Japan Geoscience Union Meeting 2015
(May 24th - 28th at Makuhari, Chiba, Japan)
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SCG60-04 Room:201A Time:May 25 11:45-12:00

S-wave ray path analysis constrains the distribution and dynamics of the hydrated mantle wedge

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Subduction fluids including H_2O are a key component of understanding the dynamics in convergent plate margins and recycling of materials from the Earth's surface into the deep interior. H_2O-rich fluids in the wedge mantle are dominantly derived from antigorite, dragged down by plate motion. Antigorite is generally thought to be distributed in the relatively warmer subduction zones where the dehydration of the subducting slab is predicted to occur. Seismic observations are commonly used to identify the location and proportion of antigorite-rich domains (low seismic velocities Vp = ~ 6.5 — 6.7 km/s, Vs = ~ 3.4 — 3.7 km/s and high Vp/Vs = ~ 1.8 — 1.9 for single antigorite crystals).

However, antigorite has a very strong seismic anisotropy (Δ Vp ≤ 46 % and Δ Vs ≤ 66 %), meaning that seismic velocities and the Vp/Vs ratio can show very large variations (Vp = 5.6 — 8.9 km/s, Vs = 2.5 — 5.1 km/s and Vp/Vs = 1.2 — 3.4) depending on the propagation path of the seismic wave. This means the analyses based on the observation of average seismic velocities cannot necessarily distinguish antigorite nearing rocks from dry olivine-rich mantle. The distribution and proportion of antigorite and hence water has thus far been impossible to determine.

In this study we calculated the shear wave splitting caused within the wedge mantle using the geometry of seismic ray paths observed in Ryukyu arc where trench-parallel S-wave anisotropy with large delay times (~ 1 s) has been observed. To match the shear wave splitting observations of both ray that arrived from forearc side and backarc side to the seismic stations, we find the alignment of antigorite must change from parallel to the subducting slab in the deepest part of the wedge to vertically aligned at intermediate depths in the wedge mantle and the proportion of these antigorite must be more than 65 %.

This type of analysis that takes into account ray paths geometry and the seismic anisotropy of deformed antigorite-bearing mantle can constrain the distribution, amount and orientation of antigorite.

The change in orientation of antigorite in Ryukyu arc suggests the presence of convective flow in the hydrated forearc mantle associated with a bulk long-term viscosity of less than 10^{19} Pa s.

The analysis of the shear wave splitting observations in other subduction zones shows that large delay times with trench parallel fast Vs within the wedge mantle, similar to the Ryukyu example, have been observed from even cold subduction zones (e.g Izu-Bonin and Tonga-Kermadec subduction zones) regardless of the age of the slab. This results implies the large-scale serpentinization and hydrous mantle flow associated with the dehydration of the slab are likely to be more widespread than generally recognized and the widespread view that the forearc mantle of cold subduction zones is dry, needs to be reassessed.

However, subduction zones with small delay times in the wedge mantle are also reported irrespective of the thermal structure in the wedge. The lack of a strong shear wave splitting in some subduction zones and the thermal structure in the subduction zones may be related to the tectonic erosion of hydrous material from the base of the mantle wedge. An additional factor may be subduction angle. Subduction zones with large splitting times show relatively steep slab dips (~ 40 — 60 ^{o}) (Ryukyu, Aleutians, Izu-Bonin and Tonga-Kermadec subduction zones) and no subduction zones with shallow slab dips are associated with large shear wave splitting. Steep subduction zone may be an important geometry requirement for convection cells to develop in the wedge mantle with both slab-parallel and sub-vertical foliation domains.

Keywords: Shear waves splitting, Antigorite, Hydrated mantle wedge, Seismic anisotropy, Seismic ray path, Mantle convection