CRATER RELAXATION ON ENCELADUS: TALES OF HIGH HEAT FLUXES IN UNEXPECTED PLACES. Michael T. Bland[1], Kinger N. Singer[1], William B. McKinnon[1], and Paul M. Schenk[2], [1]Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University in Saint Louis, MO 63130. [2]Lunar and Planetary Institute, Houston, TX 77058.

Overview: Cassini imaging has revealed large numbers of highly modified craters on Enceladus' surface. Many small craters appear anomalously shallow [1], and some larger craters have unique central mounds that stand ~1 km above the surrounding terrain (Fig. 1). Additionally, detailed crater counts have revealed an apparent deficit of craters >6 km in diameter relative to other Saturnian satellites [2]. By combining high resolution stereo topography with robust finite element modeling we investigate the extent to which viscous relaxation under high heat flows can explain Enceladus' anomalous and missing craters. These results imply that even Enceladus' cratered terrain has experience periods of extreme high heat flux in the satellite's past.

Enceladus' Modified Craters: Enceladus' "heavily cratered" terrains contains numerous, heavily-modified craters (e.g., the region 30° N, 0°-37° W). Many 2-to-20-km craters appear anomalously shallow relative to their expected depths ([1] and Fig. 2), suggesting that they have been viscously relaxed (plume fallout is currently minimal at the latitudes in question [3], and so would seem to have a limited impact on crater morphology). Figure 1 shows a comparison of the morphology and topography (derived from stereo-controlled photoclinometry) of a fresh 10-km-diameter crater, and a similarly sized relaxed crater. Analysis indicates that the ground-plane-to-floor depth (apprent depth) of the relaxed crater has been reduced by 85±15% relative to its expected depth. Such high degrees of relaxation appear common in several of Enceladus' cratered regions ([1] and Fig. 2). Furthermore, it was suggested by [2] that viscous relaxation may be partly responsible for an observed deficit in craters > 6 km in diameter on Enceladus (compared to other Saturnian satellites). They suggested that relaxation can reduce crater topography enough for in-falling plume or E-ring material to completely remove evidence of the crater.

In addition, several larger craters on Encleadus have a unique morphology that includes large, "central mounds" that have a diameter of roughly half the crater diameter and rise close to 1 km above the surrounding terrain (Figs. 1C and 1D). Modest doming of crater floors above the surrounding plain is commonly observed in studies of crater relaxation; however, the production of more than 1 km of relief inside a ~30 km crater has rarely been observed beyond Enceladus, and is more difficult to explain.

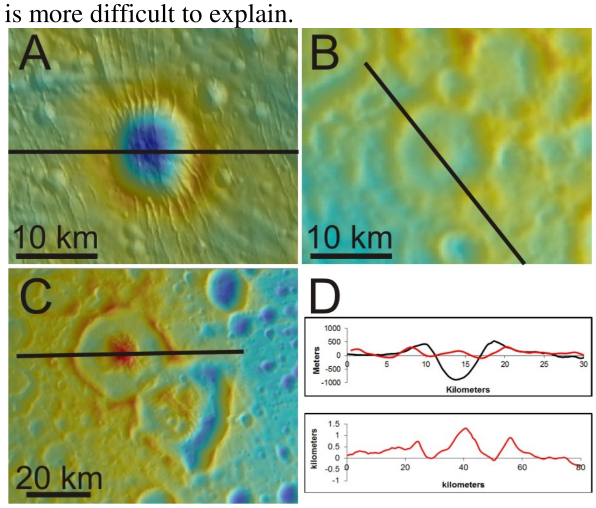

Fig 1: Stereo-controlled photoclinometry overlaid on imaging data of ***A.*** *A fresh crater.* ***B.*** *A shallow crater whose morphology is consistent with viscous relaxation.* ***C.*** *Anomalous craters with large central mounds.* ***D.*** *Topographic profiles of the craters shown in A and B (top) and C (bottom).*

Simulating Viscous Relaxation: We simulate crater relaxation using an axisymmetric, viscoelastic finite element model following the approach of [4]. The viscous rheology includes dislocation creep, grain boundary sliding (with a 1 mm grain size), basal slip, and diffusion flow mechanisms appropriate for ice I. We investigate constant heat fluxes up to 150 mWm^{-2} (greater than typical present-day terrestrial values), and relaxation timescales up to 4.6 Ga. We examine craters 4–34 km in diameter. Where possible, the initial crater profile is derived from actual topography data (e.g., the fresh crater shown in Fig. 1). Thermal conductivity is temperature-dependent.

Modeling Results: We find that viscous relaxation is ineffective at modifying crater depths at Enceladus' nominal surface temperature (~70 K) and low gravity ($g = 0.11\ m\ s^{-2}$). Figure 2 illustrates that a 10-km-diameter crater undergoes no relaxation even when a constant heat flux of 150 mWm^{-2} is applied for 1 Ga. Under the same conditions a 34-km-dimater crater is relaxed by only 15%. In order for any relaxation to occur, the lithosphere must be less viscous then assumed, perhaps due to an insulating regolith (or plume fallout) that increases the effective temperature of the lithosphere (an idea first proposed by [5]). Using an effective surface temperature of 120 K (near the upper limited suggested by [5]), which decreases the lithospheric viscosity by ~10^{14}x, we find that substantially greater relaxation occurs (Fig. 2). A 10-km-diameter crater under a heat flux of 150 mWm^{-2} relaxes by ~50% in 1 Ga, whereas a 34-km-diameter crater relaxes by ~85% under the same conditions. Still, even with extreme heat fluxes, and warm effective surface temperatures producing the degree of relaxation observed on Enceladus is challenging, implying heat fluxes well in excess of 150 mWm^{-2} in the cratered terrain. These heat fluxes are similar to those inferred for Enceladus' tectonized regions, which range from 110-270 mWm^{-2} [6, 7].

