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Generation of stagnant slabs in 3-D spherical mantle convection models

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Seismic tomography reveals the natural mode of convection in the Earth is whole mantle as subducted slabs are clearly seen as continuous features into the lower mantle. However, simultaneously existing alongside these deep slabs are stagnant slabs which are, if only temporarily, trapped in the upper mantle. Previous numerical models of mantle convection have observed a range of behavior for slabs in the transition zone depending on viscosity stratification and mineral phase transitions, but typically only exhibit flat-lying slabs when mantle convection is layered or trench migration is imposed. We use 3-D spherical models of mantle convection which range up to Earth-like conditions in Rayleigh number to systematically investigate three effects on mantle dynamics: (1) the mineral phase transitions, (2) a strongly temperature-dependent viscosity with plastic yielding at shallow depth, and (3) a viscosity increase in the lower mantle. First a regime diagram is constructed for isoviscous models over a wide range of Rayleigh number and Clapeyron slope for which the convective mode is determined. It agrees well with previous results from 2-D simulations, suggesting present-day Earth is in the intermittent convection mode rather than layered or strictly whole mantle. Long-term calculations for 4 billion years at Earth-like Rayleigh number which include effects (2) and (3) are produced, with and without the effect of the mineral phase transitions. The calculation without the phase transition produces plate-like behavior with a long wavelength structure and surface heat flow similar to Earth's value. While the observed convective flow pattern in the lower mantle is broader compared to isoviscous models, it basically shows the behavior of whole mantle convection, and does not exhibit any slab flattening at the viscosity increase at 660 km depth. The calculation which includes the phase transitions successfully exhibits the coexisting state of stagnant and penetrating slabs within the transition zone. These results indicate the importance of both a viscosity increase and mineral phase transitions for generating the structure of stagnant slabs observed by seismic tomography.