SUBSUMPTION ON EUROPA'S ICY SURFACE: A PHYSICAL ANALOGUE MODELING APPROACH.

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Introduction: Jupiter's icy moon Europa has one of the youngest planetary surfaces in the Solar System (40-90 Ma, [1]). This implies a history of intense tectonic activity and resurfacing processes [2] which lead to the assumption of the presence of a liquid, convectiong ocean beneath the icy shell of Europa [e.g., 3,4]. Details on the geometry and physical properties of the shell and ocean, however, remain unclear. For example, the thickness of Europa's solid ice shell is uncertain, but has important implications for Europa's habitability and thermal history, and the design of future space-craft missions [5]. An additional challenge is the fact that despite extension and the creation of new surface areas, there is little evidence of large-scale contraction to recycle aging terrains [2]. A variety of mechanisms have been proposed to recycle the surface of Europa [e.g., 2,6]. One such mechanism called "subsumption" – an analog to terrestrial subduction – where colder, brittle ice plunges into warmer, more ductile ice, could potentially recycle surface ice at compressional bands [2]. However, it is unclear if the thickness of the brittle ice layer plays a role in the ability to be subsumed. Additionally, it is unclear what role strain-rate could play in the ability of the brittle ice layer to be subsumed.

In this study, we aim to understand the basic physical parameters that may allow subsumption to take place using a 2-layer analogue model composed of brittle and ductile paraffin wax. By varying the thickness of the brittle layer and the strain-rate in the model, we will gain a first order understanding of subsumption processes on Europa.

Methods: Our 2-layer model consists of a lower ductile layer of wax and an upper layer of brittle wax, representing the ductile and brittle ice layers on Europa, respectively. Paraffin wax has been used in the past to model tectonic features on Europa [7]. It has a low melting point, making it ideal to model the relationship between heat transport and deformation. In our model, 1 mm equals 1 km (10^{-6} scaling factor). Ice rheology and strength at Europan temperatures and pressures is poorly understood, and thus scaling those parameters is disregarded [7].

The modeling apparatus (60.9 cm in length, 58.4 cm in width, 30.4 cm in height) and consists of 4 plexiglass stationary walls and one moving wall (Fig. 1). The moving wall is coupled to a computer controlled electric motor that can vary the deformation rate from 0-35 cm/hr along one horizontal axis (forward or reverse).

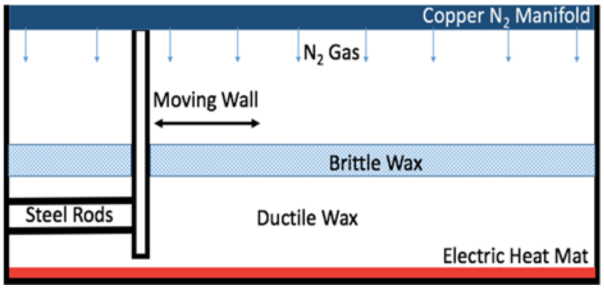

Figure 1: *Schematic sketch of the analogue modeling apparatus. Box dimensions 60.9cm x 30.4cm x 58.4cm. Not to scale.*

First, melted wax is added to the model. The wax is heated from beneath with an electric heat mat controlled by a digital temperature controller and maintain liquid wax temperatures. Next, the wax surface is cooled to a brittle state by using liquid nitrogen (N_2) that dripped onto the surface from above (Fig. 1). By the time it reaches the surface, the liquid N_2 has turned to gas cooling the surface homogeneously. By varying the flow rate of the liquid N_2, and varying the temperature of the heat mat, we are able to control the thickness of the brittle layer of wax. Once a desired thickness is reached, the gas flow rate is decreased to a maintenance rate. Finally, a constant deformation rate is set, and the model is run for 15-60 minutes. Overhead pictures are taken at set deformation intervals. Throughout the model run the temperature of the box air, brittle wax layer, and ductile wax layer are monitored and recorded.

Initial Results: Preliminary experiments are focused on varying the thickness of the brittle wax layer while holding the strain-rate constant at 30cm/hr. In the first experiment, we tested a "thin lid, fast rate" scenario. In this model, the brittle layer is approximately 1.2 cm thick, the ductile layer about 7.8 cm thick, and the displacement rate is 30 cm/hr. Brittle deformation is not observed, instead, large scale folding occurs that results in high surface relief (Fig. 2).

In the second experiment, we tested a "thick lid, fast rate" scenario where the brittle layer is approximately 2.4 cm thick, the ductile layer about 5.6 cm thick, and the displacement rate is 30 cm/hr. In this experiment, brittle deformation was observed with little surface relief, and most importantly, subsumption took place (Fig. 3) confirming the proposed process by [2]. Note that the subsumption zone is obscured younger wax that upwelled through the existing zone of weakness (Fig. 3A). Removal of this young wax shows the subsumption topography in Fig. 4.

