RIDGED PLAINS REVEAL EUROPA'S COMPRESSIVE PAST.

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Introduction: The paucity of impact craters >10 km in diameter on Europa's surface implies that the surface is relatively young, on the order of ~60 Ma [1]. Therefore, Europa must have resurfaced in its recent history, but the mechanism and driving force behind this resurfacing are unclear [e.g., 2-5]. The cross-cutting relationships documented in regional and global geologic maps of Europa imply three major periods of resurfacing: the oldest dominated by the formation of ridged plains, the next by the formation of bands, and the youngest by the formation of chaos terrain [4-7]. The resulting hypothesis that the style of deformation has transitioned from distributed to discrete over the visible surface history could imply that resurfacing is driven by ice-shell cooling-induced thickening [4-6].

Validation of this hypothesis requires knowledge of the formation mechanisms for the ridged plains, as it would imply that these oldest observable features should be contractional in origin. While the morphological observations of the ridged plains indicate folding as a viable formation mechanism [6], the mechanical basis has not been demonstrated. This study addresses this issue through Europa-scaled analogue experiments.

Although analogue models have been widely used for tectonic studies on Earth [8], they have only rarely been adapted to the studies of the icy surface deformation [cf. 9]. In order to simulate ridged plains formation, we develop a two-layer physical analogue experiment to simulate an extensional or contractional environment on Europa, and then compare the resulting morphology of the ridges produced to observations of the ridged plains.

Experimental Procedure: The analogue model consists of a ductile, lower viscosity layer underlying a Coulomb-material brittle layer. We use therapeutic putty with a measured viscosity of about 10^4 Pa s for our ductile layer and fine-grained sand for the brittle layer. We choose these materials for our experiments because they scale up reasonably well to conditions on Europa. For example, if we scale with the cohesive strength of our experimental sand (~60 Pa) and use well accepted values for Europa [10], we obtain a spatial scaling factor of $1{:}10^{-5}$, which means that 1 cm thick sand in our model represents a 1 km thick ice layer on Europa [11].

To set up an experiment, we first layer the putty into a 90 cm by 90 cm box and let it relax to a flat surface over the course of a few days before adding the desired amount of sand. We also add coffee grounds on top of the sand to act as strain markers. For experiments where we simulate extensional processes, we move one wall outward with a step motor. In order to simulate compressional processes, we move the wall inward with a step motor, creating uniform contraction in the brittle surface layer.

Initial Results: We began the analogue experiments by varying the thickness of the brittle layer, 0.25 cm, 0.5 cm, and 1.0 cm, to study the effects on the surface features. The experiments were run over the course of about 24 hours, scaling to 10^6 yrs on Europa [9]. By varying the thickness of the brittle layer, we are consequently examining the effect of varying heat flux on ice-shell deformation as expressed by surface morphological features. For example, an icy body with a higher heat flux would have a shallower brittle-ductile transition depth and a thinner overall ice-shell.

In addition to varying the brittle layer thickness, we are testing the effects of varying the ductile layer thickness. Our initial results indicate that increasing the ductile layer thickness has implications for the structural formation of ridges in the brittle layer. For example, the compressional experiments favor thrusting and discourage folding. We will also run the

