THE PHYSICS OF SUBSUMPTION: IMPLICATIONS FOR DETECTING ACTIVE CONVERGENT MARGINS IN OCEAN WORLD ICE SHELLS. S. M. Howell[1] (samuel.m.howell@jpl.nasa.gov) and R. T. Pappalardo[1], [1]Jet Propulsion Laboratory, California Institute of Technology

Introduction: The outer H_2O ice shell of Europa, a Galilean satellite of Jupiter with a global interior water ocean, has experienced significant tectonic modification in its outer ice shell over its ~60 Myr visible history. While the most prevalent tectonics are observed to be extensional in nature [1,2], Voyager and Galileo spacecraft images of Europa show little evidence of corresponding convergent tectonics. Understanding if and where tectonic transport and recycling of surface material occurs has fundamental implications for Europa habitability because such processes may allow oxidants produced at the surface to reach a reducing seafloor [3,4].

Foundational to the understanding of convergence in Europa's ice shell, *Kattenhorn and Prockter* [5] reconstructed a 134,000 km^2 region of Europa, and found evidence for the removal of ~20,000 km^2 of surface material. That study proposed that subduction-like "subsumption" may allow old lithosphere slabs to be reincorporated into the ice shell and recycled on a timescale similar to the surface age of the body.

Johnson et al. [6] investigated whether a subducting ice shell slab could remain permanently negatively buoyant, and hypothesized such a density contrast could potentially provide a mechanism for interior incorporation of entrained surface material. *Howell and Pappalardo* [7] extended these models to understand the forces acting on a subsuming plate within Europa's ice shell, and found that slabs will quickly warm, losing their viscous strength well before reaching the deep ice shell interior, precluding Earth-like subduction on icy worlds.

In this study, we use pseudo two-dimensional models of an icy slab intruding into the ice shell interior [6,7] to predict slab temperature, density, porosity, and composition over time. As a slab subsumes, we predict the isostatic topography and topographic slope, as well as the time and distance scales over which the slab is reincorporated into the interior of the ice shell.

Methods: The subsumption model (**Fig. 1**) is discretized in two ways. First, the slab is discretized perpendicular to its surface over slab thickness, *H*. Second, the solution marches forward explicitly with increasing length of subducted slab, *L*. As the slab descends, we solve conservation of heat in one-dimension within the slab, perpendicular to the slab surface,

$$\rho C_P \frac{\partial T}{\partial t} = -\frac{\partial q}{\partial s},$$

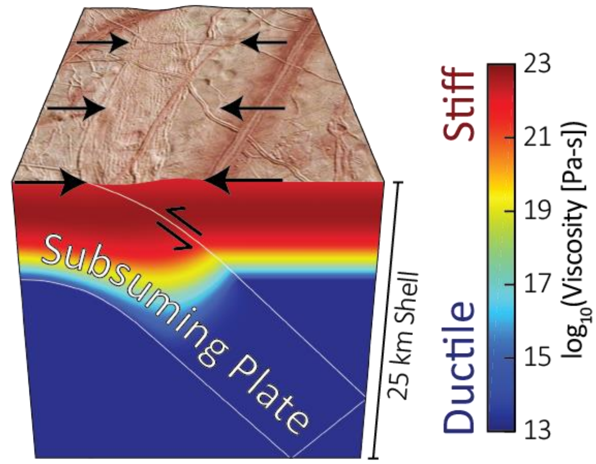

Figure 1: *Example model output in oblique view showing viscosity loss as an intruding lithosphere slab intrudes into the warmer interior ice.*

where ρ is the density, C_p, is the specific heat capacity, *T* is temperature, *t* is time, *q* is heat flux, and *s* is depth within the slab.

We calculate density profiles within the slab and within the satellite's ice shell interior as a function of: temperature-dependent thermal expansivity, α, the temperature difference across the layer, ΔT, the fraction of densifying salts by volume, f_{SALT}, the density of the salt, ρ_{SALT}, the reference density of the interior, ρ_0, and the evolving porosity, ϕ, expressed as

$$\rho = \left\{\alpha \Delta T\left[(1-f_{SALT})\rho_0 + f_{SALT}\rho_{SALT}\right]\right\}(1-\phi) \ .$$

By comparing the resulting density structure in the slab with the density structure of the surroundings, we calculate the expected isostatic topography and topographic slope at the ice shell surface.

Models: We investigate a range of initial slab and lithosphere thicknesses, spanning 10-50% of the assumed ice shell thickness (25 km). For each slab thickness, we investigate the effect of an initial porosity (up to 20%) that evolves through time with changing temperature, pressure, and viscosity. We also look at the effect of a slab containing up to 15% densifying salts.

For each combination of parameters, we run models at two convergence rates. The faster rate (40 km/Myr) is consistent with terrestrial subduction and previous Europa resurfacing calculations [5,7]. The slower rate (4 km/Myr) reduces the energy required to drive convergence. Lower convergence rates may be more plausible from a force-balance perspective in ocean world ice shells [7].

