DRIPPING TO DESTRUCTION: EXPLORING SALT-DRIVEN VISCOUS SURFACE CONVERGENCE IN EUROPA'S ICE SHELL.
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Introduction: A mismatch of visible surface creation and visible surface destruction has been a longstanding concern in the study of Europa's icy surface shell. This surface budget problem has been recently alleviated by various works [1][2] identifying regions of possible surface convergence in the shell. These convergent regions have been directly compared to Earth's subduction zones as possible sites of rigid icy slab subduction [1]. However, subsequent preliminary modeling studies of icy slab subduction [3][4] have demonstrated that the physical differences between Earth's lithosphere and Europa's icy shell present obstacles to generating a stable rigid slab subduction regime. An alternative possibility worth exploring is that geographic variation in ice salinity may drive significant lateral variation in surface ice viscosity, which may cause a catastrophic collapse of surface ice though viscous delamination.

Identified zones of icy convergence are known to be associated with elevated ice shell salt content [1] which may play a significant role in any surface downwelling [3]. This makes them a viable test bed for this idea of viscous icy collapse in a process akin to terrestrial lithospheric delamination [5]. Here, we shall outline a conceptual motivation for this phenomenon (Figure 1) and then describe a model exploring its physical ramifications, and discuss the implications that viscous deformation may have on convergent processes, shell geodynamics, and ocean habitability via shell-ocean interchange.

Conceptual Background: The two key conditions for icy Rayleigh-Taylor delamination are that the shell lithosphere develops sufficient gravitational instability and reduced viscosity such that the lithosphere, and potentially also the surface, founders into the interior. Increased salt content is an easily identifiable driver of gravitational instability in this scenario [3][4]. In addition, renewed focus on salt-enriched ice suggests that salt may also impact the ice rheology in a manner that would allow viscous deformation. Consensus is building in the Europa community on the importance of incorporated salts in the ice shell [6][7] leading to renewed focus on the work done on terrestrial sea ice exploring its formation and the physical and rheological differences between marine and meteoric ice [8][9]. These differences may have broad and significant impacts on our understanding of the Europan ice shell's physical and geodynamic behavior.

Accretion of frazil ice driven by double-diffusive ocean convection [10] during initial shell crystallization [9], along with other accretive [11] and post-accretive processes such as cryovolcanic sill formation [6], may lead to the development of geographically heterogeneous regions of salt-enrichment in the shell. While the impact of this salt enrichment in planetary ice shell contexts is poorly understood, native marine ices in terrestrial ice shelves, such as frazil ice, are known to encourage ice heating, increase porosity and brine intrusion, facilitate shear deformation and weakening, and discourage deformation by fracture [9].

Additionally, though still debated, it is generally accepted that salt-enriched ice is more susceptible to damage-driven weakening by cyclical loading (such as by tidal flexure) than meteoric ice [8]. This damaging process may impact the effective viscosity of the ice through a few possible mechanisms. The development of microfractures during cyclical loading may reduce the cohesive strength of the ice by 50% or more [8][12]. The development of lattice discontinuities may drastically reduce the ice's effective grain size,

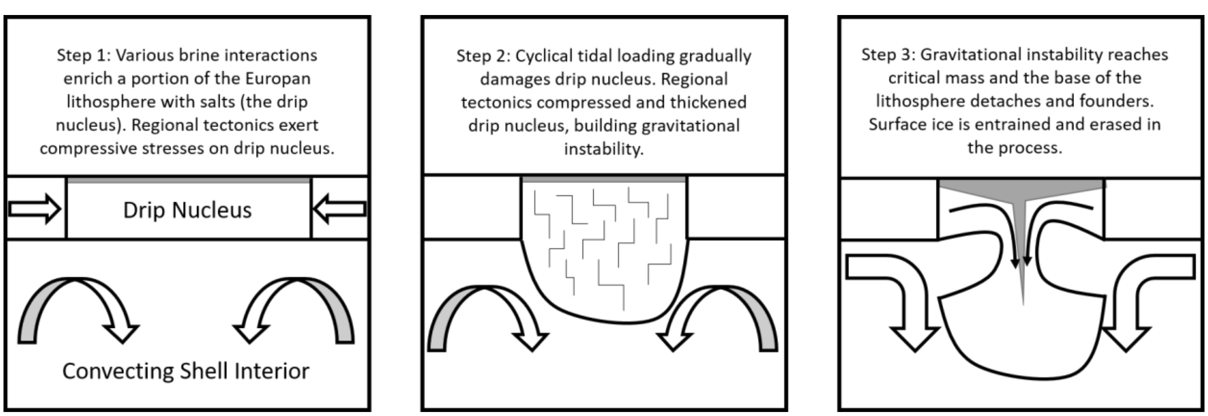

Figure 1: Conceptual model diagram illustrating the proposed viscous delamination process outlined above.

