COMPRESSIBILITY AND FREEZING RATE CONTROL FRACTURE FREQUENCY IN OCEAN WORLDS.

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Introduction: The habitability of icy ocean worlds depends on the coexistence of water, energy, and the chemical building blocks for life for sufficiently long periods of time [e.g., 1]. Transport of material across different interfaces (e.g., core-ocean, ice-ocean) can enable the mixing of different chemical reservoirs and pre-biotic processes (e.g., photolysis) [1]. As such, it is important to understand the processes governing the transport of materials between the ocean, cryomagma chambers, and the surface [2].

The myriad icy worlds in the solar system provide a rich opportunity for a comparative planetology approach to understanding the thermomechanical evolution of ocean worlds, as well as their dynamic habitability. A synthesis of surface ages of solar system icy worlds in comparison with their global stress regime (Fig. 1) reveals that the evolution of icy worlds is largely controlled by a competition between freezing vs. tidal stresses through time, though a few icy worlds require other explanations [3]; additional controls on fracture from freezing may lead to differences in surface geology on icy worlds in similar global stress states.

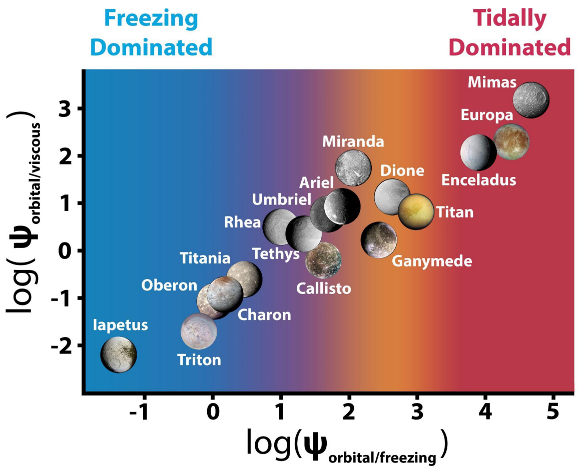

Fig. 1 A stress change rate regime diagram [3] showing whether an icy world's global stress state is dominated by tidal stresses or stresses generated during freezing of a subsurface ocean (horizontal axis).

We ask the question, "***How do underlying differences in the physical and chemical properties of icy world oceans lead to the diversity of surface expressions observed across these bodies?"***, recognizing that there are difficulties in addressing it due to data limitations (e.g., poorly constrained geologic histories of many icy worlds, lack of imaging coverage), uncertainties in key physical parameters (e.g., ice rheology, compositions of solar system ices), and the complexity of the systems we aim to model. Therefore, rather than attempting to recreate the evolution of a particular icy world, we construct a generalized model benchmarked by laboratory experiments with the aim of identifying fundamental controls on the evolution of an icy world's ocean and surface. In particular, we focus on how ocean freezing is affected by ocean chemistry, total and core radius, and tidal heating.

Modeling: We construct a 1-D, spherically symmetric thermomechanical model tracking the growth of the ice shell, ocean pressure & composition, and the volume & timing of ocean pressure release through cryovolcanic eruptions. The model is governed by a system of conservation equations for mass, volatile/solute mass, and energy. The evolution of pressure in the ocean is calculated from ocean mass conservation:

$$\underset{\textit{ice-ocean compressibility}}{\left(\frac{1}{\beta_w}+\frac{1}{\beta_i}\right)}\frac{dP}{dt}=\underset{\textit{freezing}}{\frac{Q_{out}-Q_{in}}{\rho_w L_m V}\left(\frac{\rho_w}{\rho_i}-1\right)}-\underset{\textit{erupting}}{\frac{\dot{M}_{out}}{\rho_w V}}-\underset{\textit{viscous response}}{\frac{\Delta P}{\eta_{eff}}} \quad (1)$$

When the combined hoop, tidal, and thermal stress at the ice-ocean boundary exceeds the fracture criterion, a subroutine calculates the amount of ocean material erupted to relieve ocean overpressure. The model thus produces a record of ice shell growth, ocean pressure & composition, and the timing, duration, and volume of cryovolcanic eruptions that can be used as a basis of comparison with tectonic and cryovolcanic features on planetary surfaces.

This model has several distinct strengths that can be leveraged to constrain the various roles of solutes, core size, tidal heating, and ice shell properties on the thermomechanical evolution of an icy world: (1) the model runs quickly enough (seconds per run) to densely survey a multi-dimensional parameter space, (2) the ability to model physical processes over a wide range of spatial and temporal scales which permits benchmarking against experimental results, (3) the model can account for multiple stable phases (volatiles or salts) within the ocean, and (4) the evolution of ocean pressurization is directly coupled to diking and potentially eruptions.

Freezing Ice Sphere Experiments: A suite of laboratory experiments freezing spheres of water from the outside-in are used as analog for freezing subsurface oceans and cryomagma chambers. These experiments also serve as a benchmark for the numerical model. Ice shell growth leads to pressurization of the water within until a fracture forms and relieves the overpressure. The experimental setup allows us to capture video of these fracturing cycles and the pressure time series from a miniaturized pressure transducer placed inside the water under the ice shell (Fig. 2).

Although our experiments only include elastic and brittle mechanical behavior in the ice, previous work demonstrated that the bulk compressibility of the water, and in turn the rate of fracture formation, is strongly controlled by the amount of dissolved and exsolved gas present in the water. We have conducted these experiments for spheres of 3.5, 5, & 7 cm radius.

