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Small-Scale Heterogeneity and Seismic Anisotropy in the Mid-Mantle: Oceanic Crust versus Meta-Stable Olivine

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The mid-mantle (i.e., the top lower mantle) roughly represents the mantle portion ranging from ~700 to 1 600 km depths. It has received increasing attention mainly due to two facts including (i) subducted slabs largely trapped there (Fukao and Obayashi, 2013) and (ii) plume necking and lateral ponding at ~1 000 km depth (French and Romanowicz, 2015). A number of mechanisms have been proposed to explain the slab stagnation in the mid-mantle, such as the increased viscosity, controlled by either ferropericlase (Marquardt and Miyagi, 2015) with its iron spin transition (e.g., Shahnas et al., 2017a, b; Justo et al., 2015), or bridgmanite-enriched ancient mantle structures (Ballmer et al., 2017, 2015); the viscosity jump, confirmed by reanalyzing the long-wavelength nonhydrostatic geoid (Rudolph et al., 2015), may also play a vital role in plume dynamics in the mid-mantle (Xiang et al., 2021). A recent study suggested the existence of meta-stable olivine within the subducting slabs in the mid-mantle (Kong et al., 2022), which increases slab buoyancy and thereby promotes stagnation.

The detection of the mid-mantle stagnant slabs mentioned above largely benefit from long-wavelength seismic tomography. In addition to the large-scale structures, a growing body of evidence from analyzing high-frequency waves, such as the S-to-P waves (Fig. 1; Wang and He, 2020; He and Zheng, 2018; Yang and He, 2015), suggests that small-scale heterogeneities widely distribute in the mid-mantle (Kaneshima, 2019; Waszek et al., 2018). They are characterized with higher density but lower velocity relative to the ambient mantle (Yuan et al., 2021; Zhang et al., 2020; Haugland et al., 2017; Niu, 2014; Niu et al., 2003). Their thickness varies from ~9 to 20 km and S-wave velocity decreases by a wide range of ~1.6% to 12.4%. According to their elastic properties, they have been interpreted to be a fragment of basaltic oceanic crust undergoing post-stishovite phase transition. This inference has been supported by a variety of mineral physics experiments (e.g., Zhang et al., 2022; Wang et al., 2020; Tsuchiya, 2011). All the evidence seemingly indicates that the mid-mantle short-wavelength structures can be largely attributed to the basaltic oceanic crust.

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In addition to the heterogeneities with various scales in the mid-mantle, emerging seismic evidence suggests the presence of seismic anisotropy at these depths (e.g., Kong et al., 2022; Ferreira et al., 2019; Lynner and Long, 2015; Mohiuddin et al., 2015; Nowacki et al., 2015; Foley and Long, 2011; Wookey et al., 2002), in which radial anisotropy has been largely attributed to the layering of slab materials (Faccenda et al., 2019), whereas azimuthal anisotropy was linked, for the first time, to frozen-in anisotropy of meta-stable olivine inside a slab (Kong et al., 2022). The meta-stable olivine model is attractive because it explains the azimuthal anisotropy and facilitates slab stagnation in the mid-mantle as well. Before we fully accept this model, we should understand the other alternatives. The most competing mechanism for the mid-mantle anisotropy is the crystallographic preferred orientation (CPO) of bridgmanite—the dominant mineral in the mid-mantle (Tsujino et al., 2016). It is true that sub-vertically propagating SK(K)S waves cannot lead to apparent splitting as argued by Kong et al. (2022). In reality, however, a dipping downgoing slab may induce a tilted mantle flow (Fig. 1), leading to a tilted CPO, which may be able to account for the azimuthal anisotropy to some extent.

Although the mid-mantle anisotropy solely related to meta-stable olivine seemingly requires more investigations, this model raises a question as to whether it can, in part, accounts for the small-scale heterogeneity as mentioned above. We cannot rule out this possibility because meta-stable olivine inside a mid-mantle slab is certainly characterized by a low-velocity layer, which is very resemblant to the seismological observations of scatterers. In particular, the resolved thickness of the scatterers can be up to 20 km, which is larger than ~7 km thickness of a typical oceanic crust, although a thicker crust can be expected due to higher potential temperature in the past. Such a 20 km thick anomaly, however, may be easier to be produced by a structure comprising meta-stable olivine, depending on the slab's thermal history. As such, we cannot exclude the meta-stable olivine as an alternative for explaining the small-scale heterogeneities until more solid evidence emerges. It becomes clear that the high thermal conductivity of stishovite promotes rapid warming of a sinking slab (Hsieh et al., 2022), while the precise thermal conductivity of bridgmanite plays a more deciding role in the fate of meta-stable olivine inside a slab. Future multi-discipline cooperation will certainly advance our understanding of the heterogeneities and seismic anisotropy in

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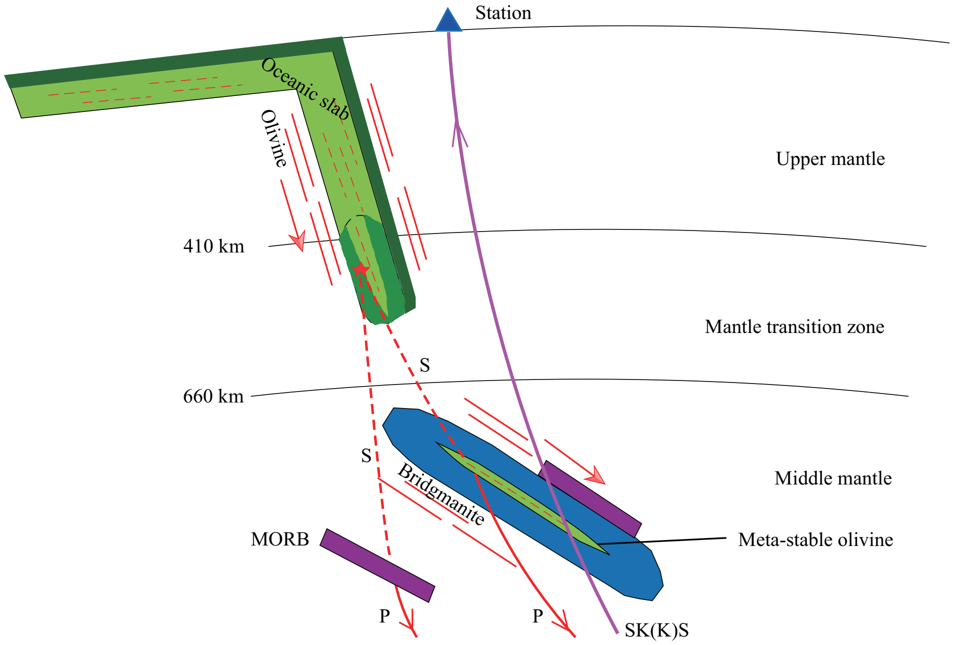

Figure 1. A cartoon illustrating the possible existence of both the small-scale heterogeneities related to MORB or meta-stable olivine and seismic anisotropy due to deformed bridgmanite or meta-stable olivine with a tilted CPO in the mid-mantle, detected by S-to-P wave (S wave is indicated with dashed red line, whereas P wave is indicated with solid red line) and SK(K)S wave (indicated with purple line), respectively. The slab-entrained flow is indicated with short red bars parallel to the downgoing slab fragment. The red star within the slab in the mantle transition zone indicates the intraslab event that generated the downgoing S-to-P wave.

the mid-mantle.

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