THE ROLE OF DIKE INTRUSIONS IN RIDGE FORMATION ON EUROPA. S. A. Johnston[1] and L. G. Montési[1], [1]Department of Geology, University of Maryland, College Park (johnston@umd.edu; montesi@umd.edu)

Introduction: Many generations of linear and curvilinear ridges and troughs cover the surface of Europa, an icy satellite of Jupiter [1,2]. Based on images from *Voyager* and *Galileo,* previous workers have differentiated between several ridge morphologies, including single ridges, double ridges, complex ridges and cycloidal ridges [3]. A successful model for the formation of Europan ridges should be able to account for the observed diversity of morphology and for the presence of transitions from one morphology to another along strike. We present numerical models of ridge development following the crystallization of linear cryomagmatic intrusion in an icy crust and show that that the cross section of the intrusion exerts a first-order control on the resulting ridge morphology. Both single and double ridges can be produced by this model.

Ridge Morphology: Europa features a wide variety of ridge morphologies. Figure 1 indicates several morphologies in a representative region of the satellite.

Existing models of ridge formation have focused on the development of specific features, most notably double ridges and cycloids, but the presence of transitional morphologies and along-strike transitions from one category to another suggests that a successful model should be able to explain all the observed morphologies.

Double ridges (morphology I), simple ridges (morphology II),and complex ridges (morphology III) are near-linear features in map view. Single ridges have an average height and width of hundred of kms and 10s of km respectively [4]. Double ridges feature a trough flanked by two parallel ridges. The trough can be narrow (Ib) or wide (I). Double ridges are a few hundred meters high on average and less than 5 km wide [16]. Complex ridges display a range of morphologies including anastomosing or near-parallel ridges (IIIa), ridge flanked by narrow troughs (IIIb) and ridges with modified summital trough, featuring a flat floor (IIIc) or an irregular ridge (IIId).

Many ridges transition along strike from one morphology to another (Figure 1). Therefore, a succesful ridge formation model should be able to reproduce all the observed categories of ridge morphology.

Cycloids are sometimes considered separate from ridges because they display arcuate segments with similar concavity and curvature, separated by a sharp cusp. The trajectory of cycloids is captured well by models of crack propagation in a rotating diurnal stress field. However, transitional features such as cycloids with smooth cusps are commonly observed, and some quasi-linear ridges suddently adopt a cycloidal trajectory. Moreover, cycloid display similar small-scale morphology as ridges. For that reason, we search for a unified model of ridge and cycloid formation.

Ridge formation mechanisms: Proposed mechanisms for the formation of ridges on Europa include shear heating [5,6], cryovolcanism [7] and incremental ice wedging [8]. While each of these mechanisms could potentially play a role in the formation of ridges on Europa, they have difficulty explaining the entire diversity of ridge types, the presence of transitional morphologies, and the similarity between ridges and cycloids.

The lack of segmentation in ridges motivates us to explore formation mechanisms related to fluid intrusion instead of faulting. We assume that liquid water fills tension cracks that open in the Europan crust in

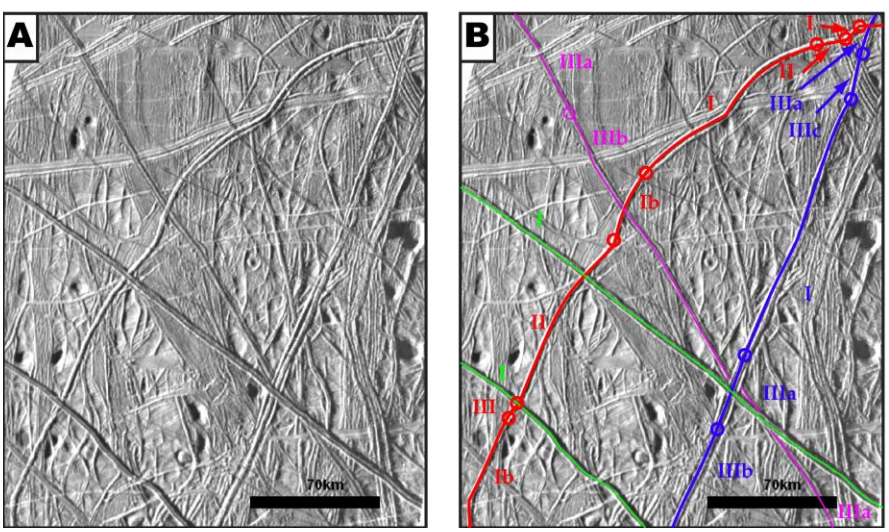

Figure 1. Galileo SSI image of Europa's surface centered at 77°W, 45°S (A) and interpretation (B). 5 major ridges are identified in the image. The type of morphology and transitions (circles) are marked. I: double ridge with variant IB as a ridge with narrow summital trough; II: single ridge; III: complex ridge with variants IIIa (subparallel ridges), IIIb (trough-flanked ridge), IIIc (ridge with flat-floored trough), IIId (ridge with modified trough).

