RIDGES, RIDGES EVERYWHERE: AN ANALOGUE MODELLING APPROACH TO ANALYZING RIDGE FORMATION ON ICY SATELITES.

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Introduction: The outer solar system is dominated by icy bodies that display a diverse range of surface morphologies. Despite these varied features, there are also striking similarities in some structures across many icy bodies—for instance ridged bands—which indicates possibly unified formation mechanisms at work [1]. Understanding the mechanical control of surface structures on these icy bodies has fundamental implications for constraining their rheological properties and thermal evolution, which in turn has implications for the presence of liquid water—an aspect key to potential habitability.

The existence of global oceans within icy satellites, such as Europa and Enceladus, implies the presence of a ductile warm ice layer because there must be some transition from the brittle ice surface to the subsurface global ocean. The role of a ductile layer has only been explored with infinitesimal strain computer models to date [e.g., 2, 3], which does not address potential finite (>1) strain icy satellites experience. We aim to address this issue by combining observations of icy satellite ridge structures with a unique two-layer analogue model containing an overlying brittle layer and a ductile creeping layer [4].

Analogue models have led to valuable insights into Earth tectonics [e.g., 5], but have been underemployed for icy worlds [cf., 6, 7]. Using the analogue experimental approach and analyzing the effects of a subsurface ductile layer, we will gain understanding of different formation mechanisms for surface features and aid in reconstructing the resurfacing history of icy satellites such as Europa.

Procedure: The basic analogue model consists of a ductile, low viscosity layer underlying a cohesive brittle layer. We initially use therapeutic putty with a measured viscosity of about 10^4 P·s for our ductile layer and fine-grained sand for our brittle layer. We chose these materials for our initial experiments because they will scale up properly to conditions on Europa (see Table 1). For example, if we scale with the cohesive strength of our sand (~60 Pa) and use well accepted values for Europa [8], we get a scale where about 2 km on Europa corresponds to 1 cm in our model, or 10^{-5} scale factor [9].

To set up the experiment, we first layer the putty into the metal analogue set-up, bounded on all sides. Because the putty is ductile, but still fairly viscous, we let it relax to a flat surface over the course of a few days before adding the desired amount of sand. Finally, we scatter coffee grounds over the surface of the sand to act as tracking particles during the experiement. In order to run an experiment, we set a step motor to move a wall either to decrease (cause compression) or increase (cause extension) the size of the box at a continuous rate that we define.

Strain Maps: The strain distribution in the model can be visualized through tracking the displacement of particles on the surface:

$$e = \frac{l_f - l_o}{l_o} \tag{1}$$

where e is the strain (linear), l_o is the initial distance and l_f is the final distance between two particles. The coffee grounds on the surface of the experiments will allow us to construct strain maps to determine where strain is being focused. This will allow us to determine how the stain is being partitioned between deformation in the surface sand and the ductile layer thickening or thinning.

Table 1: Material values for the analogue experiments, Europa and Enceladus

Material Property	**Experiment Value**	**Europa Value***	**Enceladus Value***
Cohesion, C	60 Pa	10^6 Pa	10^6 Pa
Density, ρ	1700 kg/m^3	920 kg/m^3	920 kg/m^3
Gravitational acceleration, g	9.8 m/s^2	1.31 m/s^2	0.113 m/s^2
Height Scale, h $\frac{h_{ice}}{h_{\mathrm{mod}}} = \frac{C_{ice}}{C_{\mathrm{mod}}} \cdot \frac{\rho_{\mathrm{mod}}}{\rho_{ice}} \cdot \frac{g_{\mathrm{mod}}}{g_{ice}}$	**1 cm**	**2 km**	**20 km**
Viscosity, μ (ductile)	10^4 Pa s	10^{17} – 10^{18} Pa s	10^{17} – 10^{18} Pa s
Time Scale, t $\frac{t_{ice}}{t_{\mathrm{mod}}} = \frac{\mu_{ice}}{\mu_{\mathrm{mod}}} \cdot \frac{C_{\mathrm{mod}}}{C_{ice}}$	**6 hours**	**10^5-10^6 years**	**10^5-10^6 years**

*values found in: Beeman et al. (1988); Pappalardo et al. (1999); Prockter and Pappalardo (2002); Bland et al. (2015) **equations from Hubbert (1937) and Cruz et al. (2005)

Initial Results: We run each experiment for 24 hours, corresponding to 10^5-10^6 years on the icy satellite of interest (see Table 1). Each experiment experiences the same amount of bulk strain (~33%) at the same strain rate (~10^{-6}/s), to allow for direct comparison between the experiments and investigate the effect of varying the thickness of the sand layer (corresponding to brittle ice shell thickness).

