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学 位 論 文 内 容 の 要 旨

博士の専攻分野の名称　博士（理　学）　氏　名　　松澤 仁志

学 位 論 文 題 名
Seismic Imaging of the Upper Mantle with Multi-mode Surface Waves
Using Broadband Seismic Arrays
（広帯域地震観測網を用いたマルチモード表面波による
上部マントルの地震学的イメージング）

Seismic surface waves are powerful means to map the heterogeneity and the anisotropy in the upper mantle. The use of higher-mode surface waves is essential for enhancing the vertical resolution of seismic tomography models since they are much more sensitive to the deep structure of the Earth's mantle than the fundamental modes. However, measuring the multi-mode phase speeds is not a straightforward issue since wavetrains of different modes overlap each other in a seismogram, which cannot readily be separated.

Recently, a number of high-density broad-band seismic networks have been deployed in many continental areas. One of the most remarkable continent-wide arrays is the USArray in North America. The North American continent encompasses a variety of complex structural features, including tectonically active regions and stable cratons. The deployment of the high-density Transportable Array (USArray) across the contiguous United States has facilitated seismological studies to unravel the crust and mantle structure of the North American upper mantle. To delineate the deep root of the cratonic lithosphere and asthenosphere, the use of higher-mode surface waves is essential, although such studies have still been limited.

In this study, we have developed the two-step array-based method for higher-mode analysis, which consists of (1) multi-mode phase speed measurements based on a classical *f-k* analysis using a long-range linear array with several-thousand kilometers (e.g., Nolet, 1975) and (2) modal waveform decomposition for the centroid location of the linear array using the linear Radon transform (e.g., Luo et al., 2015). The synthetic experiments reveal that the precise measurement of multi-mode phase speeds requires a long linear array, longer than 2000–3000 km. The extracted dispersion curves well represent the weighted-average structure depending on the station distribution in a linear array. The decomposed modal waveforms at the centroid of an array match well with theoretically predicted waveforms. These decomposed waveforms can be used to perform a secondary dispersion analysis.

By applying our linear array-based method to a large data set of seismograms at USArray, we mapped phase speed distributions in North America. We could obtain reliable phase speed maps of the fundamental-mode surface waves. Although the large-scale anomalies (i.e., fast phase speeds in cratons in the stable eastern U.S., slow phase speeds in the tectonically-active western U.S.) can be identified, the lateral resolution of the phase speed maps was insufficient compared to the inter-station/array-based tomography models. This suggests that the small-scale tectonic features tend to be blurred and averaged out due to long linear arrays (2000–4000 km).

We also employed the single-station method of multi-mode dispersion measurements based on a fully nonlinear waveform fitting method (Yoshizawa and Kennett, 2002; Yoshizawa and Ekström, 2010) to extract the multi-mode phase speeds for each source-receiver path for permanent and temporary stations in

North America. These measurements are then applied to the method of eikonal tomography (Lin et al., 2009). At first, in this hybrid approach, multi-mode phase speeds for all stations from a seismic event are used to reconstruct travel-time fields by tracking the phase front for each mode and period. The phase speed distributions for each event derived from the lateral gradient of travel-time fields are stacked and averaged for all events to reconstruct final phase speed models. Our hybrid method is applied to teleseismic events ($M \geq 5.8$) from 2007 to 2015, including over 700 events for Rayleigh waves and Love waves. The contiguous United States can be covered with many single-station ray paths (e.g., over 100000 paths for the fundamental-mode Rayleigh wave at 100.0 s), which allows us to reconstruct phase speed models with 3.0°×3.0° grids.

We could successfully retrieve phase speed maps of Love and Rayleigh waves for the fundamental-mode and up to the 4th higher modes with this hybrid approach. The images of small-scale features in the U.S., such as the Snake River Plains, Colorado Plateau, and Rio Grande Rift, are well imaged in the eikonal tomography models for the fundamental mode. Some large-scale tectonic features are imaged in the higher-mode models, such as the fast anomalies related to deep cratonic root. However, the interpretation of higher-mode phase speed maps is not straightforward due to their complicated vertical sensitivities.

These multi-mode phase speed maps are then used to map a new radially anisotropic 3-D shear wave model in a wide depth range, including the continental lithosphere and asthenosphere. The multi-mode phase speed maps in a wide period range allow us to image the continental mantle to the depth of the transition zone. We can image the root of the cratonic lithosphere at around 200–250 km depth. The model of the radially anisotropic parameter ($\xi = (V_{SH}/V_{SV})^2$) have shown faster SH wave speed ($\xi > 1$) under North America at depths shallower than 100 km and faster SV wave speed ($\xi < 1$) corresponding to the slab subduction and the possible delamination of the cratonic keel at depths deeper than 250 km.