The Role of Plastic Deformation and Crystallizing Water Intrusions in Europan Ridges

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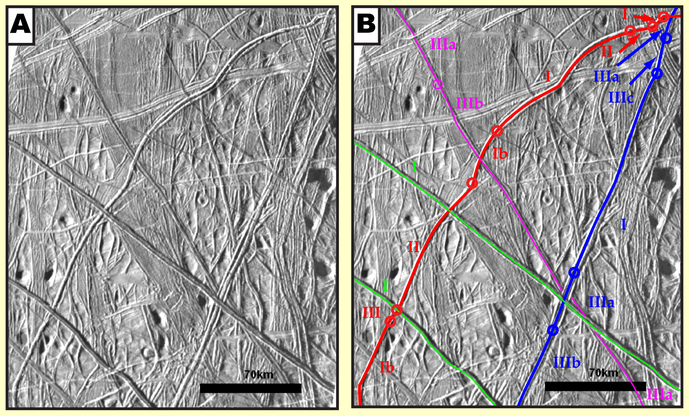
Europan Ridges

Based on images from Voyager and Galileo, previous workers [1,2] have defined several kinds of ridge morphology, including single ridges, double ridges, complex ridges.

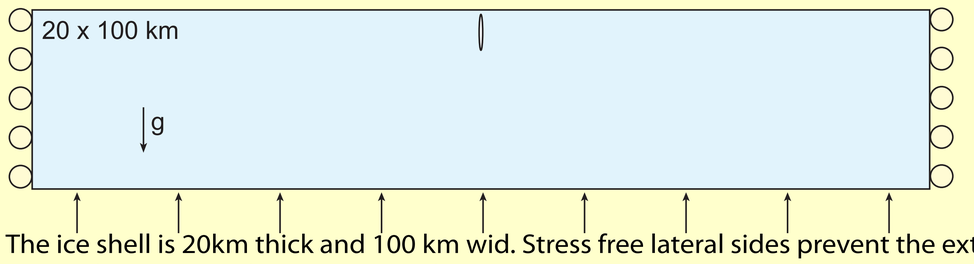
Five major ridges are identified in the image above. The type of morphology and transitions (circles) are marked. I: double ridge with variant IB as a ridge with narrow summital trough; II: single ridge; III: complex ridge with variants IIIa (subparallel ridges), IIIb (trough-flanked ridge), IIIc (ridge with flat-floored trough) [3].

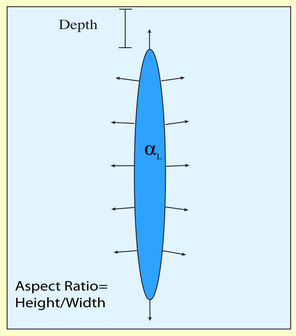


A successful model for Europan ridges formation should be able to reproduce the observed diversity of morphology and account for the presence of transitions from one morphology to another along strike.

Model Setup

The model represents a cross section of the ice shell taken perpendicular to the intrusion using the commercial finite element software, Abaqus™ . Plane strain deformation is assumed throughout.



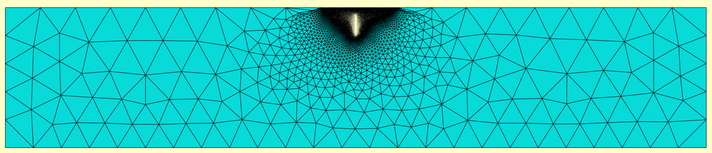


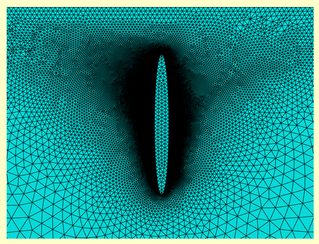
The ice shell is 20km thick and 100 km wid. Stress free lateral sides prevent the extension of the ice. The top surface is stress free. An elastic foundation is applied to the base of the model to simulate the restoring force of water beneath the ice shell. Crystallization of the intrusion is simulated by changing a phase change parameter θ from 0 to 1, with 1 representing a solid material. The material properties of the intrusion change from water-like to ice-like as the solidity ratio s increases with the phase change. The solidity ratio is used to calculate the initial Young's modulus and poisson's ratio for the water intrusion. A low solidity ratio means a liquid intrusion.

