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Fracture penetration in planetary ice shells

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ABSTRACT

The proposed past eruption of liquid water on Europa and ongoing eruption of water vapor and ice on Enceladus have led to discussion about the feasibility of cracking a planetary ice shell. We use a boundary element method to model crack penetration in an ice shell subjected to tension and hydrostatic compression. We consider the presence of a region at the base of the ice shell in which the far-field extensional stresses vanish due to viscoelastic relaxation, impeding the penetration of fractures towards a subsurface ocean. The maximum extent of fracture penetration can be limited by hydrostatic pressure or by the presence of the unstressed basal layer, depending on its thickness. Our results indicate that Europa's ice shell is likely to be cracked under 1–3 MPa tension only if it is $\leqslant 2.5$ km thick. Enceladus' ice shell may be completely cracked if it is capable of supporting ~ 1–3 MPa tension and is less than 25 km thick.

1. Introduction

Liquid water may erupt on icy satellites of Saturn and Jupiter. The presence of topographic features on Europa such as smooth regions filling topographic lows and often bounded by ridges suggests that liquid water has erupted onto the ice-covered moon's surface (e.g., Fagents, 2003; Miyamoto et al., 2005; Prockter and Schenk, 2005). On Enceladus, a mixture of water vapor and ice is currently erupting from the "Tiger Stripe" fissures in the south polar region (Hansen et al., 2006). Although the requirement of liquid water is hotly debated (e.g., Kieffer and Jakosky, 2008), some models favor the eruption of liquid, rather than sublimation of a solid, on Enceladus (Porco et al., 2006). The ongoing eruption at Enceladus' South Pole appears to occur through tensile fractures (Hurford et al., 2007a).

Water confined to a subsurface ocean faces two mechanical impediments in reaching the surface. First, it is negatively buoyant with respect to ice and second, it needs a conduit through which to flow. If tensile stresses generated in an ice shell exceed the tensile strength of ice, a fracture will form and may provide the necessary conduit. Downward penetration of tensile fractures initiated at the surface is opposed by lithostatic pressure and by the absence of tensile stresses in the lower part of the shell, which become relaxed over long time scales (Nimmo, 2004; Manga and Wang, 2007). We use a numerical model to test the feasibility of fracturing an ice shell whose lower region does not support far-field tensile stresses.

Lee et al. (2005) and Qin et al. (2007) studied fracture penetration in an elastic medium with finite thickness and variable porosity. Their results indicate that the presence of a lower free-surface enables fractures to penetrate further than they would under otherwise identical conditions in a halfspace. Neither study accounts for the presence of a basal layer in which deviatoric stresses are relaxed, which is the focus of our study.

2. Background

Estimates of the thickness of Europa's ice shell lie within the range of about 1 km to at least 32 km (Billings and Kattenhorn, 2005). The maximum thickness of Europa's ice shell is constrained by the vertical extent of its ice + water shell, between 105 and 160 km depending on the composition and structure of the underlying rocky layers (Kuskov and Kronrod, 2005; Cammarano et al., 2006). Enceladus has a mean radius of 252.1 ± 0.2 km and may be partially- to fully-differentiated (Porco et al., 2006). In the latter case, the thickness of the ice + water shell is ~ 90 km, with an ice-only thickness of 10–90 km (Schubert et al., 2007).

In order to fracture an ice shell, there must be a physical mechanism capable of producing stresses in excess of the tensile strength of the material. Europa's shell is exposed to a diurnally varying tidal stress of magnitude 0.1 MPa (Hurford et al., 2007b). Nimmo (2004) calculated the stresses due to cooling and freezing at the base of an ice shell and found that extensional stresses exceed 10 MPa for shells that thicken to more than 10 km. When the compressibility of the underlying ocean is taken into account, stresses in the shell are reduced but still large, ~ 1–3 MPa (Manga and Wang, 2007). The maximum stress due to non-synchronous rotation or true polar wander is of order 1–10 MPa (Leith and

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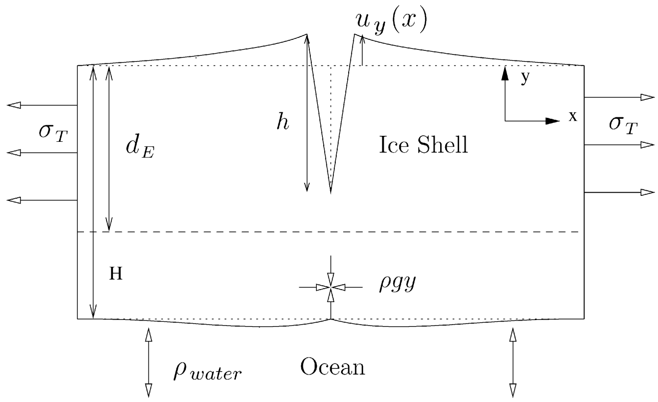

Fig. 1. Schematic illustration of our model geometry as described in Section 3.1. The dashed line at depth d_E represents the depth below which tensile stresses do not exist. The quantity $\Delta\rho$ is the difference in densities of water and ice, 90 $kg\,m^{-3}$.

McKinnon, 1996). Schenk et al. (2008) have suggested that surface features present on Europa indicate the occurrence of true polar wander. In combination, these stresses are sufficient to overcome the tensile strength of ice on Europa. Enceladus orbits Saturn with an eccentricity of 0.0047, producing tidal stresses on the order of 0.1 MPa (Hurford et al., 2007a). Nimmo and Pappalardo (2006) have proposed that Enceladus underwent diapir-induced reorientation, which would produce tectonic stresses on the order of 10 MPa. Ocean pressurization due to ice shell thickening, should a subsurface ocean exist, could also produce stresses of 1–10 MPa for plausible changes in shell thickness (Manga and Wang, 2007).

