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Effects of slab mineralogy on subduction rates

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Abstract. Although velocities of subducting slabs should be controlled primarily by their negative thermal buoyancies, their mineralogy can also have significant effects. We explore this by using thermo-kinetic modeling to predict mineralogy and compare the resultant buoyant (driving) force to the opposing viscous drag. Phase transitions of $(Mg,Fe)_2SiO_4$ in subducting slabs depend on thermal structure in two ways. First, equilibrium phase boundaries should be deflected, causing local buoyancy anomalies whose sign depends upon that of the Clapeyron slope. As slabs first enter the transition zone, negative anomalies should accelerate them, but positive anomalies that arise when they fully penetrate the transition zone should slow them. Such effects may induce geologically abrupt changes in plate motions. Second, olivine that persists metastably in slabs will form regions of positive buoyancy which should reduce slab velocities. The coldest and fastest slabs should be slowed more greatly, thus narrowing the range of feasible subduction rates. Decreased descent rates, however, allow slabs to warm and metastable wedges to thermally erode. Such negative feedback mechanisms may serve to regulate subduction rates.

Introduction

Slabs of lithosphere sink because they are colder and hence denser than the surrounding mantle [*McKenzie*, 1969; *Minear and Toksöz*, 1970]. This negative thermal buoyancy is thought to largely control slab velocities [*Elsasser*, 1969; *Forsyth and Uyeda*, 1975; *Becker et al.*, 1998]. The role of slab mineralogy in subduction also has been investigated [*Schubert et al.*, 1970; *Ringwood*, 1982], especially in terms of stresses and deep earthquakes [*Griggs*, 1972; *Goto et al.*, 1987; *Ito and Sato*, 1992; *Bina*, 1997]. However, buoyancy anomalies resulting from slab mineralogy should also affect subduction velocities [*Bassett*, 1979; *Rubie*, 1993; *Kirby et al.*, 1996], providing more complex and rapidly time-variable behavior than thermal buoyancy alone. Here we investigate these effects, using a simple model in which subduction rates are governed by a balance of buoyant body (driving) forces and viscous drag (opposing) forces, where the buoyancies are governed by temperature- and pressure-dependent mineralogy.

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Transitions in $(Mg,Fe)_2SiO_4$, from the α (olivine) phase to the β (wadsleyite) phase and from β to γ (ringwoodite), are believed to occur near 410 km and 520 km, respectively, under normal mantle conditions, accounting for seismic discontinuities at those depths [*Katsura and Ito*, 1989; *Bina*, 1991]. Within cold slabs these transitions should occur at shallower depths, due to their positive Clapeyron slopes. However, the γ to silicate perovskite (pv) + magnesiowüsite (mw) transition, believed largely responsible for the 660-km discontinuity, should be deflected down due to its negative Clapeyron slope. Low temperatures, however, may kinetically inhibit these transitions, allowing α to persist metastably into high-pressure stability fields [*Sung and Burns*, 1976; *Rubie and Ross*, 1994]. A metastable wedge of olivine might then act as a low-density "parachute," slowing the descent of the slab [*Kirby et al.*, 1996].

Thus, a slab's thermal state controls its velocity via competing effects on density and mineralogy. The thermal parameter, φ, simply represents this thermal state [*Molnar et al.*, 1979]. As a slab of finite thickness subducts into the mantle and heats by conduction, isotherms are advected downward to maximum depths proportional to the vertical descent rate, v_z (the product of the trench-normal convergence rate and the sine of the slab's dip), and the square of the plate thickness [*McKenzie*, 1969]. If the latter is proportional to age, as for a cooling halfspace model, these depths are proportional to $\varphi = v_z \cdot age$, where age is that of the lithosphere as it enters the trench. For a plate model, the utility of this parameterization begins to break down for old lithosphere [*Marton et al.*, 1997], because it is assumed to have achieved a (roughly) constant temperature structure. Nonetheless, φ adequately describes a slab's thermal state to first order, as we use it here.

Modeling

Slab buoyancy depends upon density contrasts with the surroundings, as determined by the phases present at prevailing pressures and temperatures. We computed thermal structures using a finite difference algorithm [*Minear and Toksöz*, 1970], with initial lithospheric temperatures from a plate model with GDH1 parameters [*Stein and Stein*, 1992]. Temperature effects from shear heating, radiogenic heating, and transitions in pyroxenes were not included.

