FOMENTING CHAOS: FORMATION ON EUROPA THROUGH DRY POROUS COMPACTION.

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Introduction: Europa's ice shell hosts a myriad of potentially ongoing active geologic processes, including tectonic extension, convergence, and strike-slip deformation [e.g. 1–3]. In addition to familiar tectonic landforms, Europa also hosts chaotic terrains of intact blocks of surface material rafted in an icy matrix [4,5].

The formation mechanisms for chaos are highly uncertain, with the most prominent hypotheses requiring subsurface melting within a few kilometers or less of the surface over lateral extents of 10s of kilometers or greater [5–6]. However, the high thermal conductivity of cryogenic ice and low endogenic energy available at Europa create conditions where subsurface fluids should rapidly freeze or drain on timescales of less than 10^3 – 10^4 yr [7–8], casting into question the high-energy processes that may allow melt formation.

In this study, we investigate one mechanism for chaos formation through one-dimensional models of icy evolution at Europa. We propose the resulting *porous compaction* as the most likely mechanism for chaos formation because it requires little added energy.

Modeling Method: We numerically solve heat conduction and diffusion in one dimension (1D),

$$\frac{\partial T}{\partial t} = \frac{k(T,\phi)}{\rho(T,\phi)C_p(T)}\frac{\partial T}{\partial z}. \tag{1}$$

Here, T is temperature, t is time, φ is porosity, k is thermal conductivity, ρ is density, C_p is specific heat capacity, and z is depth. We additionally solve the time-dependent porous evolution of the lithosphere,

$$\frac{\partial \phi}{\partial t} = \frac{\phi P(z)}{\eta(T)}, \tag{2}$$

where P is pressure and η is viscosity. Because the viscosity of interest is that of viscous flow in the ductile portion of the ice shell, we approximate ice viscosity with Newtonian diffusion creep [2–3,9]. This model uses a finite difference Forward Euler Approximation to the above, solved on a conservative staggered grid, and is explicit forward in time.

Because the porosity of Europa's ice shell likely varies tens-of-percent across the surface [e.g. 10], we impose a 20% porosity throughout the entire modeled domain, and then we let it evolve over the approximate average surface age of 60 Myr. The evolved ice shell is then used as the starting condition for this study, consistent with other 1D and pseudo-2D models of Europa's deformation [2–3].

The Dirichlet top boundary condition enforces a surface temperature of 100 K. Energy is introduced into the domain by allowing a Neumann bottom boundary condition to add an excess heat flux to the steady-state solution. By controlling the rate at which energy is added to the domain, we model a range of potential warming processes at difference scales on Europa, including diapirism, melt injection, tectonic thinning, etc., through the bottom boundary.

Results: An example result is shown in Fig. 1. The starting point of the model includes a porous layer of the lithosphere that rapidly transitions to a pore-free layer with depth as energy is added. This rapid transition occurs at the depth and temperature where the overburden pressure is sufficient to drive the ice of given viscosity to flow over the timescale of Europa's surface age (or faster).

As heat is introduced into the model, the exponential dependence of viscosity on temperature results in a rapid decrease in resistance to flow at the base of the porous layer. Portions of the previously porous layer become mobile, because the overburden pressure causes the now lower-viscosity material to flow, compacting its pores. This compaction and flow defines the process of *porous compaction* as used here.

As a result of porous compaction, significant strain accumulates at the base of the porous layer. In the example, a change in basal layer temperature of 50 K produces strains of ~20 %, corresponding to ~200 m of compaction and deformation at ~2.5 km depth.

Description of Porous Compaction Mechanism: We propose porous compaction as the most likely mechanism for chaos formation on Europa. Specifically, we propose that one of two scenarios can occur as a result of this mechanism, which we refer to

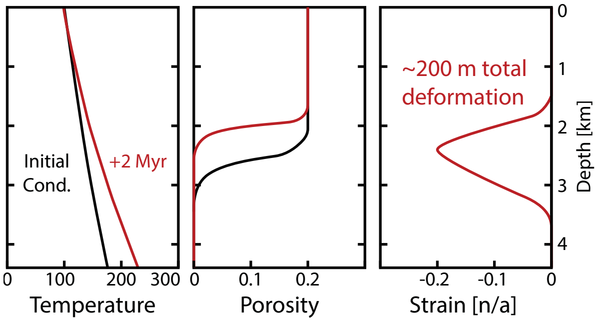

Figure 1 | Model results for an example case run with an imposed 50 K thermal anomaly for 2 Myr, exhibiting ~200 m porous compaction at ~2.5 km depth, accommodated within the top several kilometers of a porous lithosphere.

as *catastrophic collapse* and *progressive subsidence* (Fig. 2).

