UNDERSTANDING ICY MOONS AS A POPULATION OF SOLAR SYSTEM BODIES. E. M. Nathan[1], C. Huber[1], and J. W. Head[1], [1]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912, USA, (erica_nathan@brown.edu)

Introduction: Previous reviews of icy moons mainly focus on subsets of icy moons and/or moons grouped by planetary system, mission, or surface features alone [e.g. 1-7]. Attempts to link the diversity of icy moons surface features to underlying processes has provided causal links between 'activity' (cryovolcanic and tectonic) and related parameters including radius, density, silicate mass fraction, orbit, tidal heating budget, or heating rates [e.g. 8-12]. Building on previous work, we take a complementary approach and focus on the balance of stress forcing and restorative processes, taking into account both magnitudes and timescales.

Icy moons are complex Solar System bodies influenced by many processes and feedbacks, e.g. tidal forcings, changes in rotation and polar wander, differentiation, radiogenic heating, impacts, freezing, convective stresses, thermal stresses, and atmospheric processes [e.g. 1, 12-13]. Rather than attempting to capture all of these factors for a single moon or a subset of moons, we instead focus on what may be the dominant processes that shape the evolution of icy worlds and follow a comparative planetology approach to understand icy moons as a class of Solar System bodies.

Preliminary Stress Inventory: In order to calculate the governing global stresses for icy moons in the Solar System, it is necessary to first tabulate basic physical parameters including moon radius, mass, surface temperature, orbital period, orbital eccentricity, silicate mass fraction and ice shell thickness (if there is an ocean). Of these parameters, silicate mass fraction and ice shell thickness have the greatest uncertainties [e.g. 6, 9-10, 12, 14-18].

We focus on two sources of stress for the purposes of our preliminary analysis: stresses associated with the freezing of a subsurface ocean and tidal stresses. The freezing of an ocean generates stresses (maximum extensional at the base of the ice shell) due to their spherical geometry and the expansion of water upon freezing [13, 19]; this stress should have been important at some point for any moon which had an ocean, and is relevant for many moons at present. We consider the pressure needed in the ocean to fracture the ice shell based on thermal and hoop stresses, as well as the timescale needed to reach that pressure:

$$p_f = 2 * \sigma_{ice} * \left(\frac{1-(R_i/R_{tot})^3}{1+2(R_i/R_{tot})^3}\right) \quad (1)$$

$$\tau_f = \frac{\sigma_{ice}}{3*\beta} * \frac{-\rho_w L_m R_i}{k*\Delta T} * \frac{(R_{tot}-R_i)}{(1-\rho_w/\rho_i)} \quad (2)$$

where p_f is pressure, σ_{ice} is ice strength accounting for thermal stresses calculated following [19, 20], R_i is the radius to the base of the ice shell, R_{tot} is the total radius, β is the bulk fluid compressibility, ϱ_w is water density, ϱ_i is ice density, L_m is the latent heat of melting, k is the thermal conductivity of ice, and ΔT is the temperature contrast from the surface to the base of the ice shell (assumed to be 273K).

Likewise, many moons are in orbits which cause them to be stressed by tidal forcings and this can lead to significant heating (potentially slowing down freezing) and tectonic activity. A limitation of our analysis of this stress is that we only use the present-day orbital parameters, though there is reason to believe that tidal forcing was stronger in the past for some moons, e.g. Ganymede and Miranda [e.g. 21-24]. We consider the maximum possible diurnal tidal stress as in [1], as well as the orbital period:

$$\sigma_{tidal} = 3Eeh_2\,(M_p/M_s)\,(R_{tot}/a)^3 \quad (3)$$

where E is the Young's modulus for ice, e is the orbital eccentricity, h_2 is the tidal Love number (taken to be 5/2 for simplicity as in [1]), M_p is the mass of the primary object, M_s is the mass of the satellite, and a is the semi-major axis.

We consider viscous relaxation as a restoring process, which can relax stresses at the base of the ice shell generated by tidal flexing or ice shell growth. Presently, we use a constant reference viscosity at the freezing point [25] for calculating the Maxwell time for viscous relaxation to occur because we do not have enough information on the effective viscosity within the ice shell in each moon and the temperature-dependence of the viscosity is a highly sensitive parameter; this should overestimate the efficiency of viscous relaxation.

