EFFECTS OF PLASTICITY ON CONVECTION IN AN ICE SHELL: IMPLICATIONS FOR EUROPA.
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Summary: Europa's icy surface displays numerous pits, uplifts, and disrupted terrains that have been suggested to result from convection in the ice shell [1, 2]. In "stagnant-lid" convection, the topography is minimal, because the ascending and descending plumes below the stagnant lid have insufficient buoyancy to produce surface deformation [3]. However, recent studies imply that Europa's ice shell is extremely weak [4], raising the possibility that brittle deformation plays a role in the convection (thereby pushing the convection away from the stagnant-lid mode). Here we present numerical simulations of convection in Europa's ice-shell including the effects of plasticity, which provides a continuum representation for deformation along fractures. The simulations show that multiple modes of behavior are possible. In some cases, plastic deformation plays a major role in the convection by allowing the cold regions to deform, which produces large lateral density contrasts and leads to topographic features up to ~ 100 m tall. In other cases, the stresses remain low enough that little plastic deformation occurs, and stagnant-lid convection, with minimal topography, results.

Introduction: Europa's mottled terrain consists predominantly of chaos terrains, comprised of hummocky material and disrupted crustal blocks, and numerous small (3–30 km-diameter) pits, uplifts, and irregularly shaped landforms [1, 2, 5]. Pappalardo et al. [1] and others suggested that Europa's ice shell undergoes solid-state convection vigorous enough to flex, and perhaps fracture, the lithosphere, producing the observed landforms. To test this idea, Showman and Han [3] performed numerical simulations with Newtonian temperature-dependent viscosity. Topography results from horizontal density contrasts in the ice, so the issue is whether convection can generate large horizontal density contrasts. In Showman and Han's simulations, the ratio of maximum to minimum viscosity (called the viscosity contrast) was a free parameter, held constant within a given simulation, that was varied from 10^2–10^9. When the viscosity contrast $\geq 10^6$, a stagnant lid formed at the surface, rising and sinking plumes had minimal buoyancy, and isolated pits and uplifts did not form. Only when the viscosity contrast $\leq 10^5$ did substantial topography occur, because in this case the cold, dense ice at 1–2 km depth was ductile enough to participate in the convection (allowing large horizontal density contrasts). If viscous creep is the only deformation mechanism, then the actual viscosity contrast exceeds 10^{10} and convection in a pure ice shell cannot produce Europa's pits and uplifts.

However, recent models for the formation of cycloidal ridges imply that the fracture yield stress is only 0.4 bars [4]. This strength is comparable to convective stresses, raising the possibility that brittle deformation plays a role in the convection (a phenomenon that may be important on Earth [6, 7]). Here, we present two-dimensional numerical simulations of convection in Europa's ice shell including plastic deformation, which provides a simple representation for flow along fractures. Such deformation can occur over a wide range of temperatures, possibly allowing large horizontal density contrasts in the convecting region. Our goal is to elucidate how the plasticity affects the convection and determine the resulting dynamic topography.

Model and Methods. We used the Conman finite-element code to solve the incompressible (Boussinesq) fluid equations neglecting inertia, as appropriate to a viscous, slowly convecting system. The velocity boundary conditions are periodic on the sides and free-slip rigid walls on the top and bottom. The bottom surface is maintained at the melting temperature (270 K), as required by the underlying ocean, and the top surface is held at 95 K. For the simulations presented here, the layer thickness is 30 km [8] and the Rayleigh number (evaluated using the viscosity at the base) ranges from 10^7 to 10^8. In these preliminary simulations, no tidal heating is included.