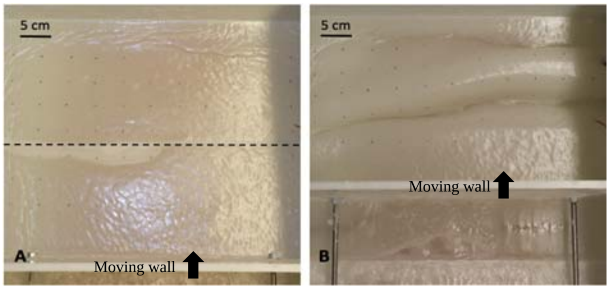

Figure 2: *"Thin lid, fast rate" analogue model with 1.2 cm brittle layer above a 7.8 cm ductile layer (map view). (A) before and (B) after 30% compression. Black dotted line = zone zone of weakness.*

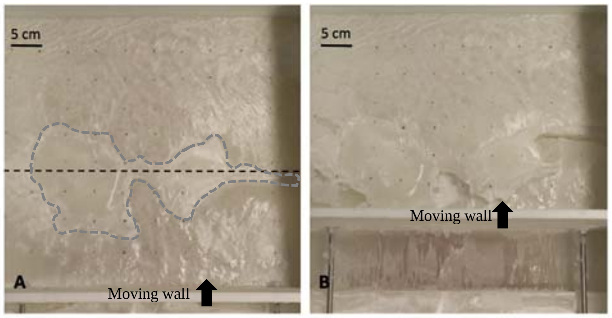

Figure 3: *"Thick lid, fast rate" analogue model with a 2.4 cm brittle layer above a 5.6 cm ductile layer (map view). Black dotted line = zone of weakness. Grey dotted line contours the warmer, underlying wax that upwelled through the zone of weakness at the beginning of the experiment. (A) before and (B) after 28% compression.*

Discussion and Implications: On the surface of Europa, little evidence exists for large-scale contraction to accomodate the creation of new surface areas at dilational bands [2]. Although rare convergence bands imply high contractional strain in some areas on Europa [8], the expected high topography that accomondates these contractions is lacking [2]. Additionally, no substantial surface erosion exists that could explain this lack of topography. [2] proposed subsumption as an effective way to recycle old surface. By analogue modeling the Europan surface deformation and recycling with a two-layer brittle-ductile wax model, we will gain insight into (1) the interaction of the brittle surface and the ductile subsurface and (2) into the formation of observed surface structures on Europa [7,9]. By varying the thickness of the brittle wax layer and strain rate, we can study the effect of different heat fluxes on the surface morphology [9], and the effect on the initiation of subsumption.

Preliminary experiments tested a zone of weakness that was created in the center of the model (Fig. 2,3) by cutting the brittle wax with a heated knife. This man-made zone of weakness in our experiments serves as an analogue for the pre-existing natural zones of weaknesses on Europa. These zones on Europa can form through exogenic (e.g., impacts) and endogenic processes (e.g., extention, cryovolcanism, ice-fatigue) that create lineaments such as ridges, troughs, and cycloidal bands [3,10] where subsumption could potentially begin.

Our preliminary experiments show that a thin brittle surface layer, although it contains a pre-existing zone of weakness, behaves ductilely during compression resulting in high topography (Fig. 2), which is not observed on Europa [2]. This is most likely due to the increased heat transfer from the ductile layer to the surface. Doubling the thickness of the brittle layer (experiment 2) creates a brittle deformational style during compression resulting in subsumption (Fig. 3), with almost no accompanying surface topography (Fig. 4) similar to Europa. During the creation of the zone of weakness in this experiment, warmer underlying wax welled up through the crack (Fig. 3A). Interestingly, this younger wax decoupled from the older, more brittle surface wax and did not impede subsumption. In Fig. 4, the young wax is removed to show the deformation beneath. Ductile wax "slush" has upwelled through the thrust fault during subsumption (Fig. 4, thin black arrow). This "slush" could explain the observed subsumption bands that accompany the subduction margin on the surface of Europa [2].

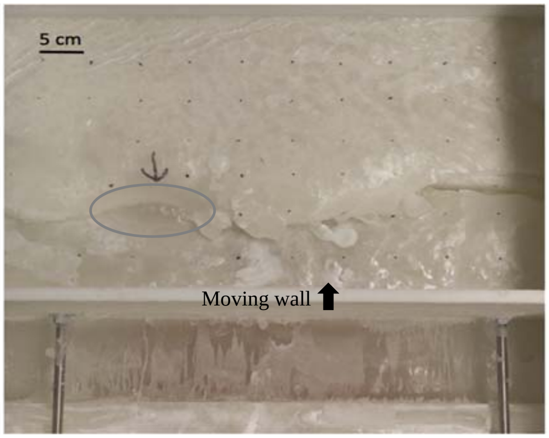

Figure 4: *"Thick lid, fast rate" scenario analog model from Fig. 3B after the removal of the younger wax above the brittle layer. Thin black arrow highlights ductile wax slush that has upwelled through the thrust fault.*

Future Work: We plan to create "natural" zones of weakness through extension to thin and weaken the brittle layer naturally followed by compressional deformation. Our goal is to create a subsumption treshhold for our analogue models to place constraints on the thickness and deformation rate that will allow or hinder subsumption.

References: [1] Bierhaus et al. (2009) in *Europa*, 161-180 Univ. Arizona Press; [2] Kattenhorn and Prockter (2014) *Nature Geosci., 7*, 762-767; [3] Pappalardo et al. (1999) *JGR* 104, 24015-24055; [4] Kivelson et al. (2000) *Science* 289, 1340-1343; [5] Nimmo et al. (2003) *Icarus* 166, 21-32; [6] Prockter and Pappalardo (2000) *Science* 289, 941-944; [7] Manga and Sinton (2004) *JGR*, 109, E09001; [8] Sarid et al. (2000) *Icarus* 158, 24-41; [9] Leonard et al. (2016) *LPSC* #2278; [10] Kattenhorn and Hufford (2009) in *Europa*, 161-180 Univ. Arizona Press.