Thermodynamic data [*Fei et al.*, 1991] for α, β, γ, pv, and mw may be used to determine equilibrium phase assemblages via free energy minimization [*Bina*, 1998], allowing compositions to vary. However, to speed the computations, we used a fixed mantle composition of $Mg_{1.8}Fe_{0.2}SiO_4$ [*Ringwood*, 1982], allowing state functions to be fit to polynomials

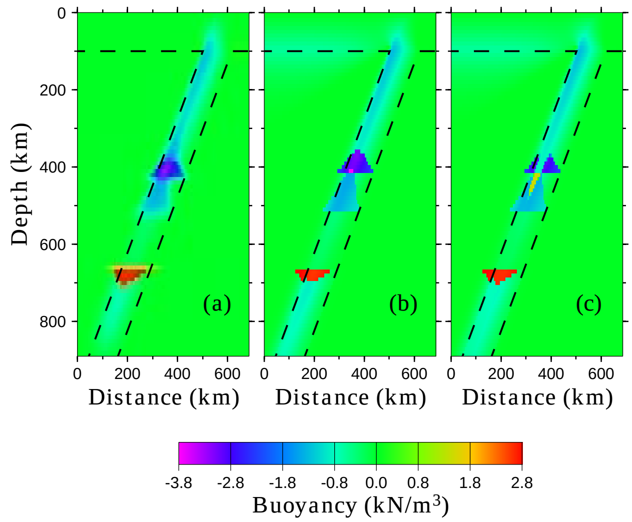

Figure 1. Buoyancy fields of slab G1 with (a) multi-component and (b) quasi-single-component equilibrium phase transitions, and (c) quasi-single-component mineralogy with metastable persistence of olivine.

in pressure and temperature. This yields a simplified quasi-single-component mineralogy. For metastability, we used *Rubie and Ross's* [1994] third model of olivine transformation kinetics (growth-limited due to fast nucleation rates) with latent heat of transformation feedback. The latter significantly affects the extent of olivine metastability [*Daessler and Yuen*, 1993; *Rubie and Ross*, 1994; *Daessler et al.*, 1996; *Devaux et al.*, 1997].

We used a simple 2-D model slab moving down-dip through a mantle with constant viscosity η at velocity v. The drag force is summed for two sides and a semi-circular tip. The drag on each side is the product of its length and

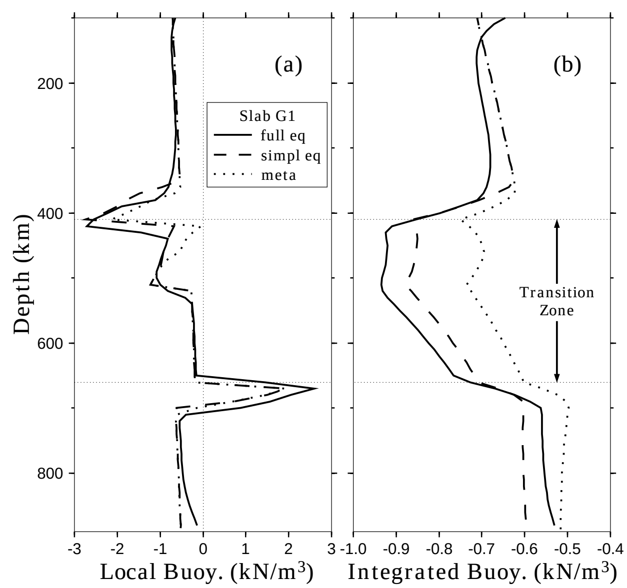

Figure 2. (a) Mean buoyancy across the width of the slabs as a function of depth. (b) Integrated buoyancy of entire slabs down to the depth of the slabs' tips.

Table 1. Model Slab Parameters ($\theta = 60°$)

Slab	Rate (cm/yr)	Age (My)	φ (km)	Rate (cm/yr)	Age (My)	φ (km)
		Group 1			*Group 2*	
A	8	50	3465	6	70	3640
B	8	65	4505	8	70	4850
C	8	80	5540	10	70	6060
D	8	95	6580	12	70	7275
E	8	110	7620	14	70	8490
F	8	125	8650	16	70	9700
G	8	140	9700	18	70	10910
H	8	155	10740	20	70	12125
I	8	170	11780			

the shear stress τ, where $\tau = \eta(\partial v/\partial x) \approx \eta v/(w/3)$ and w is the width of the slab. At the tip, as part of a sphere, we used the Stokes's law value of $3\eta v/w$ per unit area [*Batchelor*, 1967] over half its circumference, $\pi w/2$.