$$\alpha_L = \frac{\rho_w - \rho_i}{3\rho_w}$$

$$\nu = \frac{3/2 - s}{3 + s}$$

$$E = \frac{3G}{s}$$

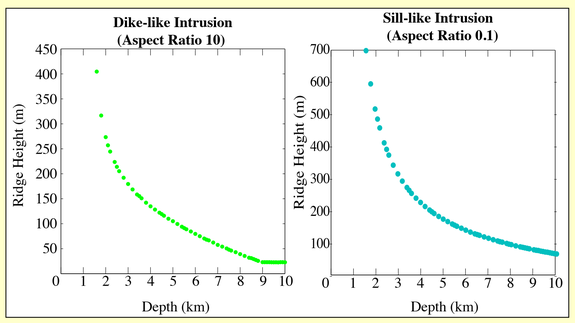




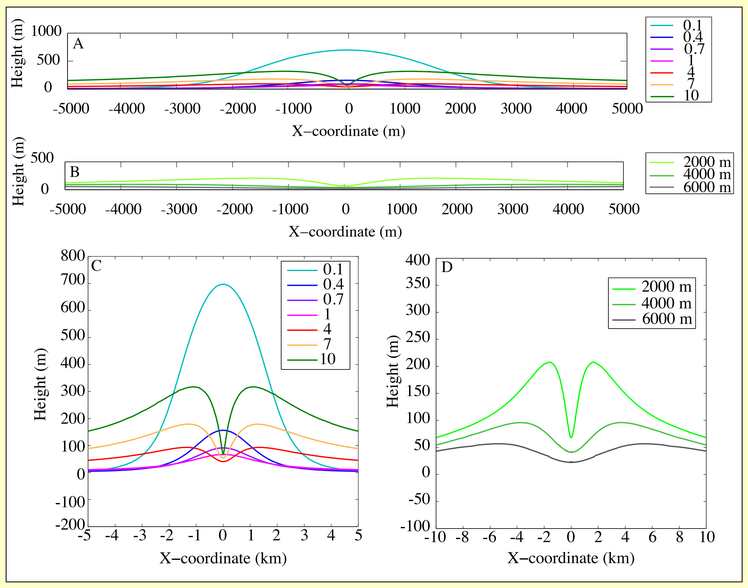
The mesh is built of linear triangular elements. The mesh must be refined around th intrusion for numerical stability and resolve plastic failure.

Elastic Model Results

Previous finite element models of the deformation related to the crystallization of a water intrusion were constructed using an elastic rheology. The intrusion was represented by a pressurized void in order to simulate the expansion associated with the freezing of a water body within the shell.