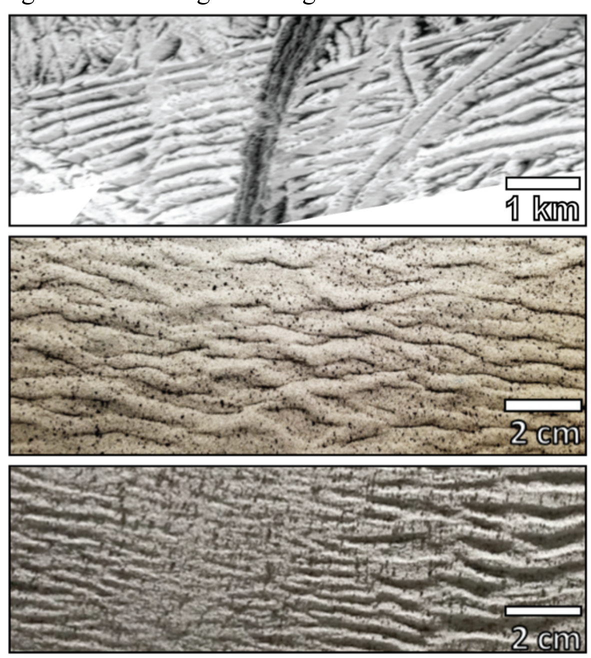

Figure 1: Ridged plains on Europa (top) compared to experimental results from compression experiments (middle) and extension experiments (bottom).

extensional experiments with a thicker ductile layer, to understand the implications. Below, I summarize experimental results under extensional and compressional boundary conditions, respectively.

Extension. In the extensional experiments, the spacing of resulting normal faults increase with the increasing thickness of the brittle layer. We expected this result based on past work on normal fault spacing on Earth [12, 13]; thus, this experiment serves as a conceptual test for our analogue model. The ridges (horsts) that form in the extensional experiments are broad (Fig. 1) and have relatively flat tops (Fig. 2). Additionally, the troughs between each ridge are broad and equally spaced.

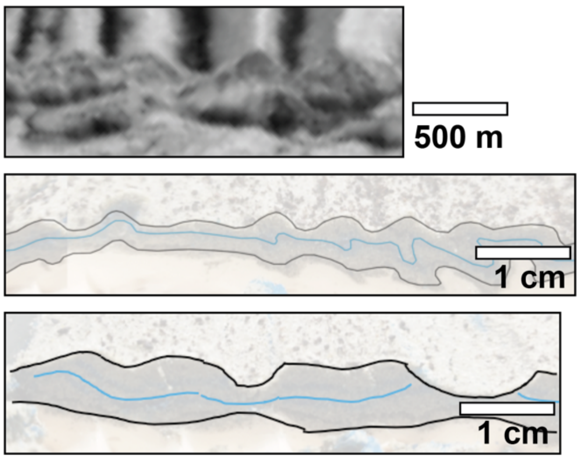

Figure 2: Ridged plains on Europa in cross-section due to a scarp cutting the ridged plains and oblique view (top). Compare to the cross-sectional view of the compressional experiment results (middle) and extension experiment results (bottom).

Compression. In the compressional experiments, the wavelength of resulting folds increases with the thickness of the brittle layer. The ridges (fold anticlines) that form in the compressional experiments are rounded in cross-sectional view (Fig. 2). They range in shape from linear to curvilinear along their length and have comparatively narrow troughs.

Implications: Comparing the observations of ridged plains on Europa (Fig. 3) to the surface structures that we observe forming in the physical analogue models (Fig. 3), we find that the resulting ridge-trough systems in the compressional experiments are a better morphological fit. Thus, we hypothesize that the ridged plains are small-scale (100-500 m) folds in the uppermost part of Europa's ice shell. This has important implications for the evolution of Europa. Ridged plains are the oldest features on the icy moon. A fold-origin indicates compression-dominated ice-shell tectonics during the earliest reconstructible history of Europa. The current prevailing thought that the more recent ice deformation (e.g., band formation) is dominated by extension [e.g., 14, 15] indicates that there must have been a transition time when the ice-shell deformation changed from compression to extension. We suggest that this change resulted from cooling and thickening of the ice shell, which caused early but brief volume contraction in the shallow subsurface of the ice-shell to produce folds, and later protracted volume expansion caused extension [16]. We will continue to explore this hypthosis with additional observations of Europa's surface structures, phsical analogue modelling, and computer modelling.

Europa	Compression Experiments	Extension Experiments
Rounded in cross section		
Linear to curvilinear along length		
Large length to width ratios (> 10)		
Narrow troughs		

Figure 3: Table comparing observations from ridged plains on Europa (left column) to results from the compression experiments (middle column) and extension experiments (right column). Green indicates the observations match; orange indicates that the observations rarely match; and red color indicates that the observations do not match.

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