In the compression experiments, we observe the formation of curvilinear ridges on the surface with varying wavelength depending on the thickness of the sand layer (Fig. 2). When the sand is brushed off the surface to reveal the putty underneath, we observe that thrusts have formed in the sand layer and penetrated to the ductile layer. These results have been found for Earth analogues in prior studies [e.g., 10, 11], but this is the first study to pick materials with proper scaling and run at propter strain rates to relate these structures to icy worlds.

There are many variables that affect whether folds or faults will dominate when ductile materials are under compressional stress. These factors include: (1) thickness of the ductile layer, (2) viscosity of the ductile layer, (3) the elastic modulous of the brittle layer, and (4) the total thickness of the combined brittle and ductile layer [12]. In this analogue set-up, the boundary between folding and faulting needs further investigation. While it appears that we are currently producing faults, quanitfying the boundaries between folding and faulting will be important to constraining formation mechanisms for ridges on icy satellites.

Another interesting feature that we observe in the analogue experiments undergoing compression is the formation of a trough separating the moving wall from the contractional structures formed in the sand (Fig. 2). We point out this feature specifically because it could have implications for the formation of ridged bands as this is a common observation [e.g., 13-15] though is usually interpreted to be the result of extensional processes [e.g., 16, 17].

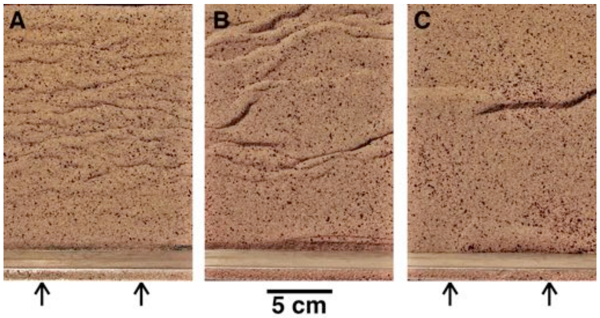

Figure 1: Examples of the analogue model run with different thicknesses of sand including 0.25 cm (A), 0.5 cm (B), and 1.0 cm (C), but otherwise under the same conditions. The arrows indicate the moving wall and its motion (same in all three experiments). Note the trough forming against the moving wall. Common scale.

To date, we have only run the analogue model in compression, but we plan to conduct the corresponding extension experiments as well. This will allow us to qualitatively compare the morphologies produced in different stress environments and analyze these with respect to the surface features observed on the icy satellites.

Future Work: In addition to running the extensional experiments, we also want to test the idea of tectonic resurfacing. As such, we will run experiments with multiple episodes of deformation. For example, because Europa is thought to have a very young surface, on the order of 60 million years [18], it must have active or recently active resurfacing mechanisms. Thus, Europa's surface today is made up of the superposition of these resurfacing events or else pre-existing structures are completely erased in some non-tectonic process, e.g. cryovolcanism. We can compare and analyze these two possibilities in the analogue model by creating multiple episodes of extension or compression and analyzing the resulting surface features visually (qualitatively), and quantitativly by creating strain maps.

Implications: By creating a two-layer analogue model for icy satellite surface deformation, we will gain insight as to how the brittle surface and the ductile subsurface interact on these bodies to form the surface structures that we observe. This interaction has implications for the resurfacing history of such bodies and could potentially reveal current or past ice shell thicknesses when the surface structures formed. Additionally, we will be able to constrain the rheology and mechanisms controlling the formation of surface structures on icy bodies such as Europa, as well as rocky bodies in the solar system with similar features, potentially.

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