NON-NEWTONIAN CRATER RELAXATION IN ICE, P.J. Thomas and G. Schubert, Department of Earth and Space Sciences, University of California, Los Angeles, CA 90024.

Viscous relaxation of impact craters is observed to have occurred on the surfaces of the Galilean and Saturnian satellites with icy lithospheres (1-3). Previous studies of crater relaxation (1-4) have generally assumed that the relaxation occurs in a Newtonian viscous medium with viscosity η independent of stress σ. Laboratory data, however, indicate that ice has a strongly non-Newtonian rheology at effective shear stresses $\approx$ 0.1MPa and temperatures T $\approx$ 135K relevant to subsurface conditions on the Jovian and Saturnian moons (5-8).

With a strain-rate $\dot{\varepsilon}$ dependence on stress given by

$$\dot{\varepsilon}(\sigma) = A \exp\left(\frac{-Q}{RT}\right)\sigma^n \tag{1}$$

(where A, Q, and n are rheological constants and R is the gas constant), viscosity is determined from

$$\eta = \frac{\sigma}{2\dot{\varepsilon}} = \frac{1}{2A} \exp\left(\frac{Q}{RT}\right)\sigma^{1-n} \tag{2}$$

Laboratory data on the creep of ice at T<195K give n=4, A=7.94 x 10^{-28} Pa^{-4} s^{-1}, and Q=31 kJ mol^{-1} (7).

Finite element simulations of crater relaxation in a non-Newtonian medium have been carried out to examine the effect of a stress-dependent viscosity on the profiles of relaxed craterforms. The viscosity law shown in equation (2) (with T=173K and the rheological parameters given above) has been adopted, although it leads to crater relaxation times t_e (t_e is the time required for the crater depth to become $1/e$ of its original value) grossly smaller than those observed on the surfaces of the icy satellites ($t_e \approx 10^4$ years for a 300km diameter crater). In reality, a silicate component of the near surface material may increase relaxation times by several orders of magnitude. We believe, however, that the behavior of pure ice is worth studying because of the uncertain effect of arbitrary additions of rock particles of unknown size distribution on the ice (9) and because of the insight yielded into the differences between Newtonian and non-Newtonian crater relaxation.

Differences between non-Newtonian (n>1) and Newtonian (n=1) crater relaxation arise from the spatial variations in viscosity (when n>1) that are a consequence of variations in stress beneath the crater. Fig. 1 shows the initial stress field beneath a 300km diameter crater; σ is greatest in a region below the center of the crater bowl. This region has a lower viscosity that its surroundings (with n>1) and as a result the initial upward adjustment of the crater bowl occurs more rapidly in the non-Newtonian case than it does with uniform η. The long term consequence of this is seen in a comparison of non-Newtonian (n=4) and Newtonian crater profiles at t_e (Fig. 2); the crater in the ice half-space with n=4 rheology has a more prominent convex central bulge than does the crater in the Newtonian medium (the shape of the crater profile at t_e in the Newtonian case is independent of η). Figure 2 also shows that the rim of the non-Newtonian crater relaxes more rapidly than the rim of the Newtonian crater. This occurs, in part, because as the crater bowl rises, the low viscosity region in the n=4 case moves to underneath the crater rim. However, at no time is the creation of rimless bowls observed.

An aditional feature of non-Newtonian relaxation is that initial relaxation occurs quickly, due to the high stresses associated with sharp

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topographic features. After this period, the partially relaxed topography relaxes at a much slower rate because the lower stresses produce much higher viscosities. This effect also relaxes large craters faster than would be expected for a constant viscosity medium, since larger craters will produce greater sub-surface stresses, and thus lower viscosities.

The central bulges of craters on icy satellites have previously been attributed (2, 3) to effects of increasing temperature (or decreasing viscosity) with depth. Our results show, however, that the central bulges can alternatively be explained by the non-Newtonian creep of ice.

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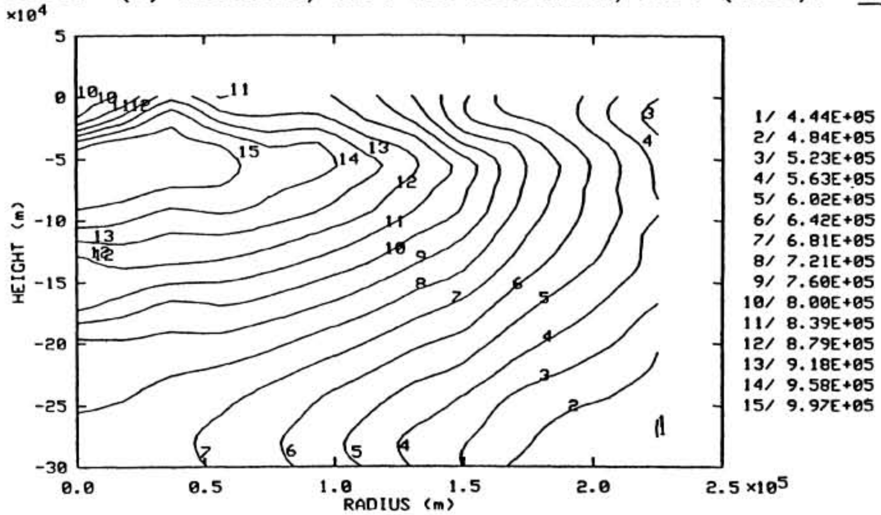

Fig.1: Initial stress contours (in Pa) for a 300 *km* diameter crater.

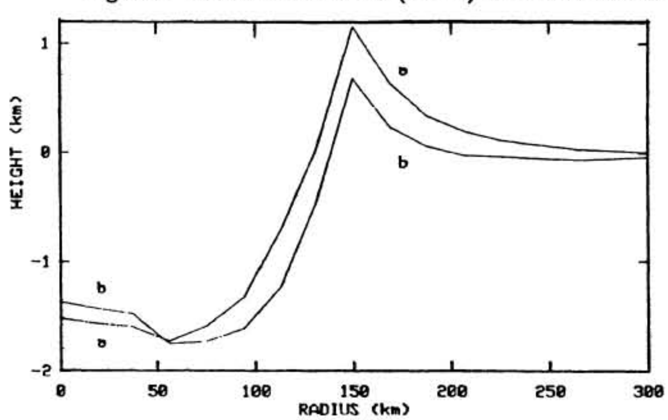

Fig.2: Crater profiles at t_e (approximately) for a Newtonian (a) and an $n = 4$ (b) rheology.

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