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Rheological mechanisms for the formation and avalanche of stagnant slabs

Michio Tagawa[1]; Tomoeki Nakakuki[2]; Yasuyuki Iwase[3]

[1] Earth and Planetary Sci., Hiroshima Univ; [2] Dept Earth Planet Syst Sci, Hiroshima Univ; [3] Dept. Earth & Ocean Sci., NDA

We have performed to numerical experiments of the slab interaction with the phase transitions to investigate mechanism for the formation and avalanche of the stagnant slab. We have systematically examined the rheology of the slab in the transition zone and the lower mantle in the models with fixed or freely moving trench. In our models, surface plate motion is produced without imposed velocity boundary condition for the plate. The trench can also freely migrate as well as the plates. We use rheological parameters, i.e., temperature dependence with Arrhenius-type function and yield strength of the lithosphere, inferred from experimental studies. The rheological parameters are verified by comparing with observation for the stress field, deformation of the plate, and torque balance analysis of forces working on the plate. The simulated subduction zone has asymmetric structure with an inclined slab. The plate boundary is generated by introducing lubricant with history-dependent rheology at the surface of the oceanic plate. Our results show that trench backward motion has important mechanism to generate the stagnant slab because the trench backward motion causes a shallow angle collision of the slab with the 660 km phase boundary. The trench retreat is strongly promoted when the slab is stagnated at the 660 km discontinuity. These are consistent with previous experiment and numerical studies (Kincaid and Olson, 1987; Christensen 1996; Christensen 1997; Zhong and Gurnis, 1997; Cizkova et al. 2002).

Because the slab has plasticity caused by the high viscosity, the slab memorizes the past deformation. This has an important role to determine the slab structures in our simulation. When the slab tip colliding with the 660 km phase transition in the case with the free trench migration, the slab is bent upward by the buoyancy of the phase transition. The slab moves along the curled shape of the slab. In this case, the stagnant slab has a shape like the cross section of spoon and the tip of the stagnant slab is suspended above the 660 km phase boundary by the slab strength. When the viscosity reduction is induced by the slow grain growth, the curvature of the stagnant slab becomes smaller. The stiffness of the slab has also important effects to generate the stagnant slab with weaker Clapeyron slope because the horizontally wide plate descend slower than vertically long plate. In this case the horizontal slab which looks like a stagnant slab is formed beneath the 660 km phase boundary.

In the case with strong stagnant slab, the subducted slab keeps to stay on the 660 km phase boundary when the Clapeyron slope is as steep as -3MPa/K. The avalanche does not occur during the calculation. When the stagnant slab has viscosity as low as ambient mantle because of the grain size reduction in the whole slab, the stagnant slab finally penetrates into the lower mantle. This can be explained by shorter growth time of Rayleigh-Taylor type instability with lower viscosity contrast between the slab and the ambient mantle. When the viscosity jumps at the 660 km discontinuity by a factor of 10 to 30, the stagnant slab is more easily formed at -2 MPa/K. Although the slab temporarily stays at the 660 km phase boundary, the slab is finally drops into the lower mantle even in the case with Clapeyron slope of -3 MPa/K, because of the lower viscosity contrast between the slab and the lower mantle. These may explain that the younger subduction zone (e.g., Izu-Bonin, Tonga) seems to have stagnant slabs and older subduction zone does penetrrating slabs (Japan, Kuril, Java, and America).