SIMULATING FORMATION OF TRITON'S CANTALOUPE TERRAIN BY COMPOSITIONAL DIAPIRS.

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Introduction: The cantaloupe terrain of Triton is characterized by regularly spaced, semi-circular depressions separated by irregular sub-parallel ridges. Schenk and Jackson [1] interpreted this morphology as similar to the surface expression of terrestrial salt diapirs, and applied a Rayleigh-Taylor instability analysis to estimate a formation time of ~1 Gyr for the terrain. The proposed instability was driven by the density contrast between a ~20 km thick layer of overlying dense ice such as CO_2 or ammonia dihydrate (ADH). The effects of thermal buoyancy were considered negligible.

Their applied Rayleigh-Taylor analysis is a parametric method that uses a constant bulk viscosity between the components and across the model space. In reality, the effective viscosity of the ices involved in overturn is highly temperature dependent and varies between the components. The thermal conductivities of CO_2 and ADH are significantly lower than that of water ice, and recent studies [2, 3] have implied that Triton's subsurface heat flow may have considerable non-radiogenic components. The effective surface age of Triton has also been revised downward, to as low as 10 Myr, challenging the relative age of formation for these putative diapirs [4].

This work seeks to re-examine and test the diapir formation hypothesis with modern numerical simulations, more realistic rheologies, and an updated understanding of Triton's surface age and dynamics, to test if the diapir hypothesis is still a plausible formation mechanism for cantaloupe terrain.

Methodology: To model numerically the flow of material within Triton's near-surface, we implement a material model for ice in the finite element code ASPECT (Advanced Solver for Problems in Earth's ConvecTion) [5]. We model the effective viscosity of the ices under consideration as that of Newtonian, temperature-dependent fluids using a formulation based on that of Nimmo and Spencer [3]:

$$\eta = \frac{\eta_0 E_A}{R} * \left(\frac{1}{T} - \frac{1}{T_0}\right) \qquad (1)$$

where η_0 is the viscosity at the reference temperature T_0, E_A is the activation temperature, and R is the gas constant. This relationship utilizes the fact that the various creep mechanisms are dominated by thermally activated processes at the low stresses of icy planetary crusts [6, 7].

The scale of an individual diapir is small compared to that of Triton's ice shell, which creates difficulties for model resolution. To avoid this problem, we run two suites of simulations: one "regional" (on the scale of cantaloupe terrain's global extent) and one "local" (on the scale of individual diapir fields). The outputs of interest in the regional simulations are the horizontal scale of the upwellings and the resulting temperature structure in the upper 50 km of the ice shell. This output is used as a boundary condition for the local simulations, in which we investigate the physical effects of deformation within the dense overlying layers.

Regional simulations: The regional-scale simulation domain is 1500 km wide by 300 km deep. Following the work of Nimmo and Spencer [3], we assume that heating from obliquity tides is sufficient to maintain an ammonia-rich ocean at this depth. The bottom boundary is thus set to 240 K, the average temperature of the proposed ocean, and the top to Triton's average surface temperature of 40 K. The other material parameters are set to those of water ice [3]. We implement the overlying layers as a compositional field with a thermal conductivity matching that of the material of interest, allowing them to insulate the subsurface *without* participating in deformation (justified below).

For a 20 km layer of pure ADH ice (thermal conductivity k = 1.5 $Wm^{-1}K^{-1}$), the maximum temperature observed at a depth of 50 km is ~160 K, and the minimum is 150 K. At the same depth, 20 km of CO_2 ice (k = 0.3 $Wm^{-1}K^{-1}$) allows temperatures to reach a maximum of 230 K beneath upwellings and a minimum of 180 K. Note that this minimum temperature is above the eutectic melting point for ADH, and the maximum potentially crosses the phase space of liquid CO_2.

Changes in the depth of the insulating layer affect both absolute temperatures within the ice shell and the vigor of convection, with thicker layers creating more organized and pronounced convection cells. For insulating layers 10 km and thinner, convection becomes time-varying, with the center of individual cells migrating over million year timescales.

