient mid ocean ridge when the seafloor spreading is fast. The emergence of Shatsky Rise might have also affected the mantle flow beneath the southeast Shatsky region.

The intensity of azimuthal and radial anisotropy could be directly compared for the first time in this study. The intensity of radial anisotropy higher than that of azimuthal anisotropy indicates that the anisotropy is produced by the AG-type fabric of olivine crystals and/or by the presence of layers or pockets of partial melts.

The multi-band analysis in this study proved that the broadband array analysis of surface waves contributes to estimate the radially and azimuthally anisotropic models in the uppermost mantle to discuss the structure and flow in the oceanic lithosphere/asthenosphere system. It means that this study could establish a new filed to the structural analysis in oceanic regions, the broadband ocean bottom seismology, which estimate the uppermost mantle anisotropic structure beneath oceanic regions by the broadband surface-wave analysis of seafloor records. This new field can elucidate the uppermost mantle structure at depths deeper than those by refraction surveys and the reliability higher than the surface-wave tomography studies, although the area is limited to the regions in which broadband ocean bottom seismometers were deployed. The results obtained by applying the method to current seafloor datasets invoke the needs and possibilities for future observation and analysis in other oceanic regions to reveal the universality and regionality of the oceanic lithosphere/asthenosphere system.