NON-NEWTONIAN CONVECTION AND COMPOSITIONAL BUOYANCY: ADVANCES IN MODELING CONVECTION AND DOME FORMATION ON EUROPA.

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Overview: Numerical modeling of non-Newtonian convection in ice shows that convection controlled by grain boundary sliding rheology may occur in Europa. This modeling confirms that thermal convection alone cannot produce significant dome elevations. Domes may instead be produced by diapirs initiated by thermal convection that in turn induces compositional segregation. Exclusion of impurities from warm upwellings would allow sufficient buoyancy for icy plumes to account for the observed ~100 m topography of domes, provided the ice shell has a small effective elastic thickness (~0.2 to 0.5 km) and contains low-eutectic-point impurities at the few percent level.

Non-Newtonian Convection: We have modified the finite-element convection software Citcom to employ a non-Newtonian rheology appropriate to ice [1]. For the low convective stresses in Europa (≤0.1 MPa), ice rheology is likely controlled by grain boundary sliding (GBS). Basal slip can become important if the grain size of ice is small (0.1 to 1 mm). The dynamics of convection in a non-Newtonian fluid are characterized by a Rayleigh number in which the viscosity and strain rate are explicitly evaluated in terms of the laboratory-derived flow law as:

$$Ra = \frac{\rho g \alpha \Delta T D^{(n+2)/n}}{\kappa^{1/n} \left(\frac{d^p}{A}\right)^{(1/n)} \exp\left(\frac{Q^*}{nRT}\right)}$$

where g is gravity, ρ is ice density, κ is thermal diffusivity, d is ice grain size, A is a rheological parameter, Q^* is the activation energy, n is the stress exponent, and p is the grain-size exponent.

In accordance with GBS rheology, the Rayleigh number appropriate to Europa's ice shell is grain-size dependent. Melting point viscosities for GBS ice evaluated at the reference strain rate (κD^{-2}) are much larger than assumed for Newtonian flow laws. GBS with the $d =$ 0.1 mm yields a melting point viscosity (T = 260 K) of 4 x 10^{16} Pa s at the reference strain rate 3 x 10^{-16} s^{-1}. Fig. 1 shows a numerical result with a Rayleigh number of 10^5, appropriate to ice with a grain size of 0.1 mm in a 60 km thick shell. Even if Europa's ice shell is its maximum 120 km thick, it may not convect in the absence of tidal forcing if it has a dominant grain size substantially larger than 1 mm.

Non-Newtonian convection drives very low amplitude topography, with the simulation of Fig. 1 predicting 14 meters of vertical relief between swells and troughs separated by ~80 km. The average surface heat flow is 20 mW m^{-2}. Strain rates within the convecting ice shell are ~3 to 8 x 10^{-13} s^{-1}, which is about 1000 times smaller than the average tidal strain rate of 2x10^{-10} s^{-1}. As in Newtonian simulations, the ice shell is in the stagnant lid regime, here spanning the top 35% of the ice shell. The shapes of convection cells are more squared than in Newtonian rheologies, so the cold columns of ice associated with convective downwellings are very narrow. Radar experiments hoping to exploit the transparency of these relatively cold downwellings are predicted to have a small target.

The simulation of Fig. 1 assumes a very small grain size (0.1 mm). In thinner ice shells or ice shells with larger grain sizes, convection controlled by GBS rheology may occur not in the absence of tidal forcing and dissipation, and tidal dissipation and/or tidal modification of viscosity may be required to trigger and sustain convection. Basal slip rheology could permit convection in thinner, basally-heated ice shells.

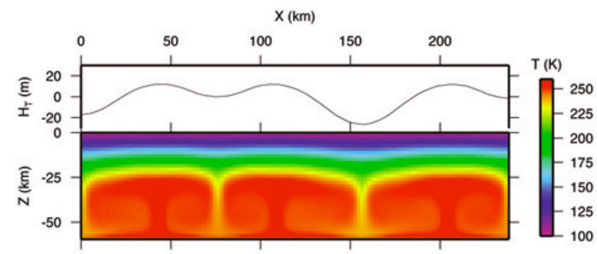

Fig. 1. Numerical simulation of non-Newtonian convection of ice with a GBS rheology and Ra = 10^5, and associated thermally induced topography (top).

Compositional Buoyancy: Differences in impurity levels serve as a potential source of compositional buoyancy to drive diapiric rise, and may be relevant to Europa dome formation (Fig. 2). A convecting icy shell is expected to have a nearly isothermal adiabatic temperature, T_{ad}, beneath a rigid stagnant lid; the non-Newtonian simulation shown in Fig. 1 gives $T_{ad} \approx 250$ K. Both sulfate and chloride contaminants are plausible constituents of Europa's icy shell [2,3]. Hydrated sulfate salts have eutectic temperatures [3,4] ~270 K, securely above the predicted T_{ad} for Europa; therefore, these salts are expected to be stable against eutectic melting. However, the eutectic temperatures of hydrated chloride salts are in the range ~220 to 250 K [4], i.e. less than or comparable to the expected T_{ad}. Moreover, the ice-H_2SO_4 system has a eutectic of 211 K [3]. If hydrated chloride salts or sulfuric acid (which we collectively term "low-eutectic" contaminants) exist within Europa's ice shell, they are expected to melt and produce brines in response to thermal convection. This should be the case throughout the warm base of the ice shell, and wherever a warm ice plume contacts colder contaminant-rich ice.

Melt is expected to drain through the ice at ~10 m yr^{-1} [5], significantly faster than the ~0.1 to 1 m yr^{-1} vertical velocity of convective ice plumes. Therefore, the warm base of the ice shell and the convective plumes that rise from it are expected to be relatively clean of low-eutectic impurities (Fig. 2).