We follow the approach of [7] for incorporating plastic rheology into the simulations. The relevant parameter is the "effective viscosity," η_{eff} defined as

$$\eta_{eff} = \min\left[\eta(T), \frac{\sigma_Y(z)}{2\dot{\epsilon}}\right] \qquad (1)$$

where $\eta(T)$ is the thermally activated viscosity, σ_Y is a depth-dependent yield stress, and $\dot{\epsilon}$ is the second invariant of the strain rate ($\dot{\epsilon} = \sqrt{\dot{\epsilon}_{ij}\dot{\epsilon}_{ij}}$). We adopt a yield stress that increases with depth within the top 3 km (as expected for Byerlee's law) and is constant at greater depth, as expected for semibrittle flow [6, 9], with a value ranging from 0.1–1 bar.

The thermally activated viscosity is Newtonian, with a strong temperature-dependence ranging over a factor of 10^8:

$$\eta(T) = \eta_0 \min\left[\exp\left\{A\left(\frac{T_m}{T} - 1\right)\right\}, 10^8\right] \qquad (2)$$

where T is temperature, T_m is melting temperature, and η_0 is the viscosity at the melting temperature. We adopt $A = 26$, corresponding to an activation energy of 60 kJ mole^{-1}.

Results. Figures 1 and 2 show two divergent modes of behavior for simulations with a deep yield stress σ_Y of 0.2 bars. The simulations were identical except for the initial condition; both used $\eta_0 = 10^{13}$ Pa sec and had a basal Rayleigh number of 9.3×10^7. In Fig. 1, the initial temperature was 90% of the melting temperature, with a small perturbation to break the symmetry. The uppermost layers rapidly cool and stiffen, forming a stagnant lid that remains intact throughout the simulation. The underlying convective region equilibrates to a temperature $\sim 97\%$ of the melting temperature. Convective plumes, which have temperature contrasts of generally $< 4\%$ relative to the surrounding ice, rise from the base of the system and descend from the underside of the stagnant lid. Because of their small density contrasts, the plumes have negligible influence on the surface topography. Instead, smooth topographic swells with ~ 25 m amplitude and ~ 40 km wavelength occur; these swells are correlated with horizontal thickness variations in the stagnant lid. In this simulation, the high temperatures below the stagnant lid allow low-enough viscosities that rapid overturning can occur despite low stresses. The deformation therefore remains predominantly viscous rather than plastic.

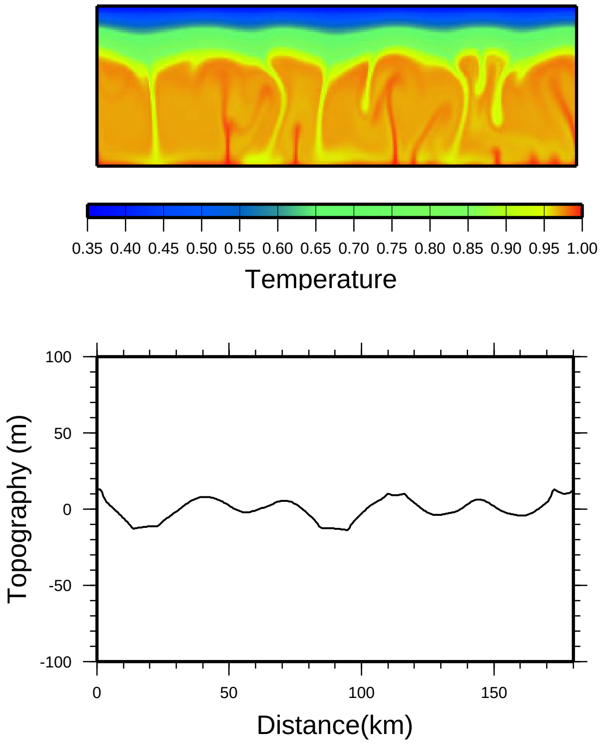

Figure 1: Temperature divided by melting temperature (top) and dynamic topography (bottom) for a simulation in a domain 180 km wide and 30 km deep.