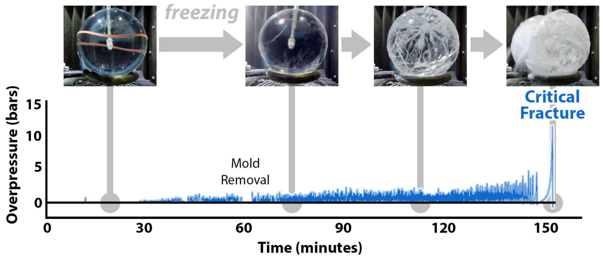

Fig. 2 A pressure time-series for a freezing 5 cm radius sphere at -25°C following [4]. Inset images show the experiment stages: (1) a plastic mold filled with water, (2) a thin ~5 mm thick ice shell after mold removal, (3) subsequent fractures cover the surface of the ice shell, and (4) a critical fracture completely disrupts the ice shell.

We are currently working to conduct new experiments incorporating salts (NaCl & $MgCl_2$) to test the effects of salt on this system, and to further benchmark model calculations with salt.

Preliminary Results: We have used our model to simulate freezing water bodies of a broad range of sizes (cm to 100s of km radii) with various relative core sizes (0 to 95% total radius) and solutes (NaCl, NH_3) at a variety of ambient temperatures (40-263 K). The overall behavior of model results for small spheres is in good agreement with experimental results (Fig. 2).

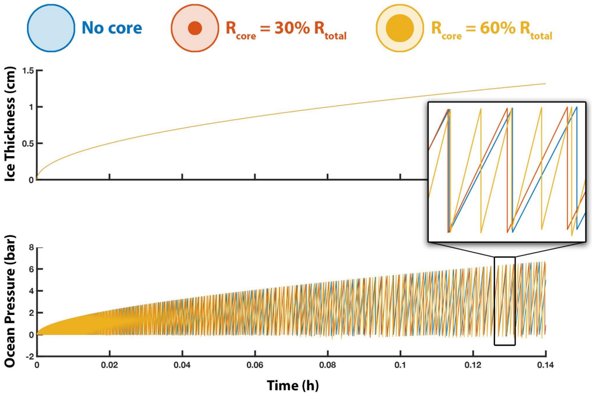

Fig. 3 Model outputs for a 5 cm radius sphere at an ambient temperature of -25°C for three different core sizes. Inset shows a close up view of a few fracture events in the pressure time series.

We observe that increasing core size increases the frequency of fracture events (e.g., rapid pressure drops in Fig. 3), whereas a range of reasonable heat fluxes from the core have a minimal effect on slowing ice shell freezing and decreasing fracture frequency. Antifreeze solutes delay the rate of freezing and lengthen the interval between fractures; these effects are more significant later in the evolution of icy worlds as freezing concentrates the solute in the remaining liquid.

Discussion: Examining our results in the context of Eq. 1, we find that solutes and a core influence the fracture frequency of ocean worlds primarily through two mechanisms: changing the ***freezing rate*** and changing the ***bulk internal compressibility***. The presence of a large and relatively incompressible core has a large effect on bulk internal compressibility and a minor effect on freezing rate. In comparison, the presence and abundance of salt solutes like NaCl strongly control freezing rate, thereby decreasing fracture frequency, but exert a limited control over the ocean compressibility. Volatile solutes such as ammonia can affect fracture frequency via both of these mechanisms: influence on the freezing rate and, especially if exsolution occurs, ocean compressibility.

A Roadmap for Comparative Planetology Application: Identification of the primary controls on icy world evolution and fracture frequency enables comparisons between similar worlds. For instance, Enceladus and Europa experience a similar global stress regime (Fig. 1), yet Europa's average surface is younger and more densely fractured [e.g., 5]. While there are certainly numerous factors that contribute to these differences, such as differences in size, ice shell thickness, core size, and ocean composition, a more extensive exploration of parameter space with the model will allow us to determine which factors are most important to these and other moons.

Conclusions: We have developed a new numerical model benchmarked by laboratory experiments that enables exploration of the primary controls governing the evolution of icy worlds. We find that the frequency of fractures reaching the surface in our model is controlled by changes to the freezing rate and bulk internal compressibility. Notably, the presence of a large silicate core leads to an increased fracture frequency. Antifreeze solutes which delay freezing slow the rate of fracture, and gaseous antifreezes (e.g., NH_3) may additionally strongly control ocean compressibility. A better understanding of the controls on icy world evolution enables new insights in comparative planetology. Additionally, constraining the controls on delivery of ocean material to the surface is important for assessing the past and present habitability of ocean worlds.

Future Work: Work is ongoing to incorporate tidal heating and stresses in the model as well as to conduct laboratory experiments freezing salt solutions.

References: [1] Hand et al. (2020), *Space Sci. Rev.*, 216(5). [2] Hendrix et al. (2019), Astrobiology, 19(1). [3] Nathan et al. (2022) LPSC 53, #1075. [4] Berton et al. (2020), *JGR: Planets*, 125. [5] Greeley et al. (2004), Geology of Europa, in Bagenal, et al. (Eds.), Jupiter. The planet, satellites and magnetosphere. *Cambridge University Press.*