CONSTRAINTS ON GANYMEDE'S THERMAL EVOLUTION FROM MODELS OF CRATER RELAXATION. M. T. Bland[1], K. N. Singer[1], W. B. McKinnon[1], and P. M. Schenk[2], [1]Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, Saint Louis, MO 63130, [2]Lunar and Planetary Institute, Houston, TX 77058.

Overview: Ganymede's dichotomous surface records a complex thermal history in which the satellite's secular cooling was interrupted by a period of high heat flows and tectonic activity. While it has long been recognized that clues to Ganymede's thermal evolution have been preserved in its population of relaxed craters [e.g., 1], a quantitative analysis combining high-resolution Galileo observations and up-to-date numerical models of crater relaxation has not yet been performed. Here we present initial results from such a study.

Using photoclinometric and stereo derived topography, we determine the extent to which individual craters are relaxed in several regions on Ganymede. We then compare these observations to numerical models of viscous crater relaxation to place quantitative constraints on the heat flux required to produce the observed relaxation. Preliminary results indicate that a minimum constant heat flux of 15 to 20 mWm^{-2} is required over 4.6 Ga of evolution to match the observations. Using a more realistic relaxation timescale of 1 Ga yields required heat fluxes of 25 to 30 mWm^{-2}. The minimum heat fluxes derived are substantially larger than present-day radiogenic values, and indicate that crater relaxation probably occurred during a period of elevated heat flow.

Observations: Topography was derived over three regions of Ganymede (northern Marius Regio, Tiamat Sulcus, and Enki Catena) using both stereo and photoclinometric techniques and Galileo SSI data. Figure 1A shows a sample portion of the topography data in northern Marius Regio. The region includes numerous relaxed craters in the ~20 km diameter range (and smaller), as well as a 22-km-diameter, simple, unrelaxed crater (upper left). A topographic profile through this crater (A-A^1) is shown in Fig. 1B (pink). The crater is 739 m deep with broad rims that rise 350 m above the surrounding terrain. A profile through a similarly sized (21 km diameter) relaxed crater (B-B^1 in Fig. 1A) is also shown in Fig. 1B (black). The relaxed crater has a maximum depth of ~60 m relative to the surrounding terrain, and a prominent up-bowed floor that is plausibly the result of relaxation, along with a remnant central peak and/or pit. Assuming that the relaxed crater had an initial (pre-relaxed) depth similar to the nearby 22 km unrelaxed crater (profile A-A^1), the relaxed crater (profile B-B^1) has a "Relaxation Fraction" ($RF=1-d_{final}/d_{initial}$, where d is the crater depth) of ~0.9. This RF is likely a minimum value because the up-bowed floor may obscure the true degree of relaxation. The crater shown is typical of craters in the region.

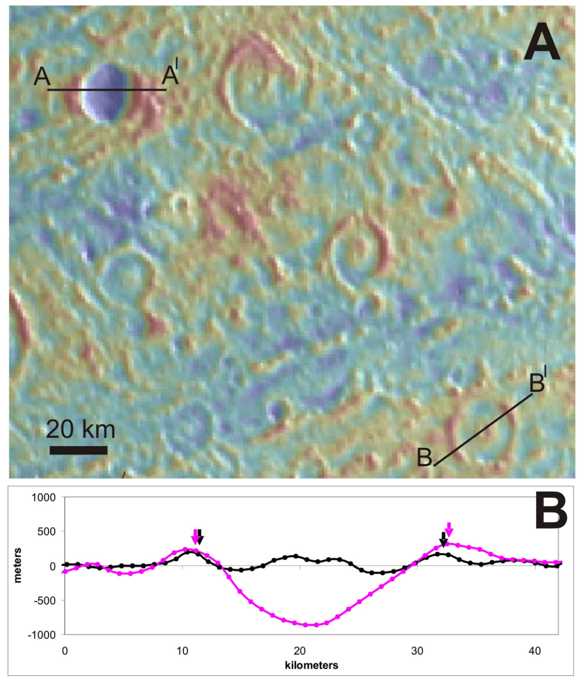

Figure 1: (A) *Photoclinometrically derived topography of northern Marius Regio overlaid on a Galileo ISS base map. Highs are red and lows are blue. Total relief is ~1 km.* (B) *Profiles through both a large, unrelaxed crater (A-A^{1}in panel* (A)*) (pink), and a similarly sized relaxed crater (B-B^{1}in panel (A)) (black).*

Modeling: We simulate crater relaxation on Ganymede using the finite element model Tekton. Recent, studies have produced robust models of crater relaxation on icy satellites [2], and we follow their approach here. Additionally, extensive benchmarking against [2] was performed to ensure our results are consistent with previous efforts. Our models are viscoelastic (E=9.3 GPa, ν=0.325) and include appropriate viscous deformation mechanisms for ice I. The assumed heat flux is imposed through the viscosity structure. We assume a constant heat flux throughout each simulation, though future work will include time-variable heat fluxes. Relaxation results from an imposed gravitational acceleration (1.4 m s^{-2}) acting on the model's topography.