The net force on the slab is zero when the drag force balances the down-dip component of the buoyant force, $F_{drag} = -F_{buoy} \sin\theta$, giving a calculated terminal velocity (CTV):

$$CTV = \frac{-g(\rho_{mantle} - \rho_{slab}) A \sin\theta}{3\eta\left[(l_1 + l_2)/w + \pi/2\right]} \quad , \tag{1}$$

where l_1 and l_2 are top and bottom slab lengths, and A and θ are cross-sectional area and dip angle of the slab, respectively. The CTV is not necessarily the same as the convergence rate used as an input parameter to the thermo-kinetic model, as the former results from the force-balance calculation.

Results

Initial calculations were done for model slabs with the parameters of *Bina* [1997]: convergence rate of 8 cm/yr, dip angle of 60°, and lithospheric age of 140 My, yielding $\varphi =$ 9700 km, values similar to two segments of the Indonesian arc [S. H. Kirby, pers. comm.]. We then varied the thermal parameter (Table 1) by changing lithospheric age (group 1) or convergence rate (group 2). The quasi-one-component mineralogy, while producing simplified phase fields, preserves the large-scale features of the multi-component mineralogy, including the buoyancy field of the slab (Figure 1).

The predicted mean buoyancies across slabs as functions of depth (Figure 2a) show that upward deflections of the $\alpha \rightarrow \beta$, $\alpha \rightarrow \gamma$, and $\beta \rightarrow \gamma$ transitions at ~400 km yield locally negative (sinking) anomalies, whereas downward deflection of $\gamma \rightarrow pv + mw$ at ~700 km yields locally positive (floating) ones. Despite such positive anomalies, integrated buoyancies of slabs sinking below 660 km remain negative (Figure 2b).

Slabs' CTVs were found using their integrated buoyancies and a mantle η of 3.7×10^{20} Pa·s. This viscosity, chosen by scaling a value of 10^{21} Pa·s [*Cathles*, 1967] so that the CTVs of the coldest group 1 slabs would approximate their input convergence rates (8 cm/yr), falls within the range of upper mantle values [*Mitrovica and Peltier*, 1993]. Results (Figure 3) show time-dependent CTVs: slabs speed up upon entering the transition zone and slow down as they extend

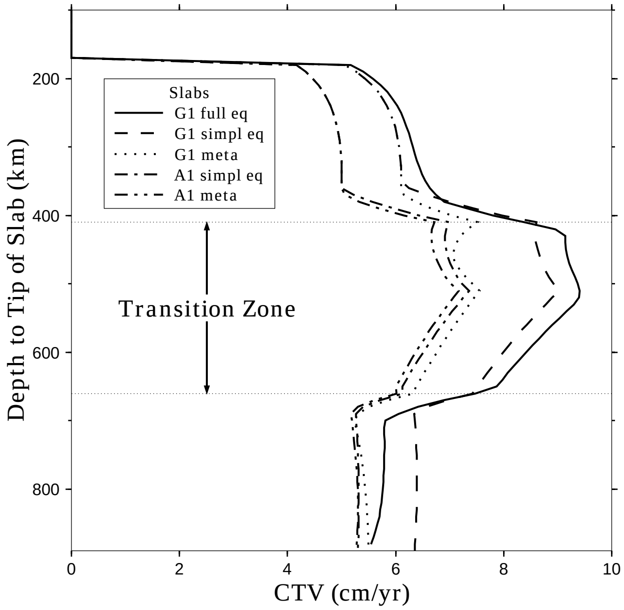

Figure 3. CTVs of slabs as functions of depth to the tips of the slabs. Individual slabs as indicated (parameters listed in Table 1). CTVs decrease in the transition zone due to the presence of metastable olivine.

completely through, due to their depth-integrated buoyancies.

