VISCOUS RELAXATION OF CRATERS ON ENCELADUS. D. E. Smith[1], E. P. Turtle[2], H. J. Melosh[1], and V. J. Bray[3], [1]Department of Planetary Sciences, The University of Arizona, 1629 E. University Blvd., Tucson, Arizona 85721; [2]Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, Maryland 20723; [3]Imperial College London, Exhibition Road, London, SW7 2AZ, United Kingdom; (dsmith@lpl.arizona.edu).

Introduction: The amount of geologic activity on Enceladus is somewhat surprising considering its lack of radiogenic heating at only about 500 kilometers in diameter and the relatively low tidal heating available [1]. Enceladus' terrain is very diverse with fractures, ridges, active plumes, and highly variable crater density [e.g., 1,2]. There are heavily cratered areas and others almost devoid of craters, and the craters display a range of morphologies including both relaxed and unrelaxed forms. In some areas both relaxed and unrelaxed craters are present together. Such a heterogeneous surface raises many questions into the nature of Enceladus' subsurface and rheology. By studying craters that have undergone different degrees of viscous relaxation, we can constrain Enceladus' subsurface rheologic and thermal properties.

Background: The nature of ice is non-Newtonian [e.g., 3]. However, to first order, we can use the Newtonian approximation in order to produce analytical solutions that reveal the basic behavior of crater relaxation on Enceladus.

In the solution for the case of a uniform viscosity down to very large depth, the relaxation time is [4]:

$$t_R = \frac{2\eta k}{\rho g}. \tag{1}$$

One can see some basic behavioral characteristics from this, namely that as the viscosity increases, the relaxation time also increases. As the density of the material or gravity increases, the relaxation time decreases. Of very important note, large features (small k) will tend to relax faster than small-wavelength features.

The solution for the case in which viscosity decreases exponentially with depth is [5]:

$$\eta(z) = \eta_0 \exp\left(-\frac{z}{d}\right), \tag{2}$$

where z is depth, and d is the distance over which the viscosity drops by a factor of e. The relaxation time for this case is:

$$t_R = \frac{2\eta_0 k}{\rho g}\left(\frac{1-2\gamma}{4kd\gamma}\left[1+\left(\frac{\gamma}{kd}\right)^2(1-2\gamma)\right]\right), \tag{3}$$

where γ is the function:

$$\gamma = (2)^{-\frac{3}{2}}[1+4(kd)^2+\sqrt{16(kd)^4+24(kd)^2+1}\,]^{1/2} \tag{4}$$

This solution is significant in that for most planetary objects, the temperature increases with depth linearly. For a material of uniform composition, this corresponds to an exponential decrease of viscosity with depth. Hence, the above equation is highly relevant for our system of interest.

In the short-wavelength limit, features will relax at the same rate as that for the relaxation time in a uniform viscosity mantle. However, in the long-wavelength limit, features will relax faster. Therefore, in observation of craters following this type of behavior, we should see features such as the crater rim (short wavelength) persist longer than the crater bowl (long wavelength).

The analysis of crater relaxation is greatly simplified due to the fact that most craters are axially symmetric, which means crater profiles can be decomposed into J_0 Bessel functions [4]. Each function relaxes self-similarly so that the component remains the same while its amplitude decreases [4]. The crater profile can be represented:

$$z(r,t) = \int_0^\infty \zeta(k)\exp(-t/t_R)J_0(kr)k\,dk, \tag{5}$$

where

$$\zeta(k) = \frac{HD_a^2}{128}(kD_a)^2\exp\left(-\frac{k^2D_a^2}{16}\right). \tag{6}$$

Here H is crater depth, k is wavenumber ($k = 2\pi/\lambda$), and D_a is the diameter at the pre-existing surface. An approximately parabolic profile for a rimmed crater is assumed. Using the solution for the relaxation time and Equation 5, crater profiles at various stages of degradation can be derived.

We know that the viscosity is strongly dependent on temperature [e.g., 6]:

$$\eta(T) = \eta_0 \exp\left(\frac{E^*}{RT}\right), \tag{7}$$

where E^* is activation energy, R the universal constant, and T is temperature. Combining this with the exponential dependence of viscosity with depth, we can calculate the viscosity e-folding depth for a variety of plausible temperature gradients. For Ice I < 195 K, $E^* \approx 39 \pm 5$ kJ mol^{-1} [3]. Enceladus has a mean surface temperature of approximately 75 K [e.g., 1,2], and for these purposes, we assume a surface viscosity of approximately 10^{21} Pa s [3], although the exact nature of Enceladus' ice is not well understood.

Results and Discussion: Using a depth-to-diameter ratio of 1/5 and applying the above equations to craters between 5 and 20 km in diameter, we have considered a suite of basic scenarios (Fig. 1). The first case is for a viscosity e-folding depth, d, of 1 km. This represents a very sharp drop in viscosity with depth, which corresponds to a high linear temperature gradient of $\simeq 1.2$ K km^{-1}. In the second case, d is 10 km, corresponding to a cooler temperature gradient of $\simeq 0.12$ K km^{-1}. Finally, in the third case, a much colder temperature gradient is used ($\simeq 0.012$ K km^{-1}) and $d = 100$ km.

