TECTONIC RESURFACING OF GANYMEDE ENABLED BY CONCOMITANT VISCOUS RELAXATION
M. T. Bland[1], W. B. McKinnon[2], K. N. Singer[3]. [1]USGS Astrogeology, Flagstaff, AZ 86001, [2]Washington University in Saint Louis, Saint Louis, MO 63130, [3]SwRI, Boulder, CO 80302. (mbland@usgs.gov)

Overview: The swaths of parallel ridges and troughs that constitute Ganymede's grooved terrain formed by completely resurfacing the preexisting terrain. Two major end-member models have been proposed for this resurfacing: cryovolcanism, in which flooding of the surface removes preexisting structures before tectonism occurs [1], and tectonic resurfacing, in which the formation of the ridges and troughs themselves disrupt preexisting structures [2]. Recent finite element simulations [3] have shown that tectonism can resurface terrains if the amplitude of the preexisting topography is relatively low; however, large amplitude topography, such as deep craters cannot be removed. This finding suggests at least some role for cryovolcanism during groove formation [3]. Alternatively, tectonic resurfacing might be accommodated in some locations (though clearly not all) by a period of high heat flow that viscously relaxes topography before extension (and groove formation) occurs. The reduction in topographic amplitudes afforded by relaxation permits tectonism to subsequently modify the preexisting terrain. Although this modification to the tectonic resurfacing mechanism cannot explain all resurfacing on Ganymede (resurfacing likely resulted from a combination of process), it provides additional support to the tectonic resurfacing end-member model.

Resurfacing Ganymede: Roughly two-thirds of Ganymede's dark, heavily cratered (ancient) original surface has been replaced by brighter terrain with a younger crater retention age [4]. The bright terrain has a morphology ranging from smooth lanes, to isolated ridges and troughs, to the iconic parallel, periodically spaced ridges and troughs known as the grooved terrain [4]. The mechanism by which the bright terrain replaced the dark terrain is uncertain [5]. Voyager-based investigations concluded that the bright terrain formed in multiple stages that included cryovolcanism as a resurfacing mechanism [1]. Cryovolcanic resurfacing was partially substantiated by *Galileo* data [6]. However, the absence of widespread evidence for cryovolcanism in *Galileo* images lead to the hypothesis that tectonic deformation alone is capable of resurfacing large portions of the satellite (i.e., tectonic resurfacing) [2]. In realty cryovolcanism and tectonic resurfacing are end-member models, and it seems likely that both mechanisms (and other mechanisms such as Europa-style band formation [7]) have contributed to resurfacing Ganymede [5].

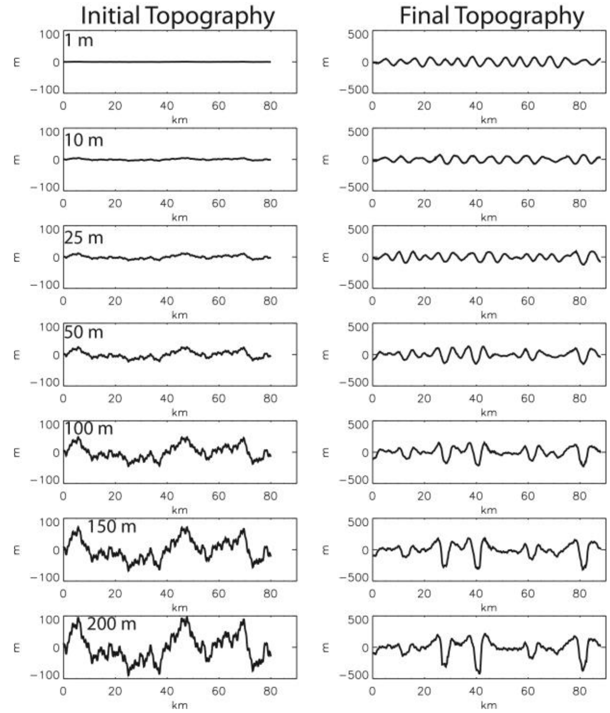

Fig. 1: The effect of increasing amplitude of preexisting topography on groove formation. Left column is the initial topography used in a finite element simulation of lithospheric extension. The right shows the resulting surface deformation after 10% extension. All simulations used a heat flux (F) of 100 mW m^{-2} and surface temperature (T_s) of 100 K.

