Slab Stagnation Depth: Buoyancies, Bending Moments, and Seismic Structure

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We have constructed kinematic thermal models of subducting slabs [Negredo et al., 2004] for both stagnant (non-penetrative) and deep-mantle (penetrative) slabs [cf. Fukao et al., 2001]. For these cases, we have determined equilibrium phase assemblages (olivine polymorphism), along with the resulting buoyancy forces and seismic velocity anomalies. Beyond the well-known thermal dependence upon subduction rate, dip angle, and lithospheric age [Kirby et al., 1996; Yoshioka et al., 1997; Tetzlaff and Schmeling, 2000; Bina et al., 2001], we focus on the role of stagnation depth (of the base of the slab), neglecting the effects of trench roll-back and viscosity contrasts [Christensen, 2001].

Upon calculating slab bending moments (and bending moment gradients) about the trench axis, we find that thermo-petrological buoyancy forces yield extrema in bending moment gradients near 700 km depth whose sign is consistent with a decrease in dip angle (i.e., stagnation) at the base of the transition zone. Furthermore, bending moment gradients exhibit extrema near 400 km depth whose sign is consistent with the increase in dip angle (i.e., drooping) sometimes observed below depths of 300 km [e.g., Chen et al., 2004]. Incorporation of potential metastable persistence of lower-pressure phases [e.g., Green and Zhou, 1996] further enhances stagnation to the extent that the bending moments themselves (and bulk slab buoyancy [Bina et al., 2001]) become positive near 700 km depth, inhibiting direct slab penetration in such cases.

Variations in stagnation depth (z_{stag}) yield significant changes in calculated bending moments (and bending moment gradients) about the stagnation axis. While z_{stag} of 660 km yields small negative buoyancy anomalies in the recumbent portion of the slab (giving a bending moment gradient that promotes downward deflection), a z_{stag} of 700 km yields small positive buoyancy anomalies (giving a bending moment gradient that promotes upward deflection), and a greater z_{stag} of 750 km yields even larger positive buoyancy anomalies (hence stronger upward deflection).

These patterns suggest the existence of an equilibrium stagnation depth governed by the thermal state of the slab. Because of the simple geometric dip-dependence which generates larger buoyant bending moments at smaller dip angles, subducting slabs may overshoot their equilibrium z_{stag} before subsequently rebounding. Furthermore, potential continuation of metastable persistence into the recumbent slab yields bending moment gradients that promote strong upward deflection, but this effect decays (due to thermal equilibration) over 600-700 km of lateral travel, thereafter yielding bending moment gradients consistent with downward deflection.

Both the vertical and lateral extent of downward deflection of the equilibrium $rw \rightarrow pv + mw$ transition (associated with the “660-km” seismic discontinuity) also exhibit dependence upon stagnation depth. Small values of z_{stag} (e.g., 660 km) yield shallow and broad depressions of the phase boundary, while larger values (e.g., 750 km) produce deep and broad depressions, and still larger values (e.g., 820 km) yield deep and narrow depressions similar to those expected for direct slab penetration. Stagnation depth further controls the seismological visibility of these effects through superposition of broad negative (vertical) velocity gradients upon the sharper $rw \rightarrow pv + mw$ transition.

Such effects may be important beneath Japan, where an apparently stagnant slab gives rise to deep and narrow depression of the “660-km” seismic discontinuity [Kawakatsu, 2005].

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