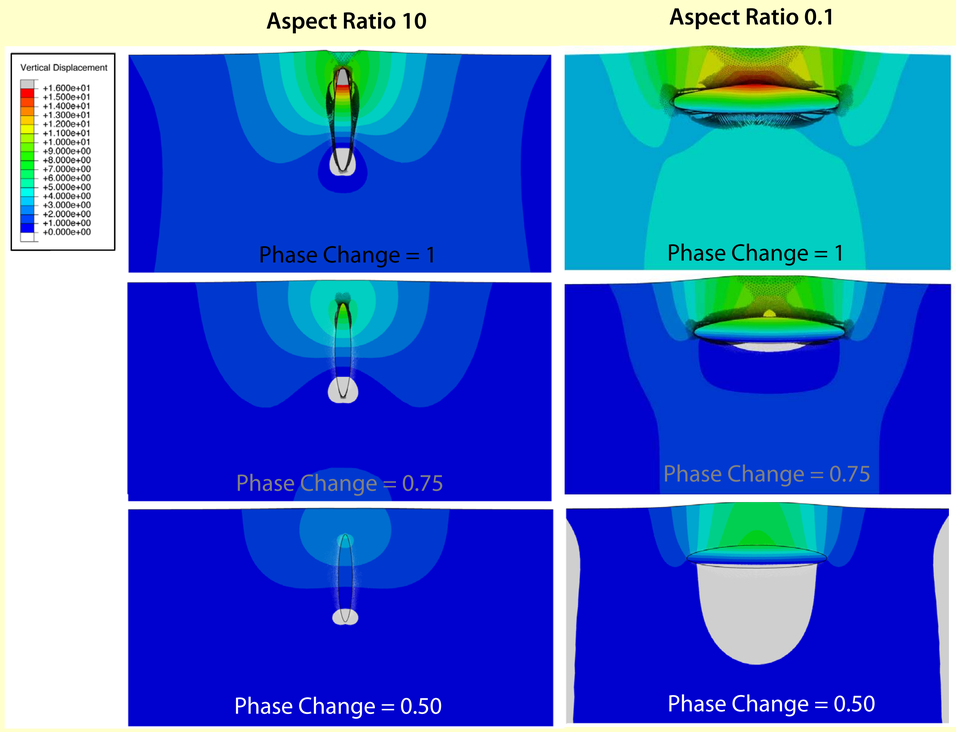
Ridges of 100 m height can be produced on top of a dike-like intrusion that is shallower than 4 km or a sill-like intrusion shallower than 9 km.



By varying intrusion aspect ratio and depth in the elastic model, the profiles to the right were generated. The aspect ratio (A and C) governed the ridge type produced and the depth (B and D) controlled the height of the ridges. A and B have no vertical exaggeration.

Plastic Model Results

The models shown below include plastic deformation according the Mohr-Coulomb failure criterion with friction coefficient 30° and non-associated flow rule with dilation angle 10° which leads to localized shear zones. Cohesion increases from 2MPa at intial failure to 5 MPa at a strain of 1. The maximum strain is typically less than 10%. The vertical displacement induced by the phase change is shown beblow with 10x exaggeration in grid deformation. The grid outlines show the elements where plastic failure occured.
Deformation on top of a dike-like intrusion (left, intrusion aspect ratio of 10) is similar to the elastic case, although the central depression appears fault-bounded.
Deformation on top of a sill-like intrusion (right, aspect ratio of 0.1) initially generates a single ridge, but a double ridge appears at later stages of crystallization due to coupling between the regions above and on the side to the intrusion.



Discussion

The previous model with elastic rheology showed that the geometry of the intrusion can have a major role in determining the surface deformation related to a crystallizing water intrusion. A dike-like intrusion formed a double ridge and a sill-like, a single. However, adding plastic behavior and thermal evolution over time dramatically changes the story.

As the dike intrusion crystallizes there is a change in its physical properties, including the density, Young's modulus and poisson's ratio. These material properties not only change the deformation and stresses within the intrusion, but also the deformation in the surrounding ice. A sill like intrusion can create both a double and single ridge through the process of crystallizing. Initially a single ridge is formed, however as the intrusion solidifies further a double ridge morphology can emerge. This evolution may be able to help explain the along strike changes in morphology. As the ridge matures a double ridge is expected to develop from a single ridge.

The ridge height with the plastic rheology is only ~10 m. This suggests that a mechanism for overpressure may be required in order to obtain the heights up to 100m observed on Europa.

Recent studies of chaos suggest the presence of large bodies of water within Europa's shell, [4] providing a possible source for the water. Dombard et al. [5] recently suggested that a sill was required to be present in the formation mechanism of ridges on Europa based on the flanking cracks and estimated thermal anomalies. While our models do not predict flanking cracks, it is possible that these could appear in future models, using different rheological properties of ice.

References

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[5] Dombard, A.J., Patterson, G.W., Lederer, A.P., Prockter, L.M. (2013) ICARUS, 223, 74-81

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