Application of a new anelasticity model to the seismic discontinuity at the lithosphere-asthenosphere boundary

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Seismic low velocity is one of the major characteristics of the asthenosphere. The boundary of the asthenosphere with the overlying lithosphere (LAB) is considered to be sharp because seismic discontinuity, called G-discontinuity, can be detected around that depth. The depth of the G-discontinuity observed in the oceanic mantle increases with increasing plate age, indicating that the position of G-discontinuity is controlled by temperature. However, it is difficult to explain the sharp velocity contrast (>≈ 5%) by the thermal effect alone, because temperature increases continuously with increasing depth. Therefore, the discontinuous distribution of melt or water has been considered as the major cause of the G-discontinuity (or LAB) [e.g., Kawakatsu et al., 2009, Science; Karato, 2012, EPSL]. However, it has been difficult to explain all geophysical and geochemical constraints consistently. In this study, we propose a new explanation of the sharp LAB by “grain boundary premelting” based on our experimental studies.

Yamauchi and Takei [2016, JGR] measured polycrystal anelasticity at near-solidus temperatures by using a rock analogue (organic polycrystals). We found that anelasticity by grain boundary sliding is significantly enhanced from considerably below the solidus temperature ($0.92 < T/T_m$; T_m is the solidus). At the same temperatures, viscosity of grain boundary diffusion creep is also significantly reduced. These observations suggest that a structural transition in grain boundary (premelting) occurs below T_m, changing the dynamical properties of the grain boundary. Another important finding is that these premelting effects have large amplitude even for the samples which generate small amount of melt (≈ 0.4%) at T_m. In contrast, the direct effect of melt, such as poroelastic effect, is negligibly small for these samples. Therefore, in the asthenosphere, where melt fraction is expected to be very small [e.g., Hirschmann, 2010, PEPI], the premelting effect dominates over the direct effect of melt.

By parameterizing the experimental results, we obtained a new empirical formula for the polycrystal anelasticity, and applied it to the temperature dependence of the seismic shear wave velocity $V_S(T)$ in the Pacific mantle obtained by Priestley and McKenzie [2013, EPSL]. The steep reduction of V_S just below the peridotite solidus can be explained well by the premelting effect without invoking melt [Yamauchi and Takei, 2016, JGR; Takei, 2017, Annu. Rev. Earth Planet. Sci.].

In this study, we apply the new anelasticity model to the G-discontinuity. Vertical seismic profile $V_S(z)$ was calculated for the oceanic geotherm (50 and 100 Ma) calculated by the cooling plate models and for the peridotite solidus calculated by the thermodynamic models. The results showed that if the solidus temperature is decreased by water, seismic discontinuity (sharp reduction in V_S) can be explained by premelting. In addition, the premelting effect can explain high attenuation in the asthenosphere. When present results are compared to the seismological observations quantitatively, the thickness (<≈ 30 km) and depth (≈ 75–100 km) of the predicted discontinuity agree fairly well, but the amount of velocity reduction (<≈ 3%) predicted by the present anelasticity model is smaller. Further parameter studies will be performed by taking into account a possible difference between analogue samples and rocks.

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