DOUBLE RIDGES ON EUROPA PRODUCED BY ICE WEDGING. M. D. Cashion[1], B. C. Johnson[1,2], M. M. Sori[1], H. Gibson[1], H. J. Melosh[1,2,†], E. P. Turtle[3], [1]Department of Earth, Atmospheric, and Planetary Science, Purdue University [2]Department of Physics and Astronomy, Purdue University [3] Johns Hopkins Applied Physics Laboratory, †Deceased September 11, 2020.

Introduction: The low number of impact craters and abundance of diverse surface features on Europa's icy surface suggests a surface age of only a few tens of Myr and likely ongoing geologic activity [1,2]. Double ridges appear more frequently than any other surface feature [3]. They consist of a pair of topographic highs, usually around 100 m tall, with a narrow trough running between them and shallow broad troughs bordering the outside. They are generally less than 5 km in total width, but can extend linearly for hundreds of km.

The origin of double ridges is still debated [e.g., 4]. In this work we build on previous studies of the incremental ice wedging model for ridge formation [5,6]. Tensile stresses during the extensional phase of Europa's 3.5-day orbit of Jupiter can open cracks within the ice shell. When the crack is open, water from the pressurized ocean below or some other liquid water reservoir within the ice shell may be injected into the crack and freeze along the walls. Over many tidal cycles, a wedge of ice is formed inside the shell, exerting stress that causes uplift of the surface into double ridge shaped topography. We present analytical and Finite Element Method (FEM) models of emplacement and growth of the wedge (respectively) that result in surface deformations consistent with observed double ridges.

Analytical edge dislocation model: A wedge of ice within the ice shell can be approximated by an analytical model of elastic deformation caused by opposing edge dislocations in an elastic half-space. The ice shell is represented by a symmetrical three-dimensional lattice structure, and an edge dislocation is an extra half plane of material inserted between rows of the crystalline ice structure. A schematic is shown in Fig. 1. We model ridge profiles using the solutions of surface deformation resulting from edge dislocations in an elastic half-space, presented in [7].

The individual surface deformations due to opposing edge dislocations at 100 m and 500 m below the surface of the shell are shown in the top panel of Fig. 2. The surface deformation profile from the superposed edge dislocations (shown in the bottom panel of Fig. 2) results in a surface feature with topographic relief of order ~100 meters, with two topographic highs surrounding a central trough.

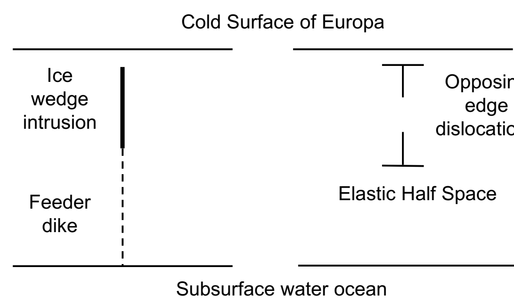

Figure 1: Model setup for opposing edge dislocations. On the left, the dashed line represents the dike that supplies ocean water to the ice wedge intrusion represented by a thick black line. The right side shows the opposing edge dislocations in an elastic half space that represent the ice wedge.

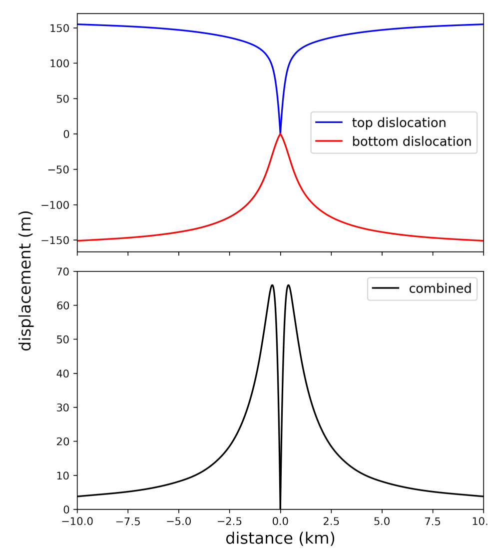

Figure 2: The surface deformation results of an analytical model of opposing edge dislocations that approximate an ice wedge emplaced in the ice shell. In this model, the top dislocation is 100 m below the surface, and the bottom dislocation is 500 m below the surface. The simulated wedge is 500 m in width. The top panel shows the surface deformation caused by the individual dislocations, and the bottom panel shows the surface deformation caused by the superposition of the two dislocations.