One can see from Figure 1 that the relaxation time is strongly dependent upon the scale of the crater and the viscosity, or temperature, gradient. As expected, small craters have

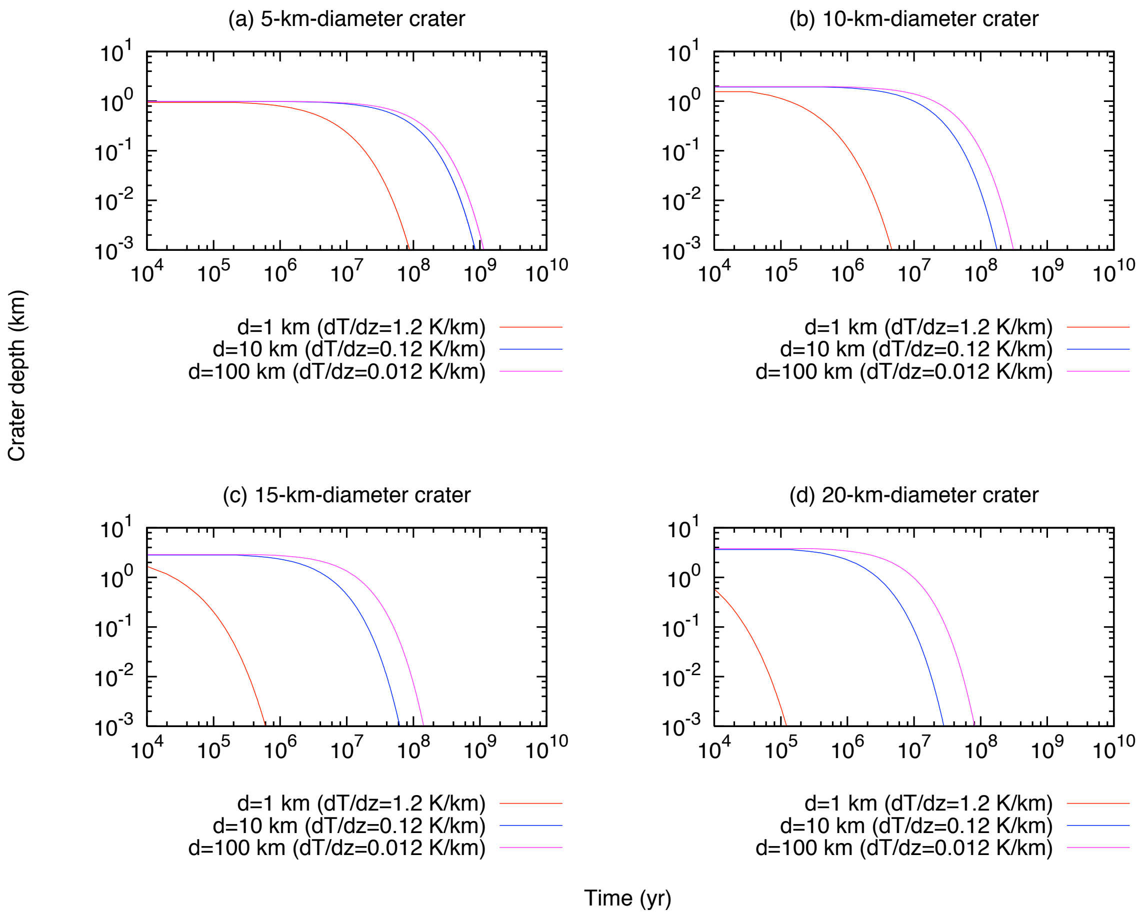

Figure 1: Plots of crater depth as a function of time for (a) 5-km, (b) 10-km, (c) 15-km, and (d) 20-km-diameter craters for a variety of temperature gradients and viscosity profiles. All assume a surface viscosity of approximately 10^{21} Poise, surface gravity of $0.311\ \mathrm{m\,s^{-2}}$, and density of ice $\approx 1000\ \mathrm{kg\,m^{-3}}$.

a significantly longer relaxation time than the larger ones: ~ 100 My for a 5-km-diameter crater in the warmest case as compared to only 100,000 years for the 20-km-diameter crater under the same thermal conditions. Also, as the viscosity e-folding depth increases (temperature gradient decreases) and becomes much larger than the size of the crater, the effect on relaxation time diminishes. Hence, for the 5-km-diameter crater, decreasing the temperature gradient by two orders of magnitude only changes the relaxation time by roughly 1 order of magnitude, from ~ 100 My to ~ 1 Gy, whereas for the 20-km-diameter crater, the same cooling of the temperature gradient results in relaxation times 3 orders of magnitude larger, i.e. from only ~100,000 years to ~ 100 My.

Considering the results of such analyses in the context of the crater distributions observed on Enceladus [7, 8] provides insight into the nature of Enceladus and spatial and temporal variations therein. We are investigating regions that contain both relaxed and unrelaxed craters, areas that are heavily cratered, and areas almost devoid of craters [7, 8]. Areas that include both relaxed and unrelaxed craters could be explained by a colder temperature gradient, possibly providing evidence for changes in the gradient with time. Results of such analyses will be presented.

References:

[1] Brown R.H. et al. (2006) *Science*, 311, 1425–1428. [2] Porco C.C. et al. (2006) *Science*, 311, 1393–1401. [3] Durham W.B. et al. (1997) *JGR*, 102, 16,293–16,302. [4] Melosh H.J. (1989) *Impact cratering: A geologic process*, Oxford University Press, 253 p. [5] Brennen C. (1974) *JGR*, 79, 3993–4001. [6] Ranalli G. (1995) *Rheology of the Earth*, Chapman and Hall. [7] Bray V.J. et al. (2007) in *38th Annual Lunar and Planetary Science Conference*. [8] Smith D.E. et al. (2006) in *AAS/Division for Planetary Sciences Meeting Abstracts*, 24.07.