FAILURE STRENGTH OF ICY LITHOSPHERES

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It has been widely assumed in the literature that the stresses required for brittle failure of an icy lithosphere under tension are limited by the tensile strength of intact ice. This assumption has led to the widespread use of 2 MPa (20 bars) for the extensional strength of predominantly ice lithospheres (e.g. Ganymede's), based on the unconfined tensile strength of ice near its melting temperature (1). However, our understanding of the maximum stress levels in the earth's lithosphere are based on the frictional resistance to sliding on pre-existing fractures. Similar friction relations for ice predict maximum stresses that are substantially greater than the apparent tensile strength of intact ice near its melting temperature. At first inspection, then, it appears that icy lithospheres would fail under tensional stress by tensile fracture of intact ice rather than sliding on pre-existing fractures. In this abstract we will introduce lithospheric strengths derived from friction on pre-existing fractures and ductile flow laws for icy lithospheres, show that the the tensile strength of intact ice under applicable conditions is actually an order of magnitude stronger than widely assumed, and demonstrate that this strength is everywhere greater than that required to initiate frictional sliding on pre-existing fractures and faults.

The maximum stress levels in the earth's crust are accurately predicted by Byerlee's law (2,3) - the frictional resistance to sliding on pre-existing fractures. Byerlee's law is $S_1=KS_3+B$, where S_1 and S_3 are the maximum and minimum principal stresses, $K=[(u^2+1)^{1/2}+u]^2$, B is a constant, and u is the coefficient of friction. For this application we use the coefficient of friction for low stress determined by Byerlee (2), u=0.85. At higher stress we use the friction data measured for ice, u=0.2 (4). The higher stress friction data for ice do constrain the applicable low stress friction law to be very close to this value, because the lowest normal stress measurements for ice (5) requires that the low stress friction law have a slope only marginally different ($u \geq 0.79$) from that used.

With increasing temperature, ice deformation occurs by ductile flow. Flow laws for ice are of the form $de/dt=A(S_1-S_3)^n \exp(-Q/RT)$, where de/dt is the strain rate, R is the gas constant, T is absolute temperature, and A, Q and n are constants. We use the flow parameters (6,5) for pure ice I_h, $A=1.2\times10^{-24}$/sec-Pa^4, $Q=4.5\times10^4$J/mole and n=4 at geologic strain rates of 10^{-15}/sec (about 3%/m.y.). A surface temperature of 100°K and a thermal gradient of 1.6°/km applicable to the early high temperatures likely in some of the larger icy satellites (e.g. Ganymede, 7) yields the strength envelope illustrated in Fig. 1. The hardening that may result from the addition of less than a few percent of silicates (8) in icy satellites lithospheres has been bracketed by an order of magnitude increase (9) in creep strength.

As can be seen in Fig. 1, the peak stress (at the brittle-ductile transition) needed to cause tensile failure of the lithosphere using the above parameters is on the order of 10 MPa (100 bars). Although this strength is strictly applicable only for large icy satellites, we have also determined strengths for the smaller icy satellites of Saturn using the appropriate gravities, densities, surface temperatures, and calculated thermal profiles (10). All strengths were found to be substantially larger than this value. As a result this value is probably a minimum for the lithospheres of the icy satellites.

Note that this peak stress (10 MPa) is significantly higher than the tensile strength of about 2 MPa used in virtually all previous studies. Because failure should occur by the mechanism requiring the lowest stress, it would appear that tensile fracture of intact ice is the relevant mode of fracture for icy satellites. However it can be shown using a Griffith failure criterion and taking the vertical lithostatic load into account that the stress difference for failure due to the tensile fracture of intact material at depth z is given by $S_1-S_3=S_o+\rho gz$ for $S_1-S_3<4S_o$ and by $S_1-S_3=4[(S_o\rho gz+S_o^2)^{1/2}-S_o]$ for $S_1-S_3>4S_o$, where ρ is density, g is gravitational acceleration, and S_o is the unconfined tensile strength (e.g. 11). The first of these relations describes the opening of tension cracks, which occurs when the confining pressure is relatively low. The second relation describes shear failure in tension (or compression) at greater confining pressures. The depth of transition between the two modes of tensile failure is given by $z=3S_o/\rho g$ (about 5 km for $S_o=2.5$ MPa on a satellite with a gravitational acceleration similar to that of Ganymede). The curve for failure due to fracture of intact ice is plotted in Fig. 1 (dashed lines). It can be seen that frictional failure is preferred at all depths for the assumed material parameters of ice. This conclusion is borne out by the experimental results, in which ice samples failed due to frictional sliding along pre-existing saw cuts rather than initiating new fractures (4). Note also that if the tensile fracture strength of intact ice increases with decreasing temperature, as is the case for the compressional fracture strength (12), the curve for fracture of intact ice under tension will move to the left and frictional failure will be even more favorable. Thus the failure strength of an icy lithosphere is significantly greater than has been previously assumed.

In conclusion, because the tensile strength of intact ice increases markedly with confining pressure, it actually exceeds the frictional strength at all depths. Thus, icy lithospheres will fail by frictional slip along pre-existing fractures at yield stresses greater than previously assumed rather than opening tensile cracks in intact ice.

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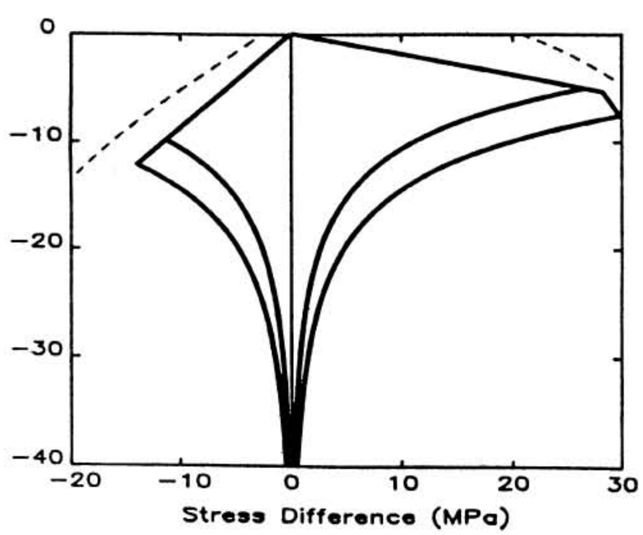

Fig. 1. Brittle (upper linear branches) and ductile (lower exponential branches) yield stress versus depth (in km) curve for compression (to the right) and extension (to the left), with a peak stress of 10 MPa (see text for discussion). The lower ductile curves simulate an increase in yield stress from the addition of silicates to the ice. The dashed lines show the failure strength of intact ice as a function of depth assuming a Griffith failure criterion. Because stresses required to break intact rock are greater than those required to initiate sliding on pre-existing fractures, lithospheric failure occurs by frictional sliding on pre-existing fractures and ductile flow.