OCEAN PRESSURIZATION, STRESS EVOLUTION, AND TENSILE FRACTURE WITHIN ICY MOONS.

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Introduction: Liquid water has been inferred to erupt in Europa's geologic past [e.g. 1] and a mixture of water vapor and ice is currently erupting from Enceladus' south polar region [2] whose source may be a liquid water ocean. Water confined to a subsurface ocean faces two impediments in reaching the surface. First, it is negatively buoyant with respect to ice. Second, it requires a pathway through which to flow. Thickening of a global or regional ice shell overlying a liquid water ocean causes pressurization of the underlying ocean owing to the volumetric expansion of water as it freezes to ice. As a result of ocean pressurization, tangential stresses of several MPa can be produced in the overlying ice shell. Stresses also arise in ice shells due to thermal contraction, but these tend to be much smaller. We solve the equations governing heat transfer and change of stress due to ice shell thickening and then use the obtained stress distribution to predict the depth to which tensile fractures may penetrate.

Background: In previous work [3], we investigated the ability of tensile fractures to penetrate downward through an ice shell whose basal region does not support tensile stresses due to viscoelastic relaxation. The evolution of thermal stresses was studied by Hillier and Squyres [4], and also by Nimmo [5]. Recently, Manga and Wang [6] studied the evolution of ocean pressure using a simplified mechanical model in which the outer portion of the ice shell was elastic and the inner portion viscous rather than solving the full viscoelastic problem.

The propagation of tensile fractures through an ice shell is made possible by tensile stresses in the upper, elastic region of an ice shell. When the tip of a fracture is sufficiently close to the base of an ice shell, the lower boundary, which is free of shear tractions, aids fracture penetration [7]. In contrast, in the warmer basal region of an ice shell, tensile stresses are relaxed due to viscous flow, and this effect tends to inhibit fracture penetration [3]. Fractures that initiate at the surface of an icy moon are essentially vacuum-filled, and consequently the pressure exerted by overburden is very important in closing fractures. The depth to which fractures penetrate on a particular satellite is a function of gravitational acceleration, which differs by about an order of magnitude between Europa and Enceladus.

Approach: We describe an ice shell as a Maxwell viscoelastic material with temperature-dependent viscosity. Thermal conductivity is inversely proportional to temperature and we account for this effect, which becomes more pronounced at the lower temperatures encountered in icy moons. The temperature profile differs depending on whether or not the ice shell convects. We explore both the conductive and convective cases for both Europa and Enceladus. As the ice shell cools, it thickens, and we solve a Stefan-like problem in spherical coordinates to determine the position of the base of the ice shell as a function of time. The energy (temperature) equation is coupled to the stress equation through the ocean pressure, ice viscosity, and radial displacement. At each timestep, we solve the energy equation first and then iteratively solve the stress equation to obtain a position for the base of the ice shell that is compatible with the ocean pressure.

Following the ocean pressurization calculation, we use the obtained distribution of tangential stresses in combination with the fracture mechanics model used in [3] to calculate the depth to which tensile fractures may penetrate. We assume that cracks form at the upper free-surface once tensile stresses exceed the tensile strength of ice, which we assume to lie in the range of 1-5 MPa [3,6,8]. On the time scale of fracture propagation, the entire shell behaves as an elastic solid. We use a boundary element model based on the code TWODD [9] with the addition of a crack-tip element to calculate the mode-I stress intensity factor for each crack. We then iteratively extend the crack until the stress intensity factor no longer exceeds the fracture toughness. Enceladus' low gravity makes it possible for shells of several tens of kilometers in thickness to be cracked in this fashion, but Europa's relatively strong gravity makes it unfeasible for ice shells thicker than a few kilometers to be cracked.

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