The initiation and persistence of cracks in Enceladus' ice shell. J. S. Jordan[1], M. L. Rudolph[2], M. Manga[3]. [1]Jackson School of Geosciences, The University of Texas at Austin, 2305 Speedway Stop C1160, Austin, TX [2]Department of Geology, Portland State University, 1721 SW Broadway Ave, Portland OR USA. [3]Earth & Planetary Science, University of California, Berkeley, 307 McCone Hall, Berkeley CA.

Introduction: The remarkable eruptions from cracks in Enceladus' South Polar Terrain (SPT) provide a unique window into the interior of an icy satellite. Here we revisit the processes that create cracks and prevent them from freezing in light of the confirmation that Enceladus has a global ocean [1,2] and analyses of the gravity field that indicate that the ice shell is thinnest beneath the SPT where the eruptions occur [3]. We use a suite of end-member models for the dissipation of energy to explore the persistence of the cracks at Enceladus' South pole.

Model: We develop 3 models for the different stages in the formation and evolution of cracks. First, we consider the generation of stresses in Enceladus ice shell by ocean pressurization induced by ice shell thickening and evaluate when these stresses can create cracks. Second, we determine whether cracks can propagate from the surface to the ocean. Third, we compute the energy dissipation in the cracks and heat tranport through the surrounding ice to determine the conditions that permit the persistence of cracks.

Ocean Pressurization: We idealize Enceladus' structure as being comprised of: 1) a rocky interior surrounded by 2) a global ocean capped by 3) an ice shell (Figure 1A). The ice shell is subdivided into two regions, an outer layer that behaves as a linear elastic solid and an inner layer that behaves viscously over time scales that the ocean freezes (Figure 1B). The boundary between these regions is controlled by temperature. Building on [4] we derive analytical expressions for the relationship beteween the amount of freezing and the stresses in the ice shell and pressure in the ocean. Fractures will initiate at the surface when the tangential stresses (Figure 2) exceed the tensile strength of ice, 1-3 MPa [5].

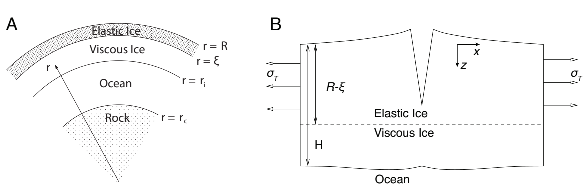

Figure 1: Geometry of the model problem. (A) Model used for crack propagation, showing rocky interior, ocean, viscous ice, and elastic ice layers. (B) Geometry used for the fracture propagation problem.

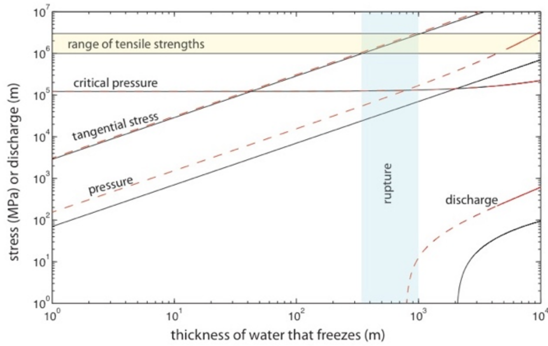

Figure 2: Ice shell thickening produces tensile stresses in the ice and pressurizes the subsurface ocean. The initial ice shell thickness is assumed to be 12 km; the solid curves correspond to an elastic layer 2 km thick and the dashed curves an elastic layer ½ of the total ice shell thickness. The yellow region indicates the assumed range of tensile strengths of ice, 1-3 MPa. Labeled curves indicate tangential stresses and ocean pressure. The blue shaded region indicates the amount of ice shell thickening required to initiate an eruption.