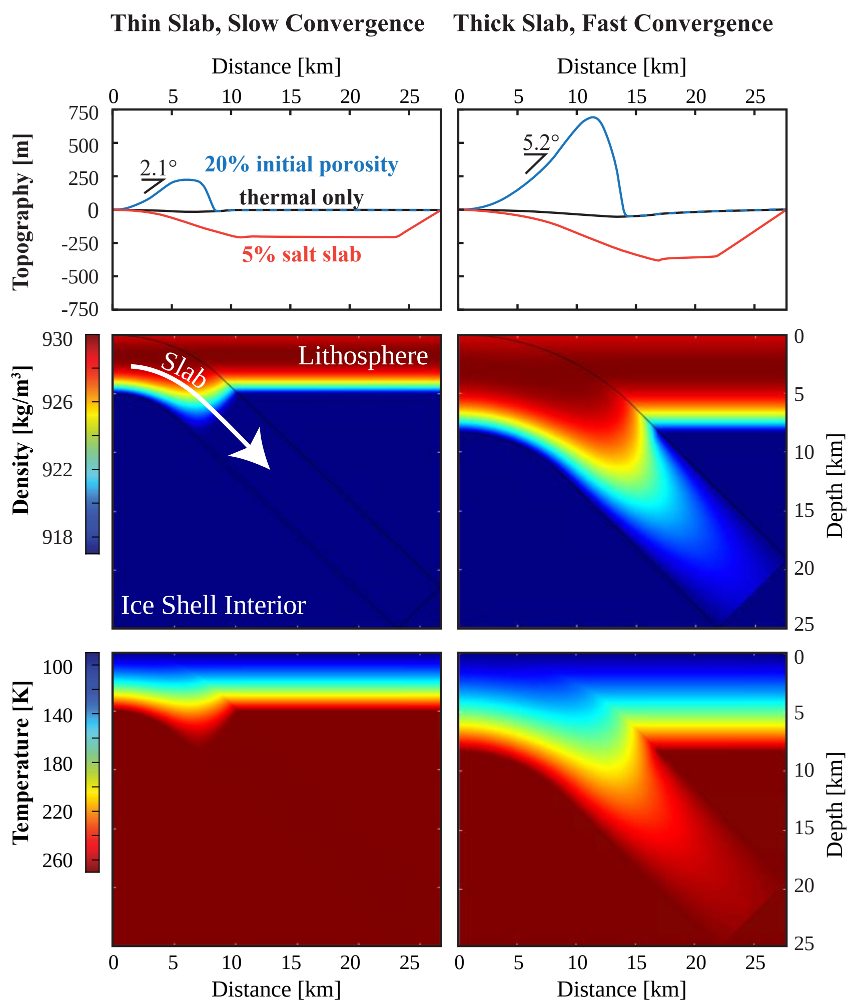

Figure 2: Example model predictions of Europa slab evolution for 25 km thick ice shells. Isostatic topography (top) is computed from the predicted density anomaly (middle) due to the temperature structure of the subsuming slab (bottom), in addition to porosity and composition (not shown). Models with (left) a 5 km thick lithosphere and 4 km/Myr convergence rate quickly lose their buoyancy and produce little topography. Models with an 8 km thick slab and convergence rate of 40 km/Myr produce more and longer-lived topography. With no initial slab porosity and for pure ice, <100 m of topographic variation is expected. This results in slopes of <1°. For large initial porosities and salt contents, topography of 100s m may produce slopes up to 5°.

Results: For increasing slab thickness, the predicted isostatic topography increases (**Fig. 2**). This occurs because thicker slabs take longer to thermally equilibrate with their surroundings, retaining their thermal structure, and thus density structure longer. Similarly, faster convergence rates result in greater topography because the faster moving slab reaches a greater depth before losing its density structure.

Limited topographic relief (<100 m) is produced by the thermal anomaly of the subsumed ice (**Fig. 2**), with predicted topographic slopes of <1°. Significant porosity or salt content within the slab may allow for 100s m topographic relief and slopes of up to ~5°.

Conclusions and Perspectives: Slabs thrust into the ice shell interior will quickly reach thermal equilibrium. As these slabs equilibrate, they subsume, losing their density and mechanical contrasts with the surroundings. In general, our models predict very little isostatic topography associated with subsumption, even if the predicted density anomalies persisted indefinitely through time. Elastic flexure at active subsumption zones may contribute to the dynamic topography, though low interior viscosities, thin elastic layers, and potentially low driving strain rates would limit any elastic behavior.

Future robotic exploration of Europa, including NASA's planned Europa Clipper mission, may have difficulty detecting topographic variations of ~100 m over distances of 10s km. Therefore, geologic mapping and reconstruction of convergent margins may continue to offer the best mechanism for detecting regions of subsumption. A possible additional method of detecting active convergent margins is radar investigation of potential compositional variations associated with active or fossil geological processes [8].

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