3. Model

3.1. Physical model

We model the ice shell as a single homogeneous and isotropic linear elastic layer (Fig. 1). The entire shell deforms elastically on the time scale of crack propagation. Prior to fracturing, the upper region of the ice shell is stressed. Meanwhile, the lower, warmer part of the shell undergoes viscous deformation and tensile stresses will have relaxed. The depth at which viscous deformation dominates depends on the time scale over which stresses are applied. The upper boundary is a free-surface. The lower boundary does not support shear tractions and the normal component of stress must be continuous across this water–ice interface. The crack walls are prescribed to be free of shear tractions. Cracks are initiated at the upper surface because the applied tension is uniform across the elastic layer and hydrostatic pressure is zero at the surface. Once a fracture forms at the upper surface, the normal tractions exerted on its walls are the superposition of overburden and extensional stresses in the upper region of the ice shell, but only overburden stresses act in the lower, unstressed region. We assume that the acceleration due to gravity remains constant with depth, a reasonable assumption since the (highly uncertain) tensile strength of ice has a greater effect on our results.

In all cases, we let the Young's modulus $E = 5 \times 10^9$ Pa (Nimmo, 2004) and Poisson's ratio $\nu = 0.33$ (Schulson, 2001). A summary of the physical quantities used in our modeling is provided in Table 1.

The relevant thickness of the stressed upper layer depends on the time scale over which stresses are applied. The time scale governing viscous relaxation is the Maxwell time $\tau_M = \mu/E$. Nimmo (2004) assumed that viscous deformation dominates after O(10) Maxwell times and defined the temperature at which the elastic-viscous transition occurs as T = 180 K. This corresponds to an effective viscosity (assuming exponential dependence of viscosity on temperature) of $\sim 10^{18}$ Pa s and a Maxwell time $\tau_M \approx 50$ years.

Table 1
Physical quantities used in the model.

	Europa		Enceladus
g	1.3 $m\,s^{-2}$		0.13 $m\,s^{-2}$
H	1–35 km		10–90 km
d_E/H	0.2–0.5		0.2–0.6
ρ_{ice}		910 $kg\,m^{-3}$	
σ_T		1–3 MPa	
E		5 GPa	
ν		0.33	

The temperature profile in an ice shell depends on whether or not the ice shell convects. Based on this choice of τ_M, if heat transfer occurs only through conduction, Europa's stressed layer has a fractional thickness (d_E/H) of about 0.5 and Enceladus' stressed layer comprises about 0.6 of its total ice shell thickness. Manga and Wang (2007) suggested time scales of $\tau_P = 10^5$ and 10^8 years for changes in stress due to ice shell thickening on Europa and Enceladus, respectively. By setting $10\tau_M = \tau_P$, we obtain corresponding temperatures of 140 K and 123 K and fractional stressed thicknesses of 0.2 for both satellites. We therefore primarily consider fractional stressed thicknesses of 0.2–0.5 for Europa and 0.2–0.6 for Enceladus.

In linear elastic fracture mechanics, the stress intensity factor describes the concentration of stresses at the tip of a crack (Irwin, 1957). There is a singularity in stress at the tip of a crack in a linear elastic material, which in nature is accommodated through plastic deformation. Here, we consider Mode-I fracture, in which crack walls undergo only normal displacement. A Mode-I fracture will grow if the crack-tip stress intensity factor, K_I, exceeds a critical value K_{IC} that is material-dependent. Stresses near a crack tip decay with $r^{-1/2}$ where r is distance from the crack tip, and K_I may be calculated by evaluating the normal traction acting on a crack-coplanar surface very close to the crack tip (Crouch and Starfield, 1983).

The tensile strength of ice on either satellite is the most poorly constrained physical property in our model. Fracture-free, avesicular ice Ih with a grain size of 1 mm has a measured tensile strength of 1.5 MPa at $-10\,°C$, while ice with finer grains may fail at 17 MPa (Schulson, 2001, 2006). Relevant temperatures on Europa and Enceladus are colder than those at which tensile strengths have been measured. Europa's low-latitude surface temperature is between 86 and 132 K (Spencer et al., 1999). The mean surface temperature on Enceladus is 75 ± 3 K and also varies with latitude (Grundy et al., 1999). The temperature increase across Europa's ice shell is about 170 K (Nimmo, 2004), resulting in laboratory-like conditions at the base of the shell. Both the compressive and tensile strengths of ice increase as temperature decreases, although the effect is less pronounced under tension (Schulson, 2001). Fractured or porous ice may be significantly weaker (e.g., Lee et al., 2005) and tensile strength may be scale-dependent; the in situ tensile strength of sea ice is $\sim 10^5$ Pa on length scales of hundreds of meters (e.g., Dempsey et al., 1999). We assume tensile strengths in the range of 1–3 MPa for consistency with previous studies (Manga and Wang, 2007; Leith and McKinnon, 1996).

3.2. Numerical method

We use an indirect boundary element method modified from the program TWODD (Crouch and Starfield, 1983) to calculate the displacements along fractures in a two dimensional linear elastic medium. Our first modification is the addition of a crack tip element that facilitates the calculation of stress intensity factors. We also account for gravity and buoyancy at the upper and lower boundaries. Rather than describing these forces as a body force