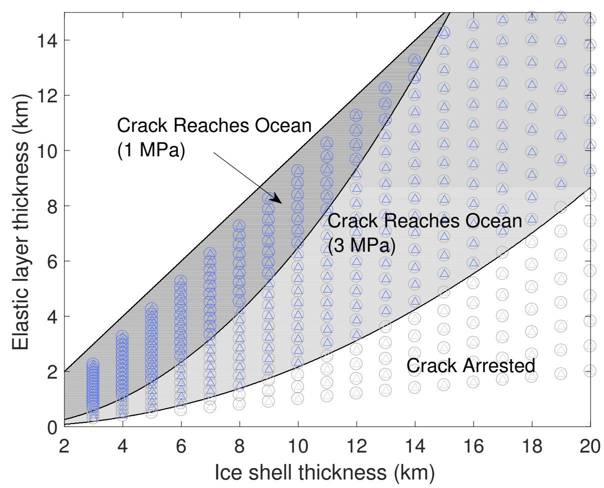

Figure 3: Results of boundary element calculations of fracture penetration. Triangles and circles indicate cases assuming 1 MPa and 3 MPa tensile strength. Blue symbols indicate that the crack reaches a subsurface ocean and grey symbols indicate cracks that are arrested.

Crack penetration: There are two barriers to crack penetration [6]. First, only the outer part of the ice shell supports elastic stresses on the timescale of ocean pressurization. Second, overburden stresses will act to shut the crack. We use a boundary element method to determine the depth to which cracks can penetrate for the geometry shown in Figure 1B for different applied stresses, ice shell thicknesses and thicknesses of the stressed, brittle layer (Figure 3).

Crack Persistence: We consider the crack persistence problem in two end-member limits. First, we use analytic solutions to approximate the initial heat loss from fractures. Second, we address the steady-state conduction of heat from fractures, in which dissipation balances conductive heat transport. If dissipation balances conduction to prevent solidification along the margins of the crack, the half-space cooling model is applied. If dissipation in the cracks is much smaller than the (initially large) conductive heat flow, the Stefan solution can be applied. These solutions are approximately valid as long as horizontal temperature gradients are much larger than the vertical temperature gradient. We consider two scenarios for each of the end-member limits. First, we consider a scenario in which all heat is supplied to the base of the ice shell by dissipation in the subsurface ocean (Figure 4, blue curves). Second, we consider an ice shell whose equilibrium thickness is maintained by tidal dissipation in the solid ice (Figure 4, red curves). The initial heat lost from the cracks is conducted into the adjacent ice and would not be immediately detectable.

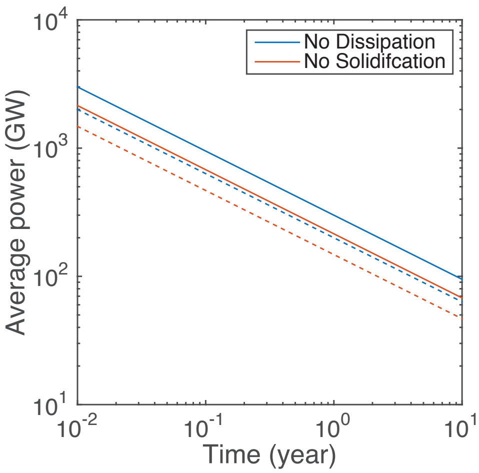

Figure 4: Heat flow through cracks after initiation, assuming no dissipation (blue), and assuming no solidification (red). Solid lines show case basal heating of the ice shell and dotted lines show model case with internal heating of the ice shell. The horizontal and vertical length of cracks are assumed to be 500 km and 12 km, respectively.

To address the long-term persistence of the cracks, we perform calculations that couple viscous dissipation in the cracks with steady-state conductive heat transport away from the cracks [7]. Turbulent dissipation in the cracks is driven by oscillatory flows induced by tidal forcing [8]. We use a realistic treatment of viscous dissipation in oscillatory, turbulent flow and couple the 1D model for dissipation in the crack with 2D heat conduction away from the crack. We solve iteratively to obtain a consistent crack-width profile. The upper portion of the crack narrows near the surface to accommodate the high heat flow produced by the steep thermal gradients where the warm crack meets the cold surface of the ice shell. The crack widens at the base, where less dissipation is required to match the smaller lateral temperature gradients. The steady-state conductive heat loss from these coupled models is small (~0.5 GW), suggesting that once cracks survive the initial, very rapid, cooling (Figure 4), long-term persistence of cracks is plausible.

References:
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