CAN EARTH-LIKE PLATE TECTONICS OCCUR IN THE OUTER ICE SHELLS OF ICY SATELLITES?

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Introduction: The outer H_2O ice shells of some icy satellites show evidence for divergent, strike-slip, and convergent tectonics. Researches propose that Earth-like plate tectonic processes may occur in the ice shells of Europa and Enceladus [1-3], raising the possibility of a buoyantly driven cycle of tectonic resurfacing and lithosphere recycling on icy satellites [1].

On Earth, a cycle of spreading and subduction is supported by buoyancy forces transmitted elastically through the lithosphere [4]. The majority of tectonic forcing comes from "slab pull," driven by the negative buoyancy of cold lithosphere "slabs" intruding into the warm asthenosphere. "Ridge push" accounts for only a tenth of these forces, and is driven by the cooling of lithosphere with increasing age for 10s Myr and over 1,000s km, causing warmer, more buoyant material to slide downhill away from the ridge axis.

On Europa, proposed "subsumption zones" at inferred convergent margins may allow old lithosphere to be reincorporated into the ice shell and recycled [2]. Johnson *et al.* [1] recently demonstrated that a subducting ice I slab on Europa may remain negatively buoyant for appropriate values of salt content, salt distribution, and porosity of the subducting plate, providing a mechanism for slab pull. Like mid-ocean ridges, extensional bands may locally bring warm isotherms to shallow depths [e.g. 5]. However, their limited width (~10s km) [6] requires either a short lifespan or slow opening rate, inhibiting the development of the large gradients in plate thickness persistent through geologic time that drive ridge push.

To explore whether Earth-like, convectively driven plate tectonics can occur in the outer shells of icy satellites, we employ a simple force balance to determine whether the buoyancy forces associated with slab pull can overcome the strength of the lithosphere to initiate or sustain subduction. We consider a range in lithosphere cohesion and coefficient of friction for pristine and weakened lithosphere, salt content, and temperature to determine the depth a slab must reach before sustaining subduction. As a feasibility test, this force balance incorporates the most optimistic first-order assumptions, promoting Earth-like plate tectonics to the greatest possible extent.

Force Balance Framework: Fig. 1 shows the geometry of the conceptual model used in the force balance. Self-driving plate tectonics requires the sum of driving forces to exceed the sum of resisting forces [7, 8]. In icy satellites, potential driving forces include the forces associated with a negatively buoyant slab, F_S, and tidal interactions, F_T. In order to sustain subduction, tidal forces must persist through geologic time. Resisting forces include the depth-integrated yield strength of the lithosphere, F_Y, the force required to elastically deform the lithosphere, F_E, and basal tractions that resist sliding between the lithosphere and asthenosphere, F_A. Thus, subduction is permitted when

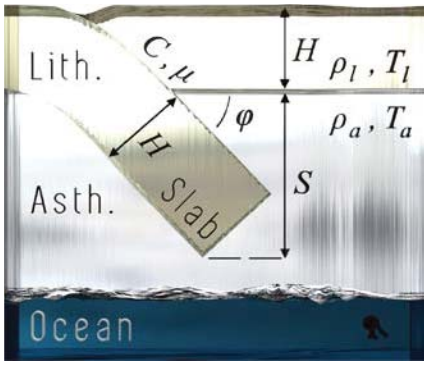

Figure 1. Geometry of conceptual model considered in the force balance. See text for parameter descriptions.

$$F_S + F_T \geq F_Y + F_E + F_A \ . \tag{1}$$

The buoyancy force exerted on the lithosphere by a penetrating slab per along-trench distance is

$$F_S = \left(\rho_l - \rho_a\right) gS \frac{H}{\sin\varphi} \ , \tag{2}$$

where ρ_l and ρ_a are respectively the densities of the cold ice lithosphere and warm ice asthenosphere, g is the gravitational acceleration, S is the penetration depth of the downwelling slab beneath the base level of undeformed lithosphere, H is the thickness of the lithosphere, and φ is the dip of the subducting slab.

Using the simplifying assumption that tidal stresses, σ_T, are uniformly distributed through the ice shell, the depth-integrated tidal forcing is

$$F_Y = \sigma_Y H \ , \tag{3}$$

The depth-integrated Mohr-Coulomb yield strength depends on the lithosphere's cohesion, C, its coefficient of internal friction, μ, and the lithostatic stress at its base,

$$F_Y = H\left(C + \frac{1}{2}\mu\rho_l gH\right) \ . \tag{4}$$

We maximize driving forces by assuming a vertical slab, and minimize resisting forces by negating elasticity and assuming that the lithosphere slides freely over the asthenosphere. Thus, Eq.1 becomes

$$\left(\rho_l - \rho_a\right) gS + \sigma_T \geq C + \frac{1}{2}\mu\rho_l gH \ . \tag{5}$$

To investigate the density anomaly required for sustained subduction, we solve Eqs. 1-6 for ρ_l, and explore the surface temperature, salt content, and external stresses required to sustain plate tectonics.

