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Enceladus' ancient heat flux: Clues from numerical simulations of crater relaxation

Michael T. Bland, Kelsi N. Singer, William B. McKinnon
Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, Saint Louis MO, USA.

Abstract

We analyze craters on Enceladus to constrain the thermal and physical evolution of the satellite. High resolution topography indicates that craters as small as 10 km in diameter are relaxed by 85±15%. Simulations of crater relaxation indicate that producing such high relaxation fractions over the age of the Solar System requires heat fluxes substantially greater than 200 mWm^{-2} if a nominal 70 K surface temperature (i.e., Enceladus' solar equilibrium temperature) and ice I rheology is assumed. If a thermally isolating regolith (perhaps due, in part, to in-falling plume material) increases the effective surface temperature, required heat fluxes are decreased, though heat fluxes were likely still in excess of 100 mWm^{-2}. Such high heat fluxes in Enceladus' cratered terrain further illustrate the complex, spatially heterogeneous thermal history of the satellite, which we continue to quantitatively constrain through a comparison of detailed mapping and numerical simulations [1].

1. Enceladus' Relaxed Craters

Enceladus bears evidence of a long and complex geologic history. In addition to tectonic activity in its south-polar and equatorial regions, several regions of cratered terrain show extensive softening of topography – most likely due to viscous relaxation. 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 of multiple topographic profiles indicates that the ground-plane-to-floor depth of the relaxed crater has been reduced by 85±15% relative to its expected depth. At the latitude of the relaxed crater (48° N), plume material in-fall is minimal [2], and so would have limited impact on crater morphology. Such high degrees of relaxation appear common in several of Enceladus' cratered regions [1].

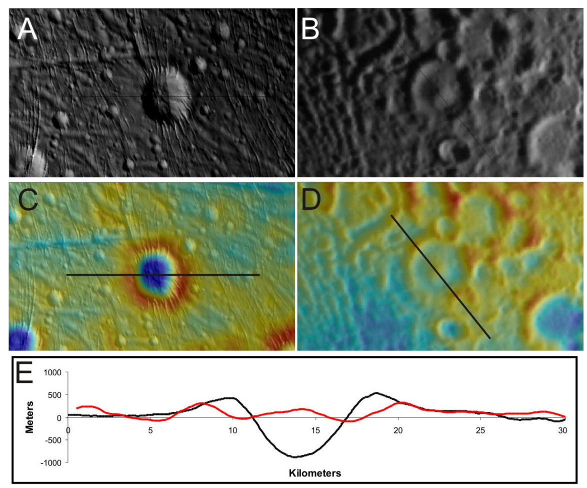

Figure 1: Cassini images and topography (red is high, blue is low) of a fresh 10-km-diameter impact crater (**A** and **C**), and a similarly-sized relaxed crater on Enceladus (**B** and **D**). Topography profiles (black lines in **C** and **D**) for the fresh (black) and relaxed (red) craters are compared in **E** [cf. 1].

3. Simulating Crater Relaxation

We simulate crater relaxation using an axisymmetric, viscoelastic finite element model following the approach of [3]. The viscous rheology includes dislocation creep, grain boundary sliding (with a 1 mm grain size), and basal slip flow mechanisms appropriate for ice I. We investigate constant heat fluxes up to 200 mWm^{-2}, and relaxation timescales up to 4.6 Ga. The initial crater profile is derived from actual topography data (e.g., the fresh crater shown in Fig. 1). Conductivity is temperature-dependent.

Enceladus' low surface gravity (0.113 m s^{-2}), and cold surface temperature (~70 K) is not conducive to the relaxation of small craters. For a 10-km-diamter initial crater (i.e., similar to the small, highly-relaxed crater shown in Fig. 1), simulations using a surface temperature of 70 K result in relaxation of less than 1% after 4.6 Ga for heat fluxes up to 200 mWm^{-2}.

3.1 Reducing the Ice Viscosity

In order for small craters (~10 km) to relax over geologically relevant timescales on a body as small and cold as Enceladus the viscosity of the near surface ice must be reduced. Passey [4] suggested that crater relaxation on Enceladus might be accommodated by the presence of viscosity-reducing non-water-ice material (e.g., ammonia). Alternatively, Passey and Shoemaker [5] suggested that a thermally insolating regolith layer might increase the effective surface temperature, thereby decreasing the ice viscosity. The latter mechanism may be especially applicable to Enceladus, where in-falling plume material can create a porous layer of fine grained particulate ice 1-10 m deep in Enceladus' north polar regions over 1 Ga [2]. Samples of fine-grained, powdered ice in vacuum have thermal conductivities several orders of magnitude less than intact ice [6], suggesting that even relatively thin layers of plume material could be an efficient insulator.

To investigate the effects of increased effective surface temperature (i.e., decreased near surface ice viscosity) on crater relaxation we simulated relaxation of our 10-km-diameter crater with surface temperatures ranging from 70 to 130 K, and heat fluxes up to 200 mWm^{-2}. The results of these simulations are shown in Figure 2. Even for heat fluxes of 200 mWm^{-2}, less than 1% relaxation occurs over 4 Ga for surface temperatures of 110 K or less. Relaxing a 10-km-diameter crater by ~80% in 4 Ga requires a sustained heat flux of at least 100 mWm^{-2} and an effective surface temperature of at least 125 K. Higher surface temperatures require smaller heat fluxes to produce the same degree of relaxation. Producing the same relaxation fraction (80%) in 1 Ga (a more relevant geologic timescale [7]) requires sustained heat fluxes in excess of 200 mWm^{-2} even with surface temperatures of 130 K. Thus, producing relaxed craters consistent with our observations over reasonable timescales requires either extremely large heat fluxes, or extreme reductions in the near-surface ice viscosity (or both).

Acknowledgements

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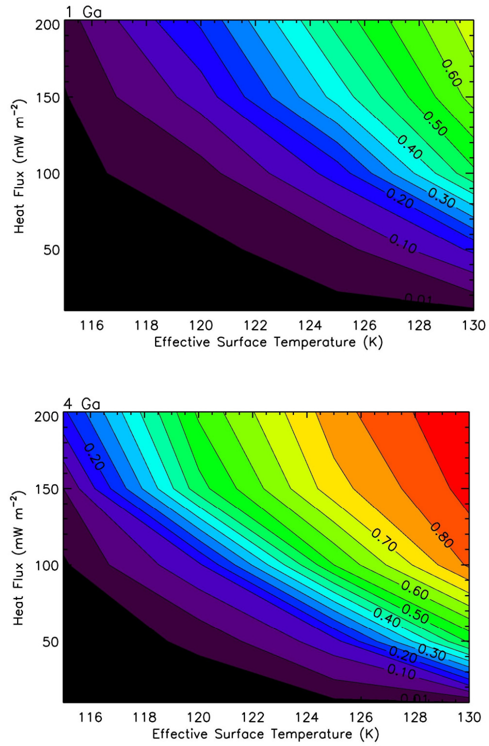

Figure 2: Contours of relaxation fraction for a 10-km impact crater on Enceladus as a function of the effective surface temperature and heat flux after 1 Ga (**Top**) and 4 Ga (**Bottom**).

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