THE ROLE OF DISSOLVED VOLATILES ON THE FREEZING OF AN OCEAN WORLD.

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Introduction: Ocean worlds are geologically active and diverse; they are also among the primary targets for finding habitable environments beyond Earth [e.g. 1]. The surfaces of icy moons are dominated by extensional features; one mechanism for their formation is stress generated by a pressurized freezing ocean, because water expands upon freezing [2-5]. Understanding the processes that control the formation of these features is critical to assessing the degree of ocean-surface exchange and characterizing habitability. In particular, volatiles, in addition to being important for ocean chemistry, may have profound mechanical effects on a freezing ocean [6-10]. We perform experiments to answer the question: How do dissolved volatiles affect the freezing evolution of an ocean world?

Methods: Freezing water sphere experiments are performed with non-degassed and degassed water. Degassed water is prepared by boiling the water under reflux for one hour followed by applying vacuum for four hours with ultrasound pulsing for the last thirty minutes. Water is injected in a spherical mold (7, 10, or 14 cm diameter) (Fig. 1A), which is placed within a freezing chamber that uses vaporized nitrogen to control ambient temperatures over a range of -15 ºC to -70 ºC [11]. While the ice shell is still thin, the mold is removed to ensure the mold has limited influence over fractures (Fig. 1B). The sphere continues freezing and fracturing until a critical fracture occurs (Fig. 1C-D).
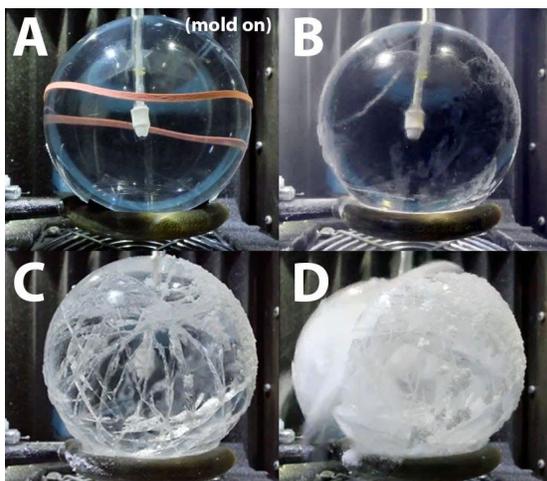
Results: For all sphere sizes and temperatures we test experimentally (N=51 experiments), we find:

1. Degassed water spheres require more time to reach final fracture than non-degassed ones, corresponding to a thicker ice shell (Fig. 3) for degassed water sphere.

2. Maximum pressure is higher for degassed than non-degassed water spheres. For all spheres, maximum pressure is higher at warmer freezing temperatures.

3. The interfracture time is shorter for degassed than non-degassed water spheres. More fractures are formed during an experiment with degassed water (Fig. 2).

4. For degassed water spheres, a sudden change to longer interfracture times is observed before final fracture.

Fig. 2. Final crack coverage comparison for degassed and non-degassed water spheres frozen at -30ºC.
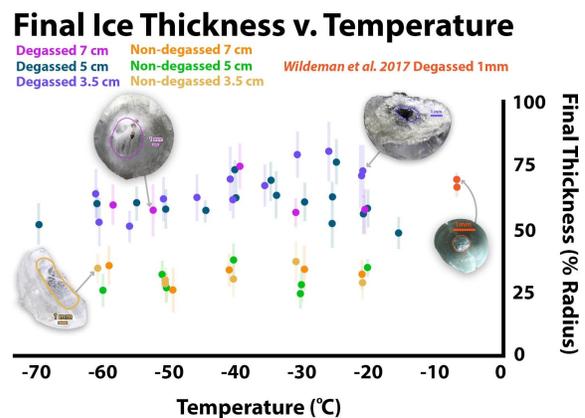

Fig. 3. Final ice shell thickness normalized by sphere radius. Error bars represent the standard deviation of measurements.

Fig. 1 Snapshots from left camera: A. after mold filling, B. after mold removal, C. during further freezing, D. final fracture.

Scaling and Thermal Stress. The scaled final ice shell thickness (normalized by the radius of the sphere) is independent of sphere size and freezing temperature (Fig. 3). Additionally, the time to the final fracture of the ice shell follows an analytical scaling law based on the freezing timescale (Fig. 4) [12]. The scaling of the final ice shell thickness and time until final fracture is also consistent with previous experiments freezing degassed millimetric water droplets (Fig. 4) [12].

