RELAXED IMPACT CRATERS ON GANYMEDE: NOT ALL SULCI ARE CREATED EQUAL.

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Introduction: Viscously relaxed craters provide a window into the thermal history of Ganymede, a satellite that shows copious geologic signs of past, high heat flows [1]. Here we present measurements of relaxed craters in four regions: near Anshar Sulcus, Tiamat Sulcus, northern Marius Regio, and Ganymede's south pole. Within these, craters-turned-palimpsests can be used in conjunction with finite element modeling [2-3] to constrain heat flow scenarios. The presence of numerous, substantially relaxed, craters independently indicates high heat flows – in excess of 40 mW/m^2, with many small relaxed craters indicating even higher heat flows. A bimodality in the crater relaxation states is observed for some regions but not others, and suggests we may be detecting regional variation in the thermal history of Ganymede.

Mapping Methods: Base mosaics and photoclinometric topography were generated from Galileo images, except in the case of the south pole, where Voyager images were used and combined stereo-photoclinometry topography is available (Fig. 1).

Relaxed Crater Shapes Similar to [2-4] we characterize the shape of the craters with the "relaxation fraction" (RF = 1 – $d_{final}/d_{initial}$), using predicted initial depths and measured final depths of the crater. These depths (d) are measured with respect to the level of the surrounding terrain ("apparent" depths).

To measure d_{final} we found the average elevation for the surrounding terrain and the crater floor. A detailed description of our methods is given in [4]. The elevation for the crater floor was measured in two ways: 1) using the average elevation in a circle 1/3 of the crater rim-radius from the center for bowl-shaped craters, and 2) using the average elevation of a radial ring extending from 1/3-to-2/3 radius for complex craters (thus excluding the central peak or pit region and rimwalls).

Initial Crater Shapes For $d_{initial}$ on Ganymede we used the depth-to-diameter ratio (d/D) found by [5] and subtracted rim heights from [6]. We use crater depths from [5] because they focused on pristine craters only.

Results: Figure 1 gives results for a) crater depth and b) relaxation fraction for all four mapped regions.

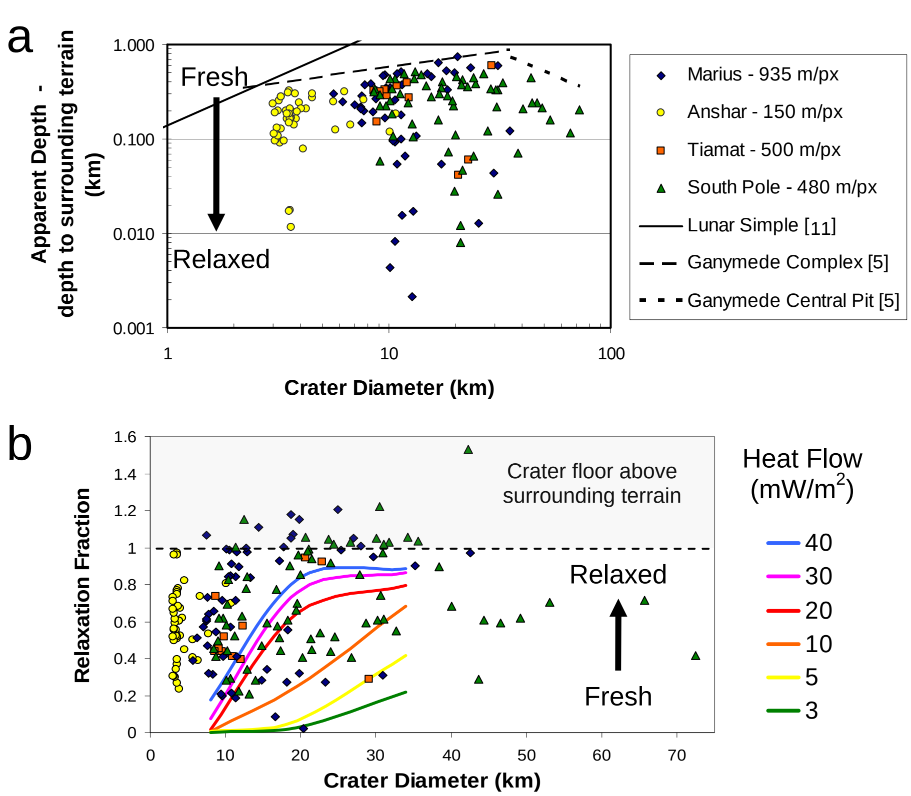

Figure 1. a) Apparent depths – floor-to-ground plane – for Ganymede craters in four mapped regions, with fresh crater d/D curves for reference. Craters with "negative" apparent depths, or whose floors are above the level of the surrounding terrain are not plotted.

b) Measured crater relaxation fractions (points) compared to finite element simulations for relaxation over 2 Ga (curves for a given heat flow). Although there is a range of relaxation states, many craters require heat flows in excess of 40 mW/m^2 in order to achieve the observed relaxation fractions. The largest modeled crater was 34 km in diameter. FEM modeling by [3] found that craters with diameters > 50 km are fully relaxed by 2 Ga.