In contrast to previous modeling, our initial crater shapes were derived from the actual topography of

Ganymede's unrelaxed craters (e.g., profile A-A[1]). This allows a more robust determination of final relaxed crater morphology and facilitates comparison to observed relaxed craters. For a given initial crater (i.e., an initial size and morphology) we performed a suite of simulations with heat fluxes varying from 0 to 40 mWm^{-2}. Crater relaxation was simulated for 4.6 Ga, the maximum conceivable timescale for relaxation to have occurred. Figure 2 shows the Relaxation Fraction for the 22 km initial crater shown in profile A-A[1] of Fig. 1B over 4.6 Ga for 11 different heat fluxes. Given a relaxed crater of known diameter and state of relaxation, and assuming its initial (unrelaxed) state was similar to nearby unrelaxed craters, such modeling can provide quantitative constraints on the heat flux experienced by individual craters.

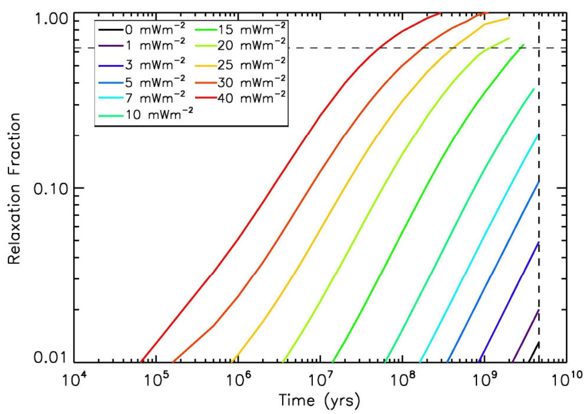

Figure 2: Results from numerical models of viscous crater relaxation for the 22 km initial crater shown in Fig. 1. The dashed vertical line indicates 4.6 Ga, while the horizontal line indicates relaxation by a factor of 1/e. Shorter relaxation time scales require larger heat fluxes to produce the same relaxation fraction.

Results: By combining the numerical modeling described above with high resolution topography of Ganymede's relaxed craters we can constrain the satellite's thermal evolution. Figure 3 shows the heat flux implied by observed RFs for a ~20-km diameter crater. The minimum heat flux required is the constant heat flux needed to produce the observed RF after 4.6 Ga. For example, if a given ~20 km crater has an observed RF of 0.5 the minimum heat flux required is ~10 mWm^{-2}. The craters in northern Marius Regio (Fig. 1A) have relaxation fractions much larger than 0.5 (~0.9 for the crater in Fig. 1B), implying absolute minimum heat fluxes of 15 to 20 mWm^{-2}. If relaxation occurred over shorter time periods (which is almost certainly the case; crater relaxation probably occurred during a finite period of Ganymede's history, and had likely ended by the end of groove terrain formation [3]) larger heat fluxes are implied. Producing an RF of 0.9 in 1 Ga requires a flux of 25 to 30 mWm^{-2}.

Even the absolute minimum heat fluxes required to produce the degree of crater relaxation observed in Marius Regio are larger than the expected time averaged radiogenic heat flux. These minimum heat fluxes are smaller, however, than the heat fluxes inferred from models of furrow flexure (60-80 mWm^{-2}) [4], and groove formation (~50-150 mWm^{-2}) [5,6], though our modeling cannot currently rule out high heat flows acting on craters over short time scales.

While the maximum heat flows are poorly constrained, the minimum heat fluxes derived here indicate that Ganymede's craters relaxed during a period of elevated heat flow. The scarcity of relaxed craters in Ganymede's bright terrain suggests that crater relaxation occurred before or during bright terrain formation, with little subsequent relaxation [3]. More precise timing of crater relaxation, as well as an analysis of the spatial variability of the heat fluxes implied by relaxed craters remains for future work. This work suggests, however, that the thermal event that accompanied groove formation (e.g., [6]) was experienced across the satellite to greater or lesser degrees and was not limited to the regions of tectonic deformation.

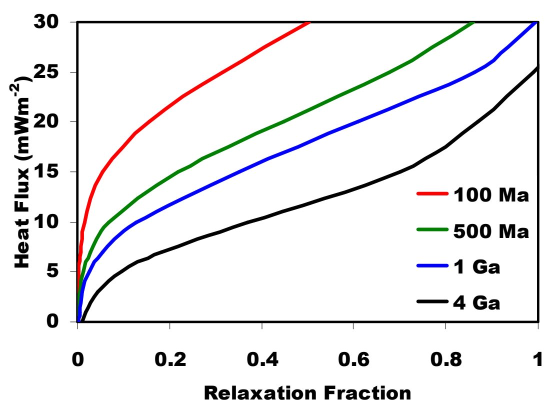

Figure 3: The implied heat flux as a function of observed relaxation fraction for four different assumed relaxation timescales. A relaxation fraction near 0.9 implies a minimum heat flux of 15-20 mWm^{-2}.

References: [1] Passey Q.R. and Shoemaker E.M. (1982) in *Satellites of Jupiter*, Morrison D. (Ed). [2] Dombard A.J. and McKinnon W.B. (2006) *JGR,* 111, E01001. [3] Schenk, P.M. (2010) *LPS XLI,* Abs. #2083. [4] Nimmo F. and Pappalardo R.T. (2004) *GRL*, 31, L19701. [5] Dombard A.J. and McKinnon W.B. (2001) *Icarus*, 154, 321-336. [6] Bland M.T. and Showman A.P. (2007) *Icarus*, 189, 439-456. [6] Bland M.T. et al. (2009) *Icarus*, 200, 207-221.