Fractures in structurally-compromised ice: Observations of rift behavior at the highly fractured Amery Ice Shelf, East Antarctica and implications for the icy shells of Enceladus and Europa.
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Introduction: The possible eruption of water from cracks in the outer planet satellites has been a strong point of interest over recent years in planetary science. Smoothed regions of ice in Europa's highly-fractured shell suggest resurfacing [1, 2, 3], reminiscent of record-erasing flows on the Earth and other terrestrial planets. Enceladus' well-known "tiger stripes", four long, nearly-parallel rifts in in south polar region, are associated with the active venting of water and trace gases that emanate from the area [4]. The eruptions have been linked to tensile forces stemming from tidal effects that control the opening of the rifts [5, 6, 7]. The study of crack penetration is highly dependent on assumptions of ice shell thickness (and subsurface liquid water ocean), surface and interior stresses, and ice properties. The tidally-induced stress fields for Europa and Enceladus, specifically, have been studied in terms of their ability to adequately open rifts in order to allow for escape of subsurface material.

Assuming a liquid reservoir beneath the surface (i.e., global ocean or localized ocean), in order to erupt onto the surface, a surface crevasse (crevasse is defined here as a crack in the ice that does not extend the full thickness of the ice), as also found in terrestrial glaciology, must vertically propagate and penetrate the entire shell to reach the liquid reservoir. On this topic, there is the issue of the subsurface water reaching the surface; once the crevasse has become a conduit, subsurface must overcome buoyancy to reach the surface, as water is more dense than ice (e.g., [8]). Initiation and further penetration of a surface crevasse is driven by tensile forces at and near the surface. At depth these forces are opposed by the overburden pressure from the weight of the ice (glaciostatic pressure) and the fact that the lower section of the ice shell undergoes viscous relaxation [9, 10]. This means that tensile stresses at the surface, capable of fracturing the shell, may not be sufficient to allow for full penetration of the shell. An additional factor to take into account is the highly-fractured nature of the icy shells, and the possible interaction of rifts, a phenomenon observed both on Earth's ice shelves and in other media, such as wave-breaker walls, airplane propellers, Arctic permafrost, mud flats in Death Valley, and others [11].

Background: The thickness of ice shelves around Antarctica can range from a kilometer or so at the grounding line (transition from grounded to floating) to a few hundred meters at its farthest extent over the ocean. Estimates of the ice shell thicknesses of Enceladus and Europa, on the other hand, have a much larger range of uncertainty. Enceladus, a small body with a radius of approximately 250 km, likely has an ice thickness between 10 - 90km [12, 13]. Europa is a larger icy body with a radius of roughly 1560 km. Estimates for the thickness of Europa's ice shell over its putative global ocean range between 1 - 32 km [14].

Estimates using these shell thicknesses have been put forward for the origin of stresses required to rupture the ice shell [8, 10]. While classical treatment of a fracture is relevant in order to make first-order estimates of the stresses present in the ice shell, and shell thickness is a crucial factor in this calculation, a factor that many of these studies overlook is the fact that the fractures in the ice shells are not isolated. The diminished structural "integrity" may affect the capability of the predicted stresses from single-crack models to open or propagate rifts in a field of fractures.

In observing the array of five rifts at the front of the Amery Ice Shelf in East Antarctica, we determined that the rifts, located within 30 km of each other interact [15]. Not only are the rift propagation events observably correlated, but these quantifiable inter-relational dynamics changed with the introduction of a new rift. The oft-cited [16] showed that linear elastic fracture mechanics could be applied to edge cracking in ice; he did not, however, consider an array of edge cracks, like that seen at the front of the Amery Ice Shelf. Likewise, studies of fractures in planetary ice shells by [6, 7, 8] and others take into account estimates of ice thickness and dynamics, but none account for the existence of an array of cracks or fractures, thereby possibly underestimating stresses necessary to open or modify existing fractures or initiate new ones.

Approach: Put simply in linear elastic fracture mechanics, a rift or fracture propagates when under a certain amount of stress. The necessary amount of stress to cause propagation can be assessed by studying the stress field at the crack tip. In considering mode I cracking only, the elastic stresses at a distance r from the crack tip can be described as

$$\sigma_{ij} = \frac{K_I}{\sqrt{2\pi r}} f_{ij}(\theta) + \ldots \quad (1)$$

where K_I is the stress intensity factor (and '…' symbolizes higher-order terms important only at far distances from the crack tip). At a certain point, predicted elastic stress surpasses the yield strength of ice, and therefore plastic deformation occurs to limit elastic stress.