Fig. 2 shows a simulation identical to that in Fig. 1 except that the initial temperature was 65% of the melting temperature (with a small perturbation to break the symmetry); similar results also occur for an initial temperature that is 79% of the melting temperature. As with Fig. 1, cold and warm boundary layers grow at the top and bottom, respectively, but in contrast to Fig. 1, the stiffer initial viscosity allows buildup of the density contrasts and stresses, triggering plastic deformation. The system finally equilibrates at a temperature ~70% of the melting temperature, with plastic deformation playing a crucial role in the convection. The upper lid is not stagnant; instead, it undergoes large-scale deformation because of the plasticity. Large lateral density contrasts occur, producing topography with amplitude of ~100 m and horizontal lengthscale of 30–50 km.

Conclusion: Plasticity can affect convection in an ice shell by allowing deformation in cold layers that would otherwise be too stiff to move. In numerical simulations with a deep yield stress of 0.2 bars, our simulations suggest that two quasi-equilibrium states are possible. In the first, the temperatures in the convecting region are warm enough for overturning to occur at stresses low enough that plastic deformation is minimal. In the second, the temperatures are cooler, density contrasts and stresses are higher, and plastic deformation allows an equilibrium to be reached that prevents the system from heating up toward the first equilbrium state (which it would do in the absence of plastic deformation). The possible relevance of the second equilibrium for Europa remains unclear, as the dynamics depend sensitively on both yield stress and initial conditions in ways that have yet to be fully elucidated. Nevertheless, the simulations show that plastic deformation can occur under Europa-like conditions, and might contribute to formation of Europa's disrupted terrains; additional simulations will help determine more precisely whether such deformation is actually important on Europa.

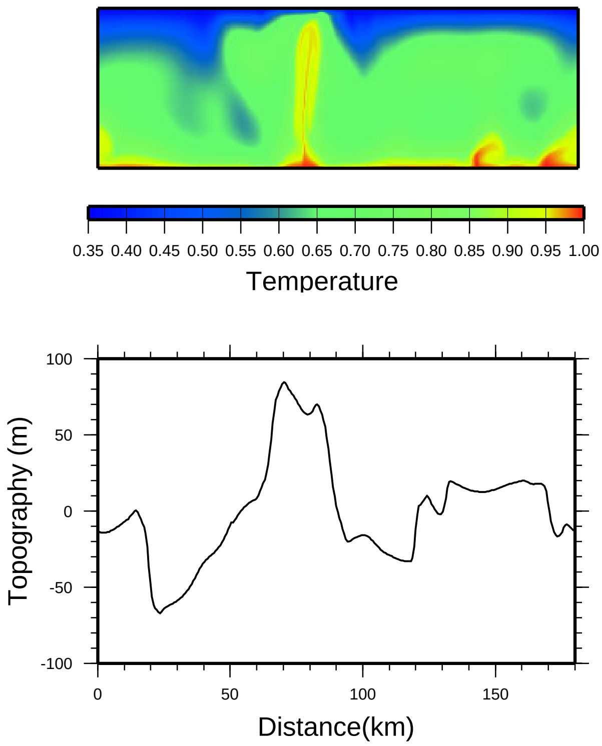

Figure 2: As in Fig. 1, for another simulation that is identical except for initial condition.

References: **[1].** Pappalardo, R.T. et al. Nature 391, 365-368 (1998). **[2].** Spaun, N.A. Ph.D. Thesis, Brown University (2002). **[3].** Showman, A.P., L. Han, JGR Planets, in press (2004). **[4].** Hoppa, G.V. et al. Science 285, 1899-1902 (1999). **[5].** Greeley, R. et al. Icarus 135, 4-24 (1998). **[6].** Tackley, P.J. Science 288, 2002-2007 (2000). **[7].** Tackley, P.J. Geochem. Geophys. Geosyst. 1, 2000GC000036. **[8].** Hussmann, H., Spohn, T., and Wieczerkowski, K. Icarus 156, 143-151 (2002). **[9].** Kohlstedt, D.L., B. Evans, and S.J. Mackwell, JGR 100, 17587-17602 (1995).