ON THE FREEZING OF WATER SPHERES: LINKING THE SURFACE FEATURES OF ICY MOONS TO THE DYNAMICS OF SUBSURFACE GLOBAL OCEANS. T. Girona[1], M. Berton[2], H. Karani[3,4], C. Huber[3], J. Head[3], P.G. Williard[2], and A. Denton[3]. [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA. [2]Department of Chemistry, Brown University, Providence, RI 02912, USA. [3]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912, USA. [4]Department of Engineering Sciences & Applied Mathematics, Northwestern University, Evanston, IL 60208, USA.

Introduction: Space missions to the outer planets of the Solar System are providing new insights into the composition, structure, and behavior of icy moons (e.g., Europa, Ganymede, Enceladus). Icy moons typically contain a rocky interior surrounded by an outer water layer, often around 100 km thick [1, 2]. The uppermost part of this layer (~5-30 km) is frozen, forming an ice shell that floats over a global ocean of liquid water. The surfaces of icy moons contain many geological features, which are generally classified as plains (i.e., apparently flat surfaces), chaos terrains (i.e., zones composed of multiple ice blocks suspended over a solidified disrupted matrix), bands (i.e., straight and curved stripes with varying albedo), and ridges (i.e., straight, curvilinear, and cycloidal positive reliefs) [3-5].

Most of the geological features observed in icy moons are driven by extensional processes. Various extensional processes have been proposed [6-9], including: (a) freezing from the outside in, which pressurizes the liquid ocean and induces stresses near the surface that bring the shell to a critical state [8-11]; (b) solid state convection in the ice shell, which can produce stresses 1-2 orders of magnitude smaller than the ice strength (~1 MPa) [12, 13]; and (c) tidal stresses from the parent planetary body, which are very small (<0.1 MPa) but may ultimately trigger the opening of dikes, cryovolcanism, and the potential transport of organic components to the surface if the shell is close to failure [14, 15]. Here, we focus on how ice shells evolve towards a critical state, and thus explore the coupling between gradual freezing of icy moons and extensional tectonism. We address this problem through a suite of innovative experimental, theoretical, and numerical analyses that involve the freezing of water spheres.

Experiments: We have designed a new experimental device to study the freezing of water spheres using a cryochamber that controls the temperature down to −90 ℃ by vaporizing liquid nitrogen. Initially, a 10 cm diameter spherical plastic mold filled with deionized liquid water is introduced in the cryochamber at a specific temperature below the freezing point. After some time, a very thin (~3 mm) but rigid ice shell is formed in the internal part of the mold; the mold is then removed and the spherical sample is further cooled at the same ambient temperature. During gradual freezing, the internal pressure in the water sphere increases while the shell thickens, which episodically opens water-filled fractures in the ice. After some time and numerous fracture events (depending on the initial conditions), a large-scale failure occurs leading to the explosion of the sphere. In every experiment, we monitor the formation of cracks at the frozen surface (recording with three webcams placed at different angles), the average thickness of the shell after the final failure, and the pressure and temperature evolution in the liquid water inside the sphere (Fig. 1).

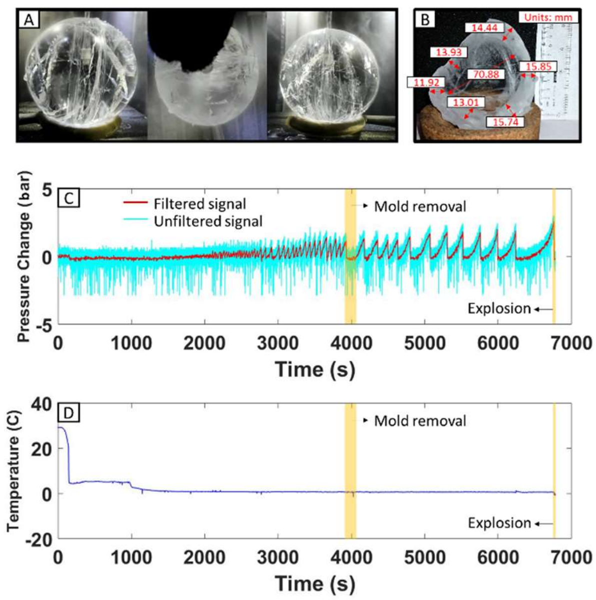

Figure 1: Example of experimental results. A) View of a 10 cm diameter freezing water sphere from three different angles; fracture patterns are formed at the surface during freezing. B) Water sphere after explosion. C) Pressure change with time inside the sphere (Kulite XCEL-072 140 bar miniature pressure transducer). D**)** Temperature with time inside the sphere (OMEGA's TJ36-CASS-010G type K thermocouple). These results are obtained for non-degassed deionized water and cryochamber temperature of -31 ℃.

