Imaging subducted slabs in the mantle through inversion of seismic waveforms

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Seismic tomographic studies (e.g., Romanowicz 2002; Dziewonski et al. 2010) have inferred the three-dimensional seismological structure of the Earth’ s deep interior. Some subducted slabs have been found to be stagnant above or below the 660 km discontinuity, while others fall through into the lower mantle and reach the core-mantle boundary (CMB) (Fukao et al. 2009), suggesting whole-mantle convection rather than layered mantle convection. Recent seismic waveform inversion studies with better resolution, especially for low velocity anomalies, have found vertically continuous low-velocity columns in the lower mantle and suggested that thermochemical plumes rooted in the D" region are associated with prominent hotspots (French and Romanowicz 2015). Hence, seismic tomographic studies have contributed much to understanding mantle convection.

It has been, however, difficult to estimate how long it takes for material in the Earth’ s mantle to migrate between the Earth’ s surface and the CMB, since seismic tomography studies provide information only on the current Earth’ s deep interior. In order to better understand the Earth’ s evolution and dynamics, dating inside the Earth is essential. Therefore, we have inferred the detailed seismic velocity structure in the mantle transition zone and D" region beneath Central America and the Northern Pacific, where continuous subduction of oceanic plates beneath the North and South American plates has been taking place since more than 200 Ma (Muller et al. 2016). We investigate the fate of subducted oceanic lithosphere and the thermal and chemical evolution of the Earth.

Waveform inversion studies

Our group’ s waveform inversion studies were conducted as follows. The events used are deep- and intermediate-focus events recorded at broadband seismic stations of the USArray, Canadian Northwest Experiment (CANOE), Global Seismographic Network (GSN-IRIS/USGS), Southern California Seismic Network (SCSN), Pacific Northwest Seismic Network (PNSN), Berkeley Digital Seismic Network (BDSN), and Canadian National Seismograph Network (CNSN). The data are filtered in the period range of 8 or 12.5 to 200 s using a Butterworth bandpass filter. The 3D model is obtained by linearized inversion with respect to a spherically symmetric initial model.

We formulated the inverse problem of waveform inversion for localized 3-D seismic structure, computing the partial derivatives of waveforms with respect to the elastic moduli at arbitrary points in space for anisotropic and anelastic media using the methods of Geller and Hara (1993). We applied our methods to the assembled dataset to invert for 3-D shear wave structure. The methods used were presented by Kawai et al. (2014) and refined in our groups’ subsequent papers.

The inferred model shows the presence of two distinct slabs at the CMB beneath Central America and Venezuela and one prominent slab beneath the Northern Pacific due to subduction ~200 Ma (Muller et al. 2016). These slabs appear to modulate the formation of passive upwelling (called “passive plume”) of hot basal mantle material (Suzuki et al. 2016; Borgeaud et al. 2017; Suzuki 2020). High-resolution seismic images (Borgeaud et al. 2019) show that such plumes interact with slabs subducting in the upper mantle and that some tearing of the subducted slab is taking place.

The inferred images beneath Central America enable us to date the slab at various depths, taking into account the geological events investigated based on plate reconstructions. We estimate a viscosity contrast between the upper and lower mantle of 9-12, which is about 5 times smaller than that estimated from post-glacial rebound (Hager 1984; Forte and Mitrovica 2001). This implies that subduction from the Earth’s surface down to the base of the mantle affects the surface environment in two ways. 1) Intermittent and localized subduction to the base of the mantle cools the CMB, influencing convection in the outer core, and thus the geodynamo and geomagnetic field. Increased heat flux from the core to the mantle might trigger geomagnetic reversals. 2) Subduction to the CMB modulates the formation of passive plumes which, if they reach the Earth’s surface, can lead to volcanism that can affect the composition of the atmosphere and the temperature of the Earth’s surface. These results suggest the importance of coupling between the Earth’s deep mantle and the Earth’s surface.

Keywords: Seismic waveform inversion, Subducted slab, Mantle convection