Figure 2 displays RFs overlaid on the Anshar region, which is the highest resolution mosaic. There is inherent uncertainty in making these measurements on uneven terrain, and also some uncertainty in the initial depth based on fresh crater measurements (scatter to the *d/D* ratio in [5]). Conservative errors, estimated from the variability in profiles across craters, are ±50 m for depth and ±0.1 for relaxation fraction.

Even given these uncertainties, it is apparent that there are a large number of moderately to very relaxed craters in a range of diameters across Ganymede. All four regions mapped exhibit small craters (<10 km-diameter) that are greater than 50% relaxed.

Implications for Heat Flow: We show finite element simulations [2-3] that predict the relaxation fraction for a given rheology, heat flow (sustained over a given length of time) and crater diameter (Fig. 1b). For a surface temperature of 120 K, and 1 mm pure water ice grain size, the majority of the craters measured indicate heat flows in excess of 40 mW/m^2 sustained over 2Ga. There is a range of RFs, however, especially in the south pole region, where some craters would give a lower limit of 5-10 mW/m^2 necessary for relaxation. Some craters with lower RFs formed later and had less time to relax, an aspect we are investigating [7].

We expect monotonically declining heat flows over time, which suggests even higher heat flows occurred over a shorter interval. The current, time-averaged, and highest heat flows (early in Ganymede's history) expected for radiogenic heating alone are ~3.16, 10 and 27 mW/m^2, respectively (based on data in [8]). Clearly these cannot account for the degree of relaxation observed, thus our results are more consistent with a heat pulse occurring between the late heavy bombardment and grooved terrain formation, such as that resulting from orbital resonance [e.g., 9].

Schenk [10] found a bimodality in the depths of craters larger than ~10 km, where craters were either relaxed, or relatively unrelaxed and still followed a d/D trend similar to fresh craters. We also find this bimodality for two regions, northern Marius and Tiamat. Craters in the Anshar region are mostly below 10 km in diameter and along with other small craters show a broad spectrum of relaxation states. However, the south pole region as mapped in this study does not show a strong bimodality – indicating the south pole may have experienced a different thermal history and hinting at the possibility of more regional, in addition or as opposed to global, heating events. This may also point to the south pole region experiencing a more drawn out decline in heating, in comparison to the terrains near Marius Regio, which the bimodality in RFs suggest may have had a rapidly declining heat flow post bright terrain formation [10].

References: [1] Pappalardo R. T. et al. (2004) in *Jupiter*, Cam. Univ. Press, 363-396. [2] Bland M. T. et al. (2011) *LPS XLII*, Abstract #1814. [3] Dombard A. J. and McKinnon W. B. (2006) *JGR, 111*, E01001. [4] Singer K. N. et al. (2011) *EPSC-DPS*, Abstract #1161. [5] Schenk P. M. (2002) *Nature*, *417*, 419-421. [6] Bray V. J. et al. (2012) *Icarus*, *217*, 115-129. [7] Phillips R. J. and Malin M.C. (1980) *Science*, *210*, 185-188. [8] Kirk R. L. and Stevenson D. J. (1987) *Icarus, 69*, 91-134. [9] Bland M. T. et al. (2009) *Icarus 200*, 207-221. [10] Schenk P. M. (2010) *LPS XLI*, Abstract #2083. [11] Pike R. J. (1977) *LPS VIII*, 3427-3436.

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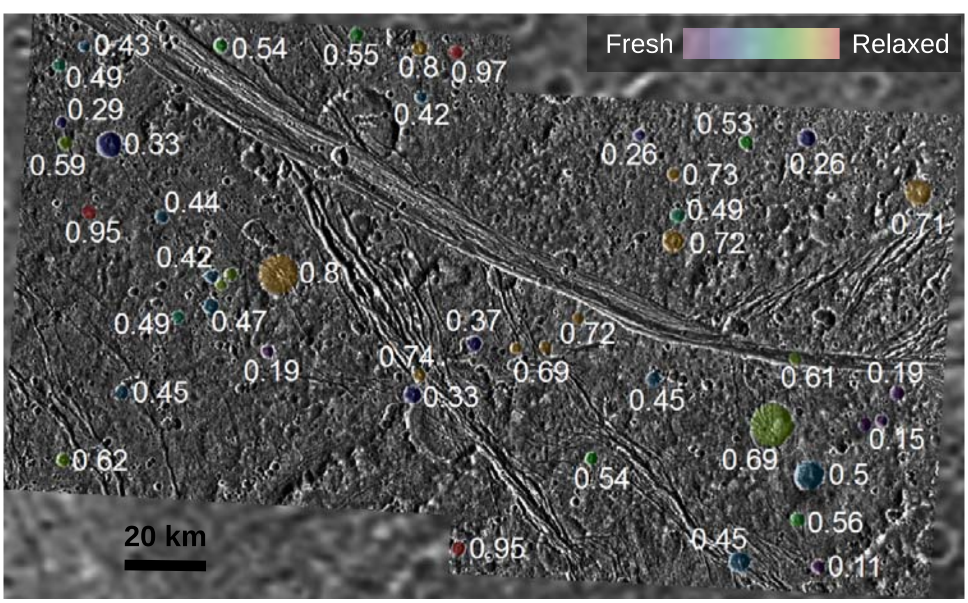

Figure 2. Relaxation fractions (RFs) for craters near the southern tip of Anshar Sulcus (152 m/px).