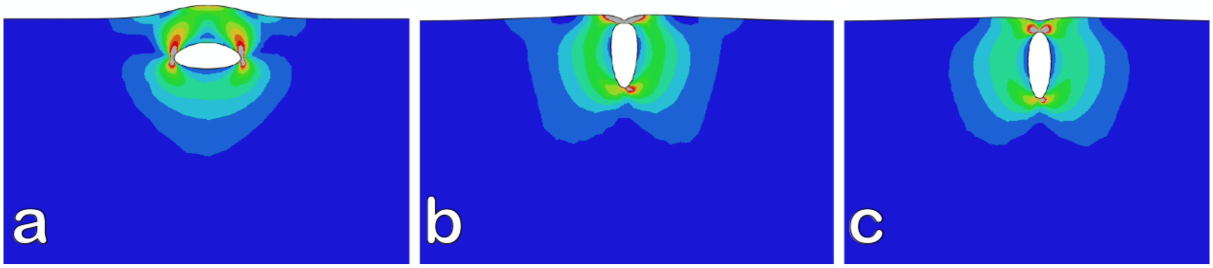

Figure 2. A single ridge was created (a) when the intrusion was sill-like a double ridge was created (b) when intrusion was dike-like and a trough like feature was created (c) when the dike was moved to greater depth. The intrusion is initially an ellipse with a 1/7.5 aspect ratio. The colors indicate von Mises stress with failure expected in the grey regions.

response to tidal stress and perhaps overpressure of a subsurface ocean [9,10,11,12,13]. The crack would be long and essentially continuous, like dikes on Earth. It may adopt a cycloidal outline under a time-variable diurnal stress cycle. Volume expansion upon crystallization of the cracks would compress and buckle the adjacent crust [8]. We developed initial models of ice deformation around a crystallizing intrusion to test the range of morphologies that may be produced.

The model is set up in 2-D, as a cross section of the ice shell taken perpendicular to the intrusion. We selected the commercial finite element software Abaqus because of its wide range of possible rheologies. However, the initial models presented here only consider the elastic response of water-ice.

The lateral edges of the model are stress free vertical walls that prevent extension of the ice layer as a whole. The surface is stress free and a winkler foundation is imposed at the base of the model. Crystallization of the intrusion is represented by a prescribed overpressure at the intrusion boundary. The model scales linearly with the overpressure. We report on the kinds of morphologies obtained by varying the depth and geometry of the intrusions, as well as the thickness of the ice layer (Figure 2). We find that the geometry of the intruding dike has a major impact on the ridge morphology. Specifically, the aspect ratio of the dike is the principal determining factor in whether a double or single ridge is observed on the the surface.

Our model is able to obtain a continuum of surface features including trough like features and both double and single ridges. The mechanism easily transitioned between forming a double ridge to forming a single ridge by changing only the aspect ratio of the intruding dike. (Figure 2). A horizontal sill-like intrusion lifts the surface above the intrusion, generating a single ridge. A vertical dike-like intrusion compresses the crust on either side of the intrusion, generating a pair of ridges due to the Poisson effect. A surface trough was generated when the intrusion is at greater depth as the double ridges become subdued with increased intrusion depth.

Implications: Our model of deformation around a crystallizing intrusion can successfully reproduce single ridge, double ridge, and trough morphologies simply by changing the aspect ratio and the depth of the intrusion.

Complex ridges may represent dike complexes, where new intrusions reutilize partially crystallized existing dikes. Flat-floored summital troughs, irregular summital ridges, and salt deposits may be evidence of extrusive cryomagmatism at Europan ridges [3], which would be expected as the intrusion crystallizes and fluid pressure increases. Future models may follow the chemical evolution of the fluid and the possibility of failure around the intrusion.

The crystallizing intrusion model can provide a unifying concept to explain the diversity of ridge morphology and transitional morphologies on Europa. As morphology is sensitive to the detailed geometry and depth of the intrusion, this model may allow for the estimation of water depth within [13], or beneath the ice shell, and the thermal structure of the ice shell.

References:

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