Some Petrological Controls on Subduction Dynamics

Craig R. Bina[1] and Hana Čížková[2]

[1]Department of Earth and Planetary Sciences, Northwestern University, Evanston, IL 60208-3130, U.S.A. (craig@earth.northwestern.edu)

[2]Department of Geophysics, Faculty of Mathematics and Physics, Charles University in Prague, Praha 8, Czech Republic (hana.cizkova@mff.cuni.cz)

Petrological and mineralogical factors exert important controls on subduction dynamics. Dynamical models of subduction indicate that processes such as slab buckling, slab stagnation, time-varying trench migration, and collisional slab detachment, as well as patterns of seismogenic stresses, all are significantly influenced by petrological factors. The role of petrology in such processes manifests primarily in two forms: through buoyancy forces (both thermal and petrological) and through rheology (of both crust and mantle). Specific petrological factors governing such roles in subduction include: effective Clapeyron slopes of phase transitions, extent of mineral metastability, oceanic crustal strength (hydration, etc.), and mantle viscosity structure.

Slab buckling consists of the undulation and folding of slabs, generally within the mantle transition zone (MTZ). Dynamically this process is driven by interplay between negative slab buoyancies near the top of the MTZ, viscous resistance near the bottom of the MTZ, and non-linear rheology within the slab. While difficult to image due to differences in spatial scales between slab thickness and seismic tomographic resolution, models of buckled slabs may yield better fits to seismically imaged velocity anomalies.

Buckling is closely linked to slab stagnation, whereby many slabs are deflected to a subhorizontal posture near the base of the MTZ. It has long been suggested that metastable persistence of olivine to high pressures in cold slabs may contribute sufficiently positive petrological buoyancy anomalies to drive slab deflection and stagnation. More recently, it has been suggested that metastable persistence of pyroxenes may offer a similar source of positive petrological buoyancy in support of slab stagnation, with attendant implications for associated seismic velocity anomalies. Several high-pressure metastable pyroxene structures have been observed experimentally.

However, in the absence of metastability, dynamical models also predict slab stagnation in certain equilibrium scenarios. Here the role of the positive petrological buoyancy contribution from the negative Clapeyron slope of 660-km phase transition is of key importance, as is the associated ~660-km viscosity increase, but the negative petrological buoyancy contribution from the positive Clapeyron slope of 410-km phase transition also plays a significant role via feedback into the nonlinear rheology of the slab.

Slab buckling and stagnation combine to drive quasi-periodic patterns of time-varying subduction velocities that are anti-correlated with trench migration (retreat or advance). Analyses of model parameters governing trench retreat indicate that the two major governing factors are petrological in nature: the effective Clapeyron slope of 410-km phase transition and the effective strength of the subducting crustal layer. The former must account for bulk composition and potential degree of metastability, and the latter (controlling interplate coupling) likely depends upon extent of hydrothermal alteration and subsequent dehydration. Models of simple two-plate subduction generally yield only trench retreat. Generation of trench advance appears to require a three-plate geometry in which the overriding plate in one subduction zone is itself being subducted, such as occurs in the modern Philippine Sea (and probably during the ancient India-Asia collision), but these scenarios are still largely governed by crustal strength and 410-km Clapeyron slope.

Arc-continent collision results in gradual steepening of subduction dip angles, a process controlled by both the negative thermal buoyancy of the slab and the negative petrological buoyancy arising from the 410-km Clapeyron slope. Such collision ultimately leads to cessation of convergence and to slab detachment. Dynamical models suggest that the fate of the detached slab is strongly controlled by the pre-collisional trench migration rate, which is in turn governed by crustal strength. However, the depth and sharpness of the viscosity contrast between upper and lower mantle also plays a role, so that variations in these petrological parameters can yield direct penetration into the lower mantle, long-term stagnation in the MTZ, or short-term stagnation just below the MTZ.

All of these processes of slab buckling, stagnation, penetration, migration, collision, and detachment impose stress fields which may be reflected in patterns of seismogenic stresses as illuminated by earthquake focal mechanisms. Dynamical models suggest potential consistency with rotation of stress axes in deep Tonga events and with shallow extensional episodes in the Philippine Sea. More detailed models reproduce near-vertical compression in a recent deep earthquake doublet on the Nazca plate as well as down-dip extension along the southern Manila trench near Mindoro island. Significant contributions to all of these stress patterns arise from petrological buoyancy forces associated with phase transitions and from crust and mantle rheological structure.