Furthermore, while crater centers are often up warped to the height of the surrounding ground plain (or higher) during relaxation, maximum crater depths are never decreased by more than ~90%. Complete crater removal by relaxation alone is therefore extraordinarily difficult, and may be a challenge even when allowing for burial by in-falling plume or E-ring material. For example, after 1 Ga with a constant heat flux of 150 mWm^{-2}, a 12-km crater still retains a maximum depth of ~180 m, requiring at least that amount of infilling material for complete erasure.

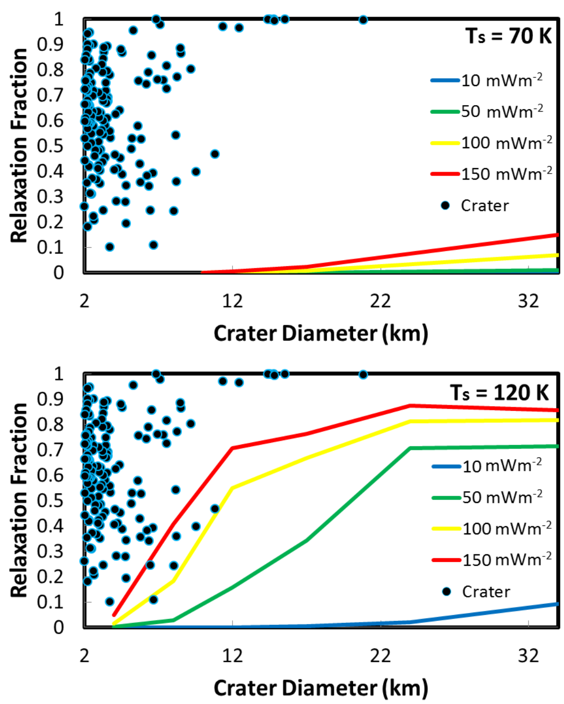

Fig 2: ***Top.*** *Curves of relaxation fraction (RF) (i.e., percent relaxed relative to initial apparent depth) as a function of crater diameter and heat flux for a surface temperature of 70 K. Blue/black points are RF values for actual Encleadus craters augmented from [1] (data from equatorial cratered region and cratered region north of Hamah Sulci).* ***Bottom.*** *As in top but for an effective surface temperature of 120 K. Note that RF<1 whilst any intracrater troughs exist.*

Forming "Central Mound" Craters: The high heat fluxes that are required to viscously relax Enceladus' small craters quickly produce high relaxation fractions when applied to larger craters. As these larger craters relax the crater floor can become strongly up warped, in some cases lifting central peaks to ~1 km above the surrounding plain. The morphology produced is similar to the "central mound" craters observed on Enceladus: uplifted rims, a deep trough around the crater floor margins, a broad, uplifted central region, and a high central peak. Notably, an initial crater with a central peak appears to be required to match the "central mound" morphology created by viscous relaxation.

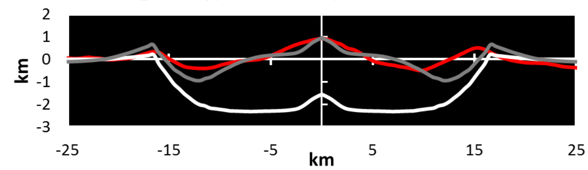

Fig 3: Comparison of a simulated relaxed crater and an actual "central mound" crater. White curve is the initial crater shape (a manually deepened Ganymede crater), dark gray curve is the simulated relaxed crater after 10^7 yrs. Red curve is the profile shown in Fig. 1.

As viscous relaxation continues, the strongly flexed crater floor subsides and the overall topographic signature of the crater becomes more subdued. In order to preserve the central mound-like structure, therefore, viscous relaxation must be cut-off before the crater becomes fully relaxed. Such a thermal history is consistent with a strong, relatively short-lived (~10 Ma) heat pulse that decays away rapidly.

Conclusions: Whether considering the relaxation of small craters, the removal of craters with diameter > 6 km, or the formation of "central mound" craters, the heat fluxes required are extremely large for a small, icy satellite (>150 mWm^{-2}). Such heat fluxes are nearly as large as those inferred for Enceladus' tectonic terrain (110-270 mWm^{-2} [6, 7]), and only a factor of two below that measured in the South Polar Region (~400 mWm^{-2} if averaged over the region [8]), suggesting the entire satellite (not just the tectonized regions) has had a spectacular, and strongly variable thermal history.

References: [1] Singer, K. N. et al. (2011) *EPSC/DPS, v. 6*, 1161. [2] Kirchoff, M. R. and Schenk, P. M. (2009) *Icarus, 202,* 656-668. [3] Kempf, S. et al. (2010) *Icarus, 206,* 446-457. [4] Dombard, A. J. and McKinnon W. B. (2006) *JGR, 111*, E01001. [5] Passey, Q. R. (1983) *Icarus, 53*, 105-120. [6] Bland, M. T. et al. (2007) *Icarus, 192,* 92-105. [7] Giese B. et al. (2008) *GRL, 35,* L24204. [8] Howett, C. J. A., et al. (2011) *JGR, 116,* E03003.

Acknowledgements: This work is supported by NASA's Cassini Data Analysis program.