Within the transition zone, metastable wedges slow the slabs, with colder ones experiencing greater slowing (Figure 3). For slabs extending to 600 km, both CTVs and decelerations (the "parachute effect") exhibit φ-dependence

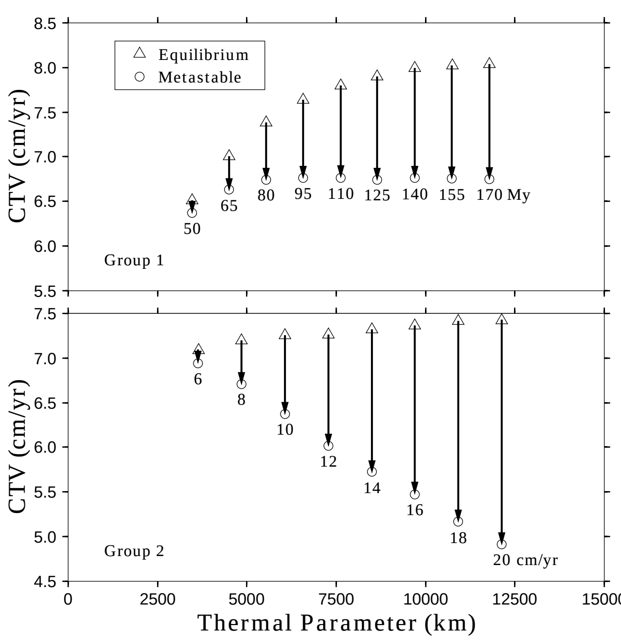

Figure 4. CTVs of slabs extending to 600 km depth for various lithospheric ages (group 1) and input convergence rates (group 2). Arrows show "parachute effect" of metastable wedges.

(Figure 4). The coldest slabs have larger velocity drops and can travel more slowly than warmer slabs. As a rough measure of uncertainty, varying the growth rates of the β or γ phases by ($\pm$) an order of magnitude changes the CTVs of the coldest metastable slabs by no more than $\pm$0.7 cm/yr and leaves the trends of CTV vs. φ unchanged.

The trends in Figure 4 reflect the influence of slab thermal structure on CTV. Equilibrium slabs in group 2 show relatively constant velocities. Age for these is fixed (70 My), so all begin with identical thermal structures. The effects of different descent rates upon conductive warming (fastest remaining coldest) become important as metastable wedges develop. Slabs in group 1 have fixed input convergence rates (8 cm/yr), so differences in CTVs are due to lithospheric age. Here, equilibrium slabs show an increase in CTV that falls off with increasing age, demonstrating the limitations of φ. Metastable slabs, however, show roughly constant CTVs, indicating that warming of slab interiors due to conduction is the limiting factor in metastable wedge growth, as in group 2. Independent of these trends, the parachute effect increases in magnitude with φ: the colder the slab, the more greatly it is slowed by metastability.

Discussion and Conclusions

The arrival of a slab in the transition zone and its subsequent egression should affect the rate at which it travels. While magnitudes of such rate changes (of order 1 cm/yr) depend on slab thermal state (20-40% for warm slabs, 15-30% for colder ones), the form of the depth-dependence does not (Figure 3). These accelerations are independent of metastability, because a wedge forms below the upwardly deflected $\alpha \rightarrow \beta$ or $\alpha \rightarrow \gamma$ boundary and, with latent heat feedback, should thermally erode above the $\gamma \rightarrow pv + mw$ transition [*Daessler and Yuen*, 1996; *Marton et al.*, 1997]. Such mechanisms may cause geologically sudden changes in plate motions, unlike other proposed thermal and mechanical mechanisms which induce gradual changes [*Lithgow-Bertelloni and Richards*, 1998].

When metastable wedges of olivine are present, they will act as "parachutes," increasing buoyancies and slowing slabs by as much as 1.5-2.5 cm/yr (~20-30%), as hypothesized [*Bassett*, 1979; *Rubie*, 1993; *Kirby et al.*, 1996; *Schmeling et al.*, 1998]. This process will act as negative feedback on subduction rates: the colder the slab, the larger the metastable wedge and the greater the parachute effect. Slowing slabs, however, will warm by conduction, shrinking the wedge as more α transforms to β or γ, thus increasing the negative buoyancy. This feedback should narrow the range of subduction rates, perhaps helping to control plate speeds.

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