decreasing its viscosity in a diffusion creep regime [13]. Also, the effective Young's modulus of the ice may be sharply reduced, decreasing the ice's viscoelastic strength [14]. These factors may work in aggregate to weaken the ice sufficiently and trigger an episode of viscous surface collapse.

Model Overview: We constructed a numerical model in the geodynamic modeling engine Underworld 2 [15] to systematically study the conceptual model of icy viscous delamination outlined previously. We defined the model domain as a plane layer of water ice of 30 km thickness and 45 km width with the basic physical properties of ice. We included a salt-enriched "drip nucleus" (white region in Fig, 2) of increased density and decreased viscosity. Viscosity was Newtonian and temperature-dependent. We assumed that the aggregate effects of the various ice weakening mechanisms may be conceptualized by a general effective viscosity criterion f_d weakening the ice by up to three orders of magnitude. We considered three weakening conditions (f_d = 10, 100, 1000) and two density conditions (ρ = 0.95 g/cm^3, 0.99 g/cm^3) in the nucleus region for our simulations. We ran the simulations until a majority of the drip nucleus material has been removed from the surface.

Results: We found that a viscous Rayleigh-Taylor delamination process is capable of recycling and erasing surface ice, transporting it to the base of the shell in 3 Myr or less, depending on the severity of salt-driven lithospheric weakening. Lithospheric drips can accommodate 10s of kilometers of surface convergence within the salt-enriched region of the shell. We discovered that surrounding salt-poor ice locks the boundaries of the dripping region in place, encouraging lithospheric thinning and extension, which may initiate cryovolcanic processes. Due to this pinning, the ability of Rayleigh-Taylor delamination alone to accommodate regional shell convergence is limited, but delamination may facilitate the initiation of plate subduction processes and provide a pathway for surface material to access Europa's ocean and hypothetical biosphere.

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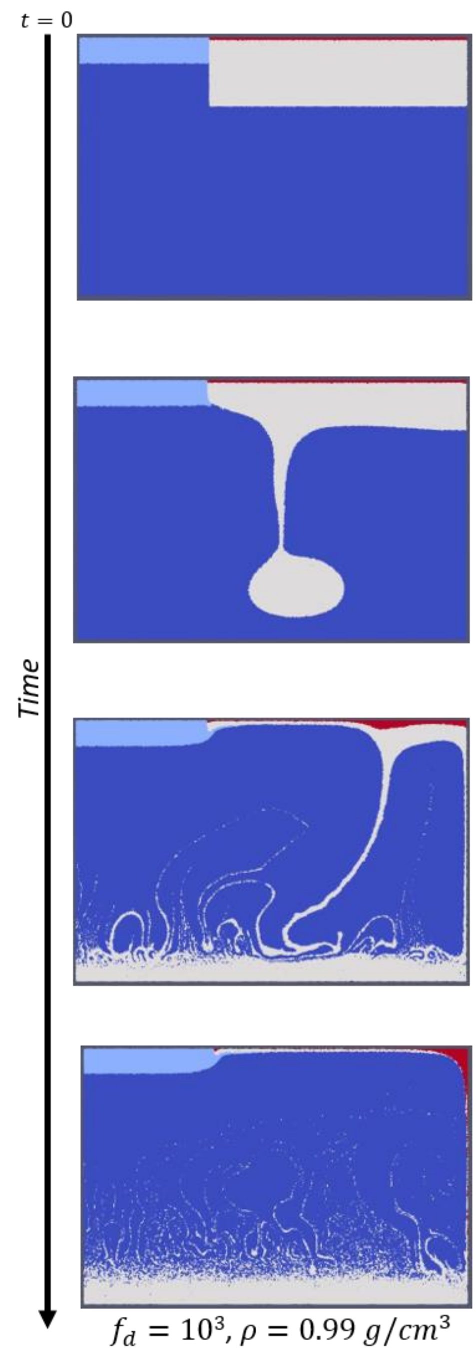

Figure 2: Model evolution of icy viscous delamination.

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