Finite elements method models: Using the FEM we can simulate more realistic wedge geometries and accurately handle finite strains. We created FEM models using the COMSOL Multiphysics software to study how the growth of an ice wedge generates stress and elastically deforms the surface of the shell. The ice shell is represented by a rectangular mesh that is 8 km tall and 14 km wide. The sides of the mesh have freeslip boundary conditions, the top is a free surface, and the base is held in place.

We vary the depth of the top of the wedge from 100 m to 1 km, in 100 m increments, to explore the effect on the resulting surface features. The ice wedge is rigid and has a vertical length of 900 m in each case. The horizontal expansion rate of the center of the ice wedge is 4.554×10^{-10} m/s, and the rate decreases via a parabolic function to 0 m/s at the top and bottom of the wedge where there is no expansion. The wedge grows for 1.5×10^{12} seconds (~50 kyr) in every model, so that the final maximum width of the wedge is 1366 m.

The horizontal growth of the wedge compresses ice surrounding it, causing uplift at the surface via the Poisson effect. For all depths we model, this results in two topographic highs with a topographic low in between, centered above the wedge. We find that the width of surface deformation linearly increases with depth of the top of the ice wedge, and the final topographic relief generated decreases as the depth to the wedge increases. The width of deformation is measured as the distance at which the free surface returns to the horizontal axis on the outside slope of the topographic high. Examples of surface deformation resulting from ice wedge depths of 100 m and 500 m are compared in Fig. 3, where the shallower wedge creates taller and narrower ridges.

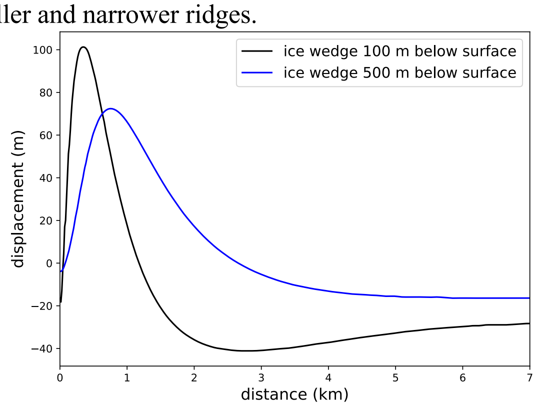

Figure 3: The surface deformation profiles caused by ice wedge growth, simulated using COMSOL. The topography formed by an ice wedge 100 m below the surface and the result when an ice wedge is 500 m below the surface are shown by the black and blue curves respectively. The ice wedge is 900 m tall in both cases. The topography is symmetrical around the vertical axis.

Discussion: The water that forms the ice wedge may be sourced from the ocean if the vertical crack in which the water intrudes reaches the bottom of the ice shell and extends along the entire length of the ridge. Alternatively, water may be locally sourced if the crack reaches the ocean at one point, if a cryovolcanic dike intersects an existing crack, or if the crack intersects with another source of water within the ice shell. Local sourcing may be more likely to occur since it requires only a limited number of points that intersect with a water source, instead of a continuous intersection along the entire length of the crack which may extend for hundreds of km. The models presented in this work are exclusively elastic and therefore not sensitive to where the water comes from, but we expect the results to be accurate representations of surface deformation that occurs on geologically rapid timescales for non-local sources (e.g., ~10^3 yrs) [5] or on potentially longer time scales if the ice wedge is locally sourced.

The FEM models (Fig. 3) presented here display topographic troughs that flank the outside of the ridges. These outer troughs are observed in actual Europan ridges as well and have previously been interpreted to form because of flexure from the topographic load of the ridges [2]. The heat flow budget from within Europa necessary to facilitate the formation of these troughs, however, is higher than Europa's estimated heat budget [8]. Our models are elastic and ignore the effect of gravity, yet still produce outer troughs suggesting that double ridges with flanking troughs can form exclusively from stress experienced within the ice shell without any flexural influence. Thus, the outer troughs may not be the result of flexure and may not constrain the thermal structure of the ice shell.

Conclusions: We have used both analytical and numerical methods to model the process of elastic surface deformation caused by a wedge of ice freezing within cracks in the ice shell of Europa. Our models are consistent with the shape and scale of Europan ridges, indicating that the ice wedging hypothesis may be a viable mechanism for producing double ridges on the surface of Europa. Radar analysis of an apparent Earth-analog for Europan double ridges presented in [9] reveal its formation due to growth of a subsurface wedge over time, suggesting that radar data from NASA's upcoming Europa Clipper mission may greatly improve our understanding of double ridge formation.

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