Catastrophic Collapse: In the collapse scenario, porosity compaction at depth is decoupled from broader porous layer deformation. The mechanical strength of the ice prevents the full porous layer and surface from deforming broadly in response to porous compaction at depth. Thus, compaction proceeds at depth and a cavity is formed that preserves the original bulk porosity. As the base of the porous layer is compacted, it is insulated by the growing cavity that prevents the efficient transfer of heat by conduction. After reaching some lateral extent, the overriding ice would fail and catastrophic collapse would occur. This process is analogous to chaos formation on Mars resulting from sublimation of the supporting layer [11].

Progressive Subsidence: In the subsidence scenario, the strain related to porous compaction is accommodated at the base of the porous layer, resulting in a depressed surface layer. Over time, the downflexed surface may be stressed by this subsidence until failure, resulting in the progressive formation of disrupted surface blocks. This mechanism is akin to those previously invoked to explain long-wavelength topography on Enceladus through porous compaction above warm subsurface material [12]. Follow-on work will force-balance analyses of how bending stresses induced by the down-flexed porous plate might result in near-surface failure as subsidence progresses [e.g. 13].

Discussion: The simplest and most broadly available endogenic energy source for chaos formation is the gravitational potential energy of the ice shell itself. This gravitational potential energy can be converted into kinetic energy and mechanical deformation by erosion or compaction of the underlaying layers. The mechanisms presented here produce chaos by forming a large, weak cavity that facilitates gravity-driven surface deformation.

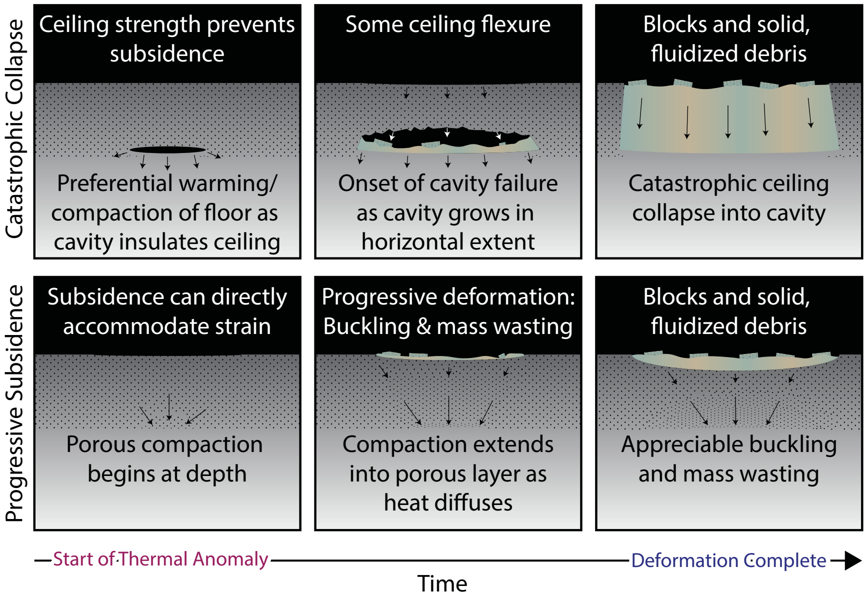

Figure 2 | Formation of chaos in response to a local thermal anomaly through porous compaction by (top) the catastrophic collapse of surface ice into a growing void, and (bottom) the progressive subsidence of surface material.

The porous compaction mechanism contrasts with previously published models that require subsurface melt, which is energetically disfavored. As energy is added to Europa's ice shell, porous compaction must precede melting. For example shown in Fig. 1, the energy added to the ice shell is 2.3×10^{11} J/m^2. In contrast, melting the region to erode a similar amount of material would require $>2.1\times10^{12}$ J/km^3.

Conclusions: 1) Porous compaction provides a mechanism for the local gravitational failure of Europa's ice shell; 2) the porous compaction mechanism results in significant strain at shallow depths that can cause failure through subsidence or catastrophic collapse; 3) the relatively low energy required to explain chaos formation through dry porous compaction are an order of magnitude less than required by shallow melting, reducing the burden of finding a suitable endogenic source of heat for formation.

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