Local simulations: We conduct the local scale simulations in a domain 250 km wide by 50 km deep. The upper portion of the domain is designated a compositional field of variable thickness with the full rheologic properties of the material. The bottom boundary of the domain is set to a range of average temperatures observed from the regional simulation. To promote the formation of a Rayleigh-Taylor instability, we perturb the boundary between the two materials by periodically varying its elevation. Three cases are tested: CO_2 overlying water ice; ADH overlying water ice; and CO_2 overlying ADH.

Three regimes of deformation are observed to develop. In the first regime, the boundary is stable over the age of the solar system. This regime occurs when the bottom temperature is relatively low (< 180 K), the upper, thermally insulating layer is thin (< 10 km), or both. All simulations involving ADH as the overlying layer fall into this regime, so we conclude that a layer of pure ADH is unlikely to overturn.

In the second regime, the boundary diffuses. Small downwellings of dense material begin to develop, but no overturn occurs. This regime occurs when the bottom temperature exceeds 180 K- effectively ruling out ADH as the underlying layer, as it exceeds the eutectic melting temperature of 176 K.

In the third regime, the bottom portion of the overlying layer rapidly delaminates, sinks, and mixes with the material below on a timescale of 10,000-100,000 years. The top 5-10 km of the thinned layer remains rigid, and no stable diapirs develop. This regime develops only when bottom temperatures are high (> 200 K) and the overlying layer is thick (up to 20 km).

Discussion: None of our model setups successfully recreate diapiric upwellings on the scale of cantaloupe terrain as predicted by [1]. Despite the relatively high temperatures produced by mantle convection and thermally insulating upper layers, Triton's extremely cold surface temperature (~40 K) creates a strong geothermal gradient. The effective viscosities within the upper 50 km of crust varied by as many as 5 orders of magnitude due to these thermal effects. In such an environment, the isoviscous flow required by a true Rayleigh-Taylor instability cannot function because upward-flowing material becomes too rigid to move. The compositional differences in rheology effectively prevent the two layers from deforming in a co-equal fashion; if the stronger layer is weak enough to deform, the weaker layer is so weak as to collapse and mix with the material below.

We note that although no diapirs breached the surface, the formation of incipient downwellings on the material boundaries is associated with concentrated stresses on the surface of up to ~3-4 MPa (Fig. 1). This is well in excess of the yield strength of these ices, implying that even incomplete overturn may substantially fracture the surface at periodic intervals. These fracture zones may subsequently be prone to increased sublimation of volatile ices (CH_4, CO, and N_2) within the substrate, as suggested by Croft et al. [8]. The depressions and ridges may have formed from advanced sublimation and associated scarp retreat. The most favorable case for this formation mechanism is a 10 km-thick layer of CO_2, which provides the best fit of subsurface temperatures (200-210 K at 50 km depth over a horizontal scale of ~750 km) and localization of stress without total delamination of the layer. A layer of this thickness would also result in time-varying convection deeper in the ice shell, allowing the center of the convection cells to migrate over time and potentially resurface a larger surface area.

Conclusions: Numerical simulations of the diapir model of cantaloupe terrain formation do not successfully recreate overturn as predicted by [1]. A high geothermal gradient in the near-surface, differing material rheologies, and the boundary conditions imposed by convection within the ice shell result in large viscosity contrasts that prevent diapir formation. The presence of a dense, rheologically weak, and thermally insulating ice on the surface may, however, promote localized fracture of the surface. Extensive sublimation of surface materials resulting from this fracture may play a role in resurfacing cantaloupe terrain. Estimating the time scales and required extent for such a process is the next phase of this work.

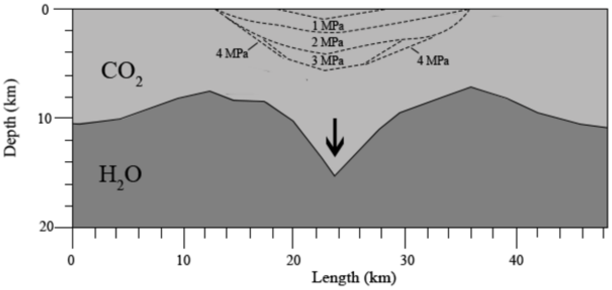

Figure 1: Schematic detail of local simulation output for a 10 km-thick CO_2 layer. The high density CO_2 has begun to sink (arrow), but the H_2O is too viscous to rise as a diapir. The incipient downwelling concentrates significant stress in the upper 2-4 km of the overlying CO_2.

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