Our preliminary results are as follows: (a) the pressure inside the sphere varies cyclically with time in response to pressure buildup by freezing and release by the formation of cracks in the shell; (b) every pressurization cycle creates new cracks in the shell instead of reopening previous fractures; (c) the overpressure required to open new cracks, as well as the inter-fracturing period, increase with time and thus with the degree of fracturing of the shell; (d) the opening of big fractures trigger the formation of gas bubbles in the liquid water due to cavitation; (e) the higher the temperature in the cryochamber, the thicker the ice shell after explosion; (f) the lower the volatile content in water (mostly: N_2, O_2 and Ar), the thicker the ice shell after explosion and the larger the number of fractures per minute; and (g) the fractal dimension of the fractured surface decreases exponentially with time.

Model: We have developed a theoretical model to interpret our experimental results, including the shell thickness variation and the internal pressure and temperature evolution of the ice-water system. Our model is based on mass and energy conservation, and takes into account water expansion upon freezing, elastic deformation of the shell, and a critical threshold based on hoop stresses for fracture initiation [16]. From the scaling analysis of the governing equations, we find that the pressure between consecutive fracture episodes increases with time according to:

$$\Delta P(t) = \alpha \left[\frac{1}{\left(1-\beta\sqrt{t}\right)^3} - 1 \right] \quad ,$$

where α and β are two constants. This functional form fits very well our experimental results (Fig. 2).

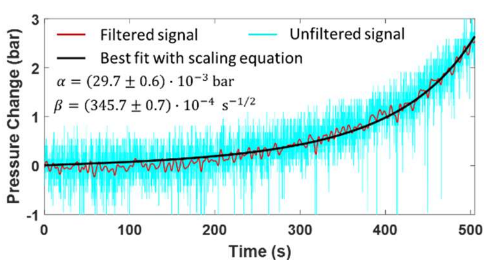

Figure 2: Comparison between experimental results and scaling equation obtained with our model. This corresponds to the last cycle of pressurization depicted in Figure 1C.

The resolution of the governing equations with a semi-implicit finite difference numerical model also reproduces: (a) the general trend of increasing peak pressure before fracture with time, (b) the temperature of the water at the center of the sphere, and (c) the overall fracture periodicity and its increase with time (Fig. 3). Although the trends are similar to laboratory observations, the final modeled ice shell thickness is about 40% larger because convective heat transfer in the liquid water is not accounted for in the model. This also explains the higher peak pressure recorded before fracturation (thicker shell affects hoop stresses) and the slower cooling at the center of the sphere. In the future, we will extend our model to add convective heat transfer and explore the effects of viscous relaxation.

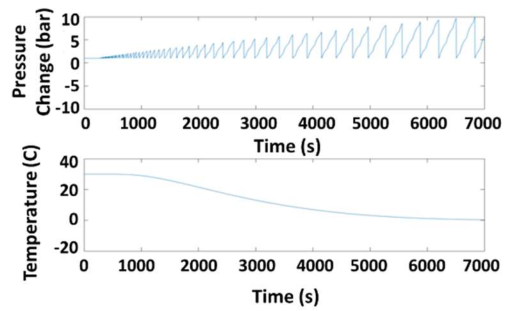

Figure 3: Numerical simulation of the evolution of the pressure and temperature at the center of a sphere subjected to freezing (conditions identical to Fig. 1C and 1D)

Implications For Icy Moons: Our experimental and numerical results have important implications for the overall dynamics of icy satellites:

(-) Cycles of high-low activity are expected during the evolution of icy moons. This is a consequence of the coupling between internal pressure, thickening of the ice shell, and cracking.

(-) The presence of dissolved volatiles in the liquid water changes the ice rheology upon freezing, reducing resurfacing activity.

(-) The fractal dimension of the shell surface is related to the age of the satellite. This requires further investigation since tidal perturbation is not taken into account in our experiments.

(-) Icy moons are unstable systems whose destiny is to suffer one or more explosions at a global scale. This could potentially explain the formation of irregular satellites (e.g., Phoebe [2]), asteroids, and icy particles in parent body rings [17].

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