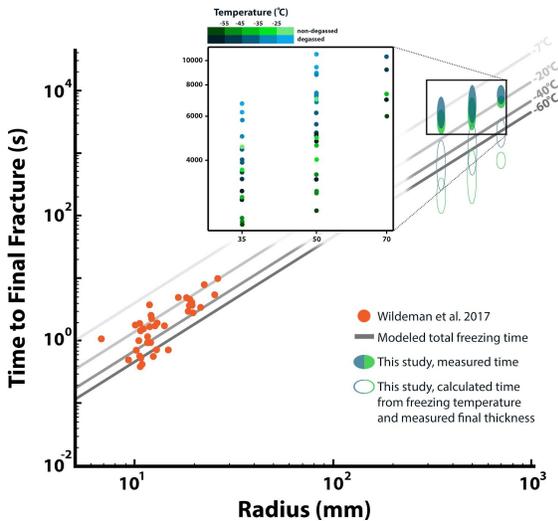## Time Freezing Until Final Fracture

Fig. 4. Comparison of calculated maximum freezing time to experimental results.

To apply results more generally, we must also account for the addition of thermal stresses on the ice shell. Assuming linear elasticity and constant coefficient of thermal expansion, we calculate tangential stress from pressure and thermal loading on the ice shell [13]. We find that maximum tensile stress is scale-independent and depends linearly on temperature; there is an offset between degassed and non-degassed spheres (Fig. 5).

Discussion: The difference in behavior for degassed and non-degassed water spheres, as well as the sudden change in interfracture time for degassed experiments, can be explained by the effects of gas on the compressibility of the water. As the ice shell grows inward, gas concentrates in the liquid. For degassed experiments, the dissolved gas concentrates and crosses a exsolution threshold; the resultant gas bubbles give the fluid a higher compressibility, leading to a longer interfracture time. Using an assumed threshold and initial volatile content, we can model when the change in interfracture time should occur [11] and our numerical predictions agree well with the experimental results for all sphere sizes.

Our results indicate that the ice shell thickness upon final fracture does not depend on sphere size or temperature, but rather on the starting volatile content of the water. Additionally, a simple scaling law can calculate the time until the final rupture of the sphere from the freezing temperature, sphere size, and volatile type (Fig. 4). When this scaling law is extrapolated for water spheres with radii of hundreds of kilometers, the timescales predicted are ~ billions of years.

Ambient temperature not only affects the freezing time to final fracture, but also the thermal stresses on the ice shell. We find thermal stress is independent of sphere size (Fig. 5), which is expected because the thermal gradient has fixed boundary conditions at the outer and inner surface of the ice shell. The offset in stress at final fracture between degassed and non-degassed experiments (Fig. 5) is likely caused by differences in the strength of the ice shell, perhaps due to bubble inclusions in non-degassed experiments. However, the values we find are consistent with previous experimental tests of tensile strength in low temperature ice [14].

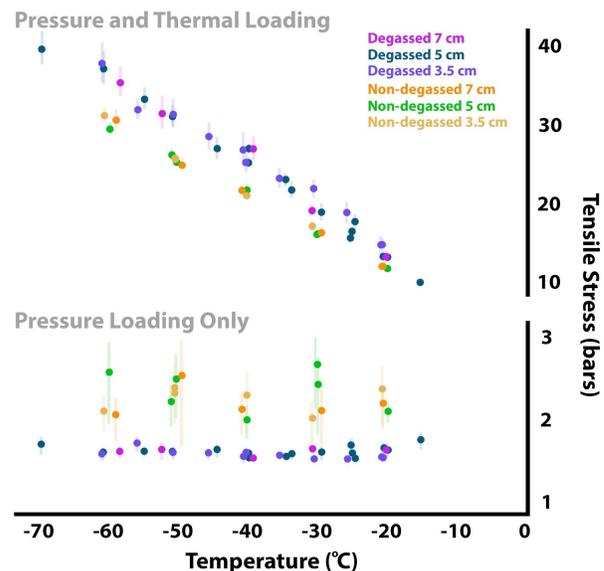## Maximum Tangential Stress

Fig. 5. Tangential stress at final fracture calculated from ice shell thickness, final pressure, and experiment temperature.

Further work will focus on understanding the effects of a core on the freezing evolution as well as using experimental results to understand the formation of an array of features on the surfaces of icy moons.

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