Optimistic Assumptions: Continuing optimistic assumptions that promote slab pull-driven subduction, the slab is assumed to be perfectly insulated from the warm interior, retaining its initial temperature contrast. The porosity of the slab and interior are ignored to maximize the buoyancy contrast. The convecting asthenosphere is assumed free of salt, preferentially partitioned into the melt and extracted to the ocean. Furthermore, we assume no diffusion of salt from the downwelling slab to the convecting asthenosphere.

The ice shells are taken to be sufficiently thick so that the maximum slab penetration can be large (25 km for Europa, 50 km for Ganymede, 145 km for Enceladus), and the lithosphere thickness is minimized at 3 km (F_B increases with H, while F_Y increases with H^2). This is appreciably thinner than lithosphere thicknesses predicted by thermal and tectonic models [e.g. 5].

Results and Discussion: With this simple force balance, we investigate whether it is plausible for slab pull to initiate and/or maintain subduction and drive Earth-like plate tectonics in outer H_2O ice shells. We perform this analysis for Europa, Enceladus, and Ganymede, spanning from the smallest to the largest icy satellites with observed tectonics.

While the large gravity of Ganymede and potentially thick ice shell of Enceladus are more conducive to subduction than the ice shell of Europa, we find that negative slab buoyancy alone is unlikely to allow the initiation of subduction in any of the broad range of icy satellites considered (Fig. 2). For example, initiating subduction on Europa in pristine lithosphere ($\mu = 0.6$, $C = 1$ MPa) requires a density contrast of >400 kg/m^3 when the slab has penetrated 10% of the ice shell, and >70 kg/m^3 if the lithosphere has somehow already penetrated to the base. For comparison, Johnson *et al.* [1] find that on Europa, maximum sustained density contrasts may be just ~30 kg/m^3.

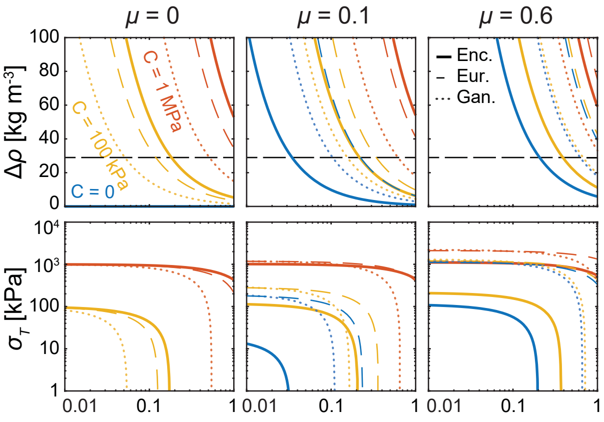

Figure 2: Force balance predictions of the density contrast between the downwelling lithosphere slab and warm asthenosphere (top) and regional driving stresses (bottom) required to satisfy Eq. 5. Colored lines show failure curves for different cohesion values for Enceladus (solid, bold), Europa (thin, dashed), and Ganymede (thin, dotted). Columns show results for differing coefficients of internal friction. The black dashed line (top figures) shows the maximum sustained buoyancy contrast predicted by Johnson *et al.* [1].

If a slab penetrates far into the ice shell in response to external forcing, subduction can be maintained only if the subduction zone has greatly reduced strength. For example, if cohesion is reduced to ~100 kPa and the coefficient of internal friction is reduced to 0.1, subduction can be buoyantly maintained on Ganymede for a density contrast of 30 kg/m^3 once the slab has penetrated ~10% of the ice shell thickness. While the gravity of Enceladus is low, the ice shell may be very thick. If subduction zone cohesion is reduced to 100 kPa and the coefficient of friction remains 0.6, subduction becomes self-sustaining when the slab has penetrated ~50% of the ice shell thickness (~70 km).

The external forces required to initiate subduction in pristine ice are 1-2 MPa. For comparison, diurnal tidal forces on Europa are on the order 100 kPa and reverse sign cyclically [9]. Thus, sustained secular tidal stresses, e.g. non-synchronous rotation or true polar wander, would be required to initiate subduction for realistic density contrasts [1] and to sustain subduction unless ice shell strength is greatly reduced.

Conclusions: In the outer ice shells of icy satellites, the density contrast between subducting lithosphere and warm asthenosphere is small compared to the mechanical strength of the lithosphere, even under the most favorable assumptions. Thus, slab pull is unlikely to initiate subduction in the outer H_2O ice shells of icy satellites, and will maintain ongoing subduction only when the subduction zone is weakened significantly compared to pristine lithosphere. An Earth-like cycle of convectively driven plate tectonics is therefore unlikely on any icy satellite.

If the strength of the ice shell is significantly lower than considered here (i.e. if the cohesion and coefficient of friction are orders of magnitude smaller), the negative buoyancy of the slab could plausibly drive subduction. However, such a weak ice shell would have to be reconciled with the reliance of slab pull on the elastic transmission of stresses, and inferences of elastically supported topography from spacecraft observations.

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