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3D numerical modeling of subduction dynamics: plate stagnation and segmentation, and crustal advection in the mantle transition zone

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Water content in the mantle transition zone (MTZ) has been broadly debated in the Earth science community as a key issue for plate dynamics [e.g., Bercovici and Karato, 2003]. In this study, a systematic series of three-dimensional (3D) numerical simulation are performed in an attempt to verify two hypotheses for plate subduction with effects of deep water transport: (1) the small-scale behavior of subducted oceanic plate in the MTZ; and (2) the role of subducted crust in the MTZ. These hypotheses are postulated based on the seismic observations characterized by large-scale flattened high velocity anomalies (i.e. stagnant slabs) in the MTZ and discontinuity depth variations. The proposed model states that under wet conditions the subducted plate main body of peridotite (olivine rich) is abutted by subducted crustal materials (majorite rich) at the base of the MTZ.

The computational domain of mantle convection is confined to 3D regional spherical-shell geometry with a thickness of 1000 km and a lateral extent of $10^\circ \times 30^\circ$ in the latitudinal and longitudinal directions. A semi-dynamic model of subduction zone [Morishige et al., 2010] is applied to let the highly viscous, cold oceanic plate subduct. Weak (low-viscosity) fault zones (WFZs), which presumably correspond to the fault boundaries of large subduction earthquakes, are imposed on the top part of subducting plates. The phase transitions of olivine to wadsleyite and ringwoodite to perovskite+magnesiowüstite with Clapeyron slopes under both “dry” and “wet” conditions are considered based on recent high pressure experiments [e.g., Ohtani and Litasov, 2006]. Another recent experiment provides new evidence for lower-viscosity (weaker strength) of garnet-rich zones than the olivine dominant mantle under wet conditions [Katayama and Karato, 2008]. According to this, the effect of viscosity reduction of oceanic crust is considered under wet condition in the MTZ.

Results show that there is a substantial difference in the behaviors of subducting plate and the trace of crustal materials between the models under dry and wet conditions. Under wet conditions, the weaker and denser crustal materials are fed into the WFZs and the subducting plate tends to stagnate with a maximum lateral extent of over 1000 km, and is segmented by crustal materials. Under wet condition the crustal layer of garnetite is advected faster than the peridotite body due to the rheology and density contrasts in the MTZ, resulting in its separation from the main body subducting plate. The viscosity contrast between the crustal material and the peridotite permits the separation of the crustal layer from the bulk peridotite and then, crustal materials gradually sink into the lower mantle along with the penetration of the subducting slab main body. As a deep mantle cycling of basaltic oceanic crust is suggested by mineralogy recently [Walter et al., 2011], this numerical result may suggest to re-examine the fate of subducted oceanic crust in the deep mantle.