Plotting ratios of these stresses and timescales allows us to build a regime space that provides a dynamic context for the geologic observations of these icy moons. By looking at a ratio of the freezing and tidal stresses and timescale (Eq. 1-3), we observe an arrangement of icy moons where those plotting less than 1 on the x-axis are dominated by freezing and those above 1 on the x-axis are dominated by tidal stresses (Fig. 1); Plotting near the center are Callisto, Umbriel, and Tethys, which are all relatively unmodified moons [17, 26-27] and may have avoided a dominant tidal or freezing stress in their evolution.

On these regime diagrams, it is informative to follow trajectories where all but one parameters are held constant. For instance, increasing the radius only moves moons strictly horizontally; note that we have made many simplifying assumptions (e.g. neglecting high pressure ice structure, assuming perfect differentiation) and the stress histories of icy worlds are much more complicated than we capture here. Another insightful plot concerns the ratio of ice shell thickness to ice shell and ocean thickness (Fig. 2). The overlain trajectories consider a growing ice shell and a fixed radius starting from Charon as a reference point. The point of this trend is to illustrate the trajectory of icy bodies during freezing. Some moons clearly deviate from these expectations and this may indicate that more complicated factors are not only at work, but significant for the evolution of these moons. Yet, we may already draw insights from comparisons of moons (e.g. Callisto vs. Ganymede [14]) and their placements on these plots (Fig. 1, 2).

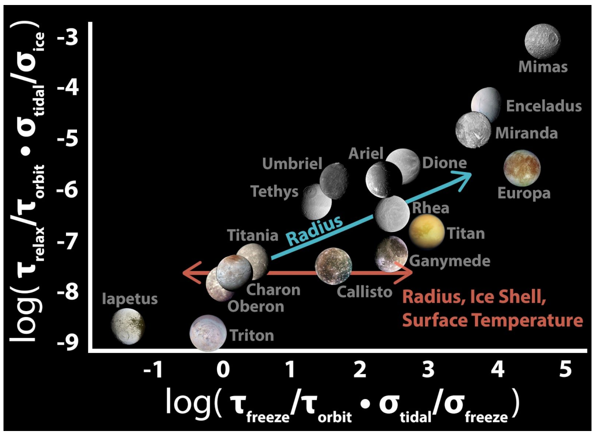

Fig. 1 Comparison of stress and timescale ratios where $\boldsymbol{\tau}_{freeze}$ is the freezing timescale (Eq. 2), $\boldsymbol{\tau}_{orbit}$ is the orbital period, $\boldsymbol{\sigma}_{tidal}$ is the maximum tidal stress (Eq. 3), $\boldsymbol{\sigma}_{freeze}$ is the freezing stress (Eq. 1), $\boldsymbol{\tau}_{relax}$ is the Maxwell time, and $\boldsymbol{\sigma}_{ice}$ is the ice strength. The blue trajectory shows the effect of increasing Charon's radius, keeping the silicate mass fraction and ice shell thickness constant. The red trajectory shows the effect of increasing the radius while holding the density and ice shell thickness proportional to Charon, increasing the surface temperature, and/or increasing the ice shell thickness.

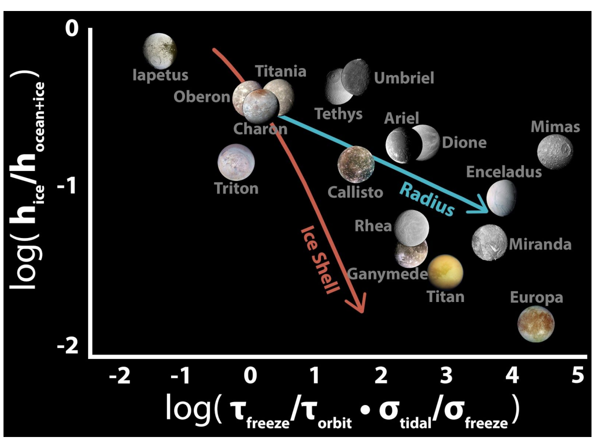

Fig. 2 Comparison of the ratio of ice shell thickness (h_{ice}) and the combined ice shell and ocean thickness ($h_{ocean+ice}$) against the same x-axis as in Fig. 1. The blue trajectory is as in Fig. 1. The red trajectory shows the effect of a growing ice shell for Charon's fixed radius and silicate mass fraction.