In considering both fracture initiation and penetration of a fracture through the ice, we must consider all contributions to the stress intensity factor at the crack tip. In a singular, isolated crack, these contributions are [17]: (1) tensile (or compressive) stress; (2) weight of ice above the fracture, or overburden pressure; (3) water pressure if the crack is water-filled.

$$K_1^{(1)} = F(\lambda)R_{xx}\sqrt{\pi d} \quad (2)$$

$$K_1^{(2)} = \frac{2\rho_i g}{\sqrt{\pi d}}\int_0^d \left[-b + \frac{\rho_i - \rho_s}{\rho_i C}\left(1 - e^{-Cb}\right)\right] G(\gamma,\lambda)\,db \quad (3)$$

$$K_1^{(3)} = \frac{2\rho_w g}{\sqrt{\pi d}}\int_a^d (b-a)G(\gamma,\lambda)\,db \quad (4)$$

where superscripts (1-3) refer to the contributions listed above, *F(λ)* is a function of the ratio of fracture depth *d* to the ice thickness *H*, ρ is density of ice and water, C is a constant between 0.0165 to 0.0314 m^{-1} [18], b is compensation depth, and G(γ,λ) is a function described by [19]. This calculation is commonly used to compute stresses necessary to propagate a fracture along a surface or penetration of a crevasse to the base of an ice sheet or shelf.

However, an interesting notion detected when we observed rift interaction in the Amery Ice Shelf, along with studies of other fractured media mentioned previously, is that the existence of other fractures nearby can affect and individual rift's propagation. This raises the question of the significance in the difference between the isolated crack model so often used versus modeling shell-penetrating cracks as part of an array of rifts. We follow the approach of [17], using results from [19] to model closely-spaced fractures on Enceladus and Europa as parallel finite cracks in an infinite plane. While the stress intensity factor contribution from the overburden pressure is the same, the contribution by tensile stresses (Eq. 2) must be modified:

$$K_1^{(1)} = D(S)R_{xx}\sqrt{\pi d S} \quad (5)$$

where D(S) is a function dependent on S, defined as

$$S = \frac{W}{W+d} = \frac{1}{1+\frac{d}{W}} \quad (6)$$

where W is the spacing between rifts (*d* is fracture depth). The result of multiple fractures is to reduce the net stress intensity factor, an effect that increases with closer spacing (or equivalently deep fractures). Because of this decrease in $K_1^{(net)}$, a larger tensile stress is necessary to allow for propagation deeper into the ice. An example is provided in Fig. 1, in which we apply a tensile stress of 2 MPa to the Enceladus ice shell (upper limit 90 km) for two cases: (1) a single fracture in the shell; and (2) multiple parallel fractures spaced ~35m apart, matching topographic observations of the tiger stripes (e.g., [20]). It can be observed that the single fracture surpasses the predicted yield strength of ice much faster than fractures within an array. This has significant implications for computations of stresses in planetary ice shells, the ability of fractures to penetrate the entire ice shell, opening rates, and initiation of new fractures. We plan to conduct studies in each of these areas for both Enceladus and Europa.

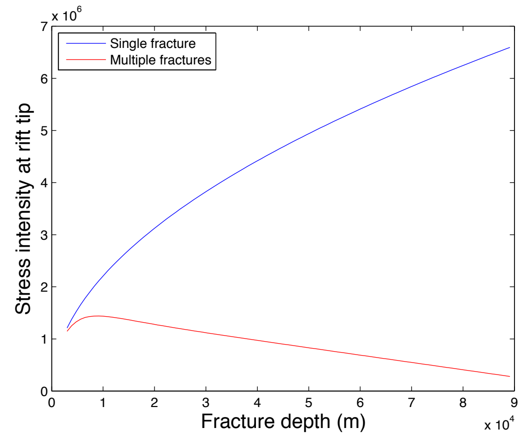

Figure 1. Net stress intensity factor at the crack tip, used to predict fracture propagation, for a single isolated crack in Enceladus' ice shell (blue) and for a fracture in a field of other fractures, e.g., tiger stripes (red).

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