In this model, low-eutectic contaminants are expected to become depleted in the ice shell over time unless replenished. It is plausible that Europa's ice shell is not in steady-state, but that instead its youthful surface age reflects a latest incarnation of the ice shell, which began as relatively contaminant-rich and is more recently depleted in contaminants over time.

The warmer ice of a rising diapir will be cleaner and thus compositionally buoyant relative to its surroundings. Assuming isostasy above a column cleaned of low-eutectic contaminants through diapiric rise,

$$P_d = \phi(\rho_{le} - \rho_o)\, g\, D$$

where ρ_{le} is the average density of the low-eutectic solids, ρ_o is the ambient density of the impure ice shell, and ϕ is the volume fraction of low-eutectic contaminants that melt and drain from diapiric plumes.

Choosing ρ_o = 1000 kg m^{-3} and ρ_{le} = 1500 kg m^{-3}, $\phi \sim 2\%$ can produce $P_d \sim 10^5$ Pa for a range of reasonable ice shell thicknesses, sufficient to upwarp domes to observed (~100 m) heights for intrusions beneath a brittle ice cover of T_e ~0.2 to 0.5 km for Young's modulus $E \sim 10^9$ to 10^{10} Pa [6]. The minor amounts of low-eutectic contaminants required are consistent with geochemical models of Europa's evolution [3].

Thermally-driven compositional segregation may be analogous to double-diffusive convection (DDC), in which both thermal and compositional gradients trigger fluid motions. DDC systems are governed by the thermal Rayleigh number

$$\mathrm{Ra} = \rho g \alpha \Delta T D^3 / \kappa \eta$$

for viscosity η, and a compositional Rayleigh number

$$\mathrm{Ra_c} = \rho g \beta \Delta C D^3 / \eta \kappa_c$$

where ΔC is the vertical composition gradient of low-eutectic contaminants across the ice shell, $\beta = (\rho_{le} - \rho_o) / \rho_o$, and κ_c is compositional diffusivity.

In the finger regime, compositionally buoyant material rises in narrow upwellings much smaller than the shell's thickness. This could be the case for Europa. The onset of the finger regime can be expressed as:

$$\kappa_c < \kappa \beta \Delta C \left[\frac{27\pi^4}{4} \frac{\eta}{\rho g D^3} + \frac{\alpha \Delta T}{\kappa} \right]^{-1}$$

[7]. For an ice shell viscosity $\eta = 10^{18}$ Pa s, thermal diffusivity $\kappa = 10^{-6}$ m^2 s^{-1}, and D = 20 km, convection in the finger regime occurs if $\kappa_c \leq 10^{-7}$ m^2 s^{-1}.

$$\frac{\rho_o g D^4}{\eta} \left[\frac{\beta \Delta C}{\kappa_c D} - \frac{\alpha \Delta T}{\kappa D} \right] > 657$$

Compositional diffusion may be governed by melt composition, drainage velocity, and a characteristic length scale for a Europan drainage channel. These parameters are poorly constrained, so we cannot draw firm conclusions regarding the relevance to Europa's ice shell. True DDC predicts that the system evolves toward a steady state, but here contaminants are depleted in the ice shell over time, so DDC serves as only a starting point for modeling relevant processes.

Thermally induced compositional buoyancy offers a comprehensive and geophysically plausible means for forming Europa's domes [6]. An analogous model has been applied to bands [8] and is potentially applicable to the satellite's larger chaos regions. The model implies compositional heterogeneity on a local scale within the ice shell, possibly detectable by future missions using ground penetrating radar. The process would allow deep interior material to breach Europa's cold brittle lithosphere, potentially transporting oceanic and astrobiologically relevant materials to the surface where they could be examined by spacecraft.

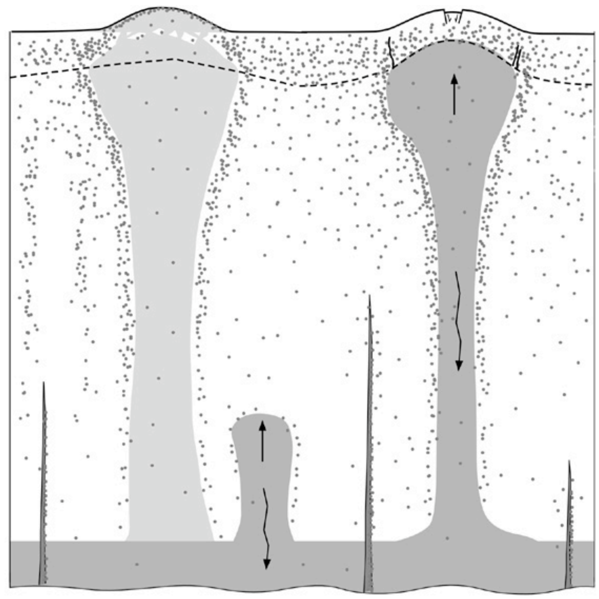

Fig. 2. Schematic illustration of thermally induced compositional diapirism. As warm ice (dark gray) rises from the base of the ice shell, it melts overlying low-eutectic contaminants (stipples) and brines drain downward (squiggled arrows). This allows compositional buoyancy to aid diapiric rise. Domes can be created by extrusion (left) or intrusion (right) of diapiric material. Low-eutectic contaminant concentration is least in the warmest ice and locally concentrated around the diapirs from which they are expelled. Dome topography and subsurface compositional gradients persist after plumes have cooled (left, lighter gray) until subsequent ice flow redistributes the constituents. Diking or other processes might replenish some oceanic contaminants, but it is likely that the ice shell will become depleted in contaminants over time.

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