As we continue work in adding complexity to our understanding of governing stresses and timescales for icy moon evolution, we become increasingly limited in the number of data points which the Solar System has provided us and thus it is necessary to involve modeling of artificial icy worlds to populate our regime spaces and to discuss the relationships between these parameters and the icy body's 'activity' level in a rigorous quantitative manner.

Modeling Approach: Our strategy for the modeling is motivated by our objective: we consider first order physical processes common to many icy bodies rather than reconstructing the detailed evolution of a single body. Given the uncertainty that we have on more detailed parameters for some bodies, which becomes even more apparent as we aim at reconstructing the evolution of the body backward in time, it is advantageous to consider simpler processes with better-constrained parameters. Our strategy lies on three fundamental principles:

1. Our model will be based on a consistent (mass, momentum and energy balance) framework to couple the different stress contributions and dynamics of the ocean-ice shell system.
2. Our model needs to be numerically efficient so that we may explore a wide parameter space (e.g. orbital and internal parameters), including laboratory experiments conditions [19].
3. Our model will be modulatory. From the base model, it will be easy to add more complexity to our picture of icy moon evolution.

Conclusion: The wealth of data collected on icy moons in the previous decades provides us with the opportunity to synthesize our observations to build an integrated understanding of icy worlds that can serve as a framework for motivating future exploration. By simplifying the problem to the stresses and timescales associated with dominant processes affecting icy moons and supplementing our icy moon regime space with numerical modeling results, we can better understand icy moons as a class of Solar System bodies and learn how fundamental physical processes control the evolution of their geology and habitability.

References: [1] Collins et al. (2009) in *Planetary Tectonics*, p. 264-350 [2] Jaumann et al. (2009) in *Titan from Cassini-Huygens*, p. 75-140 [3] Johnson (1998) in *Solar System Ices*, p. 511-523 [4] Johnson (2005) in *The Outer Planets and Their Moons*, p. 401-420 [5] Lunine (2017), *Acta Astronautica*, 131 [6] Schubert et al. (2010), *Space Sci Rev*, 153 [7] Stephan et al. (2013) in *The Science of Solar System Ices*, p. 279-367 [8] Castillo-Rogez et al. (2018) in *Enceladus and the Icy Moons of Saturn*, p. 285-305 [9] Hussmann et al. (2010), *Space Sci Rev*, 153 [10] Hussmann et al. (2015) in *Treatise on Geophysics: 2nd Ed.*, p. 605-635 [11] Matsuyama (2014), *Icarus*, 242 [12] Nimmo & Pappalardo (2016), *JGR: Planets*, 121 [13] Manga & Wang (2007), *GRL*, 34 [14] Cassen et al. (1980), *Icarus*, 41 [15] Castillo-Rogez & Lunine (2012) in *Frontiers of Astrobiology*, p. 201-228 [16] Ellsworth & Schubert (1983), *Icarus*, 54 [17] McKinnon (1997), *Icarus*, 130 [18] Schubert et al. (2007), *Icarus*, 188 [19] Berton et al. (2020), *JGR: Planets*, 125 [20] Bayat et al. (2012), *Arch Appl Mech*, 82. [21] Showman et al. (1997) *Icarus*, 129 [22] Pappalardo et al. (2004) in *Jupiter: The Planet, Satellites and Magnetosphere*, p. 363-396 [23] Tittemore & Wisdom (1990), 85 [24] Hammon & Barr (2014), *Geology*, 42 [25] Kirk & Stevenson (1987), *Icarus*, 69 [26] Smith et al. (1986), *Science*, 233 [27] Plescia & Boyce (1982), *Nature*, 295