Testing the Tectonic Resurfacing Hypothesis: Recent finite element modeling has demonstrated that tectonic resurfacing is capable of erasing pre-existing structures and replacing them with periodic ridges and troughs, but only if the amplitude of the preexisting topography is relatively low (25-50 m) (Fig. 1) [3]. Simulations of lithospheric extension in the presence of large-scale topography result in isolated troughs rather than periodic structures (Fig. 1). According to this work, forming groove-like deformation requires that Ganymede's preexisting surface was relatively smooth – smoother than the knobby, cratered surface typical of Ganymede's dark terrain. This in turn suggests that cryovolcanism is required before groove-forming extension occurred, effectively providing a "clean-slate" on which to form the ridges and troughs, a scenario that recalls Voyager-era conceptions [1]. However, cryovolcanism is not the only way to reduce the amplitude of preexisting topography. Viscous relaxation under high heat flow conditions can also remove topography, especially that associated with impact craters [8].

Viscous Relaxation of Impact Craters on Ganymede: Evidence for viscous relaxation is widespread on Ganymede [8, 9] (Fig. 2). Many craters within Ganymede's dark terrain have apparent depth (d_a) near zero, and many others are at least partially relaxed (Fig. 3). Except for the oldest craters, the relaxation states of Ganymede's craters require heat fluxes well in excess of radiogenic heating (Fig. 3). Finite element simulations indicate that these relaxed craters can be explained by one or more pulses of high heat flow (>50 mW m^{-2}). The heat fluxes required are consistent with (or somewhat lower than) those inferred for the formation of Ganymede's grooved terrain [e.g., 10, 11], and it is plausible, if not likely, that the heating event that resulted in groove terrain formation also caused the viscous relaxation of Ganymede's craters.

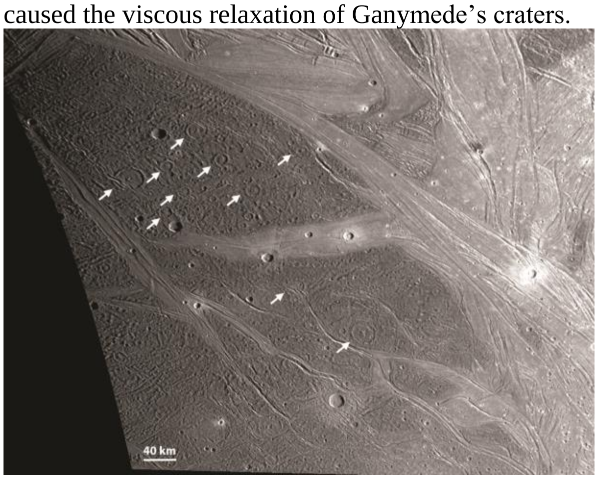

Fig. 2: Portion of Marius Regio (dark region) with numerous viscously relaxed impact craters (white arrows). Note that few relaxed craters occur within the bright terrain.

Tectonic Resurfacing and Viscous Relaxation: Finite element simulations of lithospheric extension suggest that tectonism alone is incapable of "erasing" large, pristine craters and replacing the surface with periodic ridges and troughs (a result substantiated by analog modeling [12]). As extension occurs, strain becomes localized within the crater itself, resulting in the formation of a localized trough almost a kilometer deep (Fig. 4a, b). However, if the crater has undergone viscous relaxation (Fig. 4c), extension results in the formation of periodic ridges and troughs consistent with Ganymede's grooved terrain. Unlike the deep crater, the viscously relaxed crater has effectively been tectonically resurfaced.

A New Resurfacing Scenario: Our simulations of groove formation and crater relaxation on Ganymede suggest that, if tectonic resurfacing has occurred, it was mediated by viscous relaxation. In this scenario, an increasing heat flux or sudden heat pulse (perhaps driven by resonance passage [13,14]) would cause widespread relaxation of impact craters (and other preexisting topography – such as furrows). Subsequent or simultaneous lithospheric extension could then tectonically resurface the topographically subdued cratered terrain. The scenario does not preclude cryovolcanism or band formation also playing an important role.

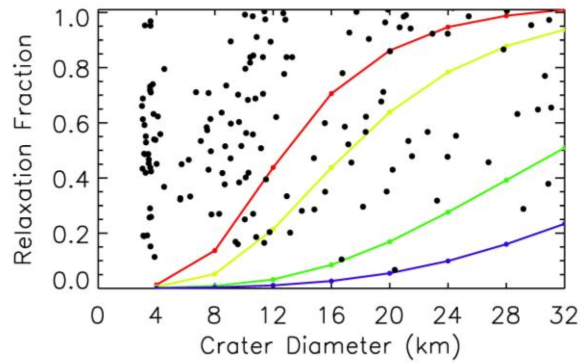

Fig. 3: The measured relaxation fraction (black dots: RF=1-(d_a/d_{inital}), RF=1 is completely relaxed (flattened)) of impact craters from four locations on Ganymede: Marius regio, near Tiamat Sulcus, near Anshar Sulcus, and the south pole. Colored curves show the expect RF due simply to radiogenic heating for craters with ages of 4.6 Ga (red), 3.8 Ga (yellow), 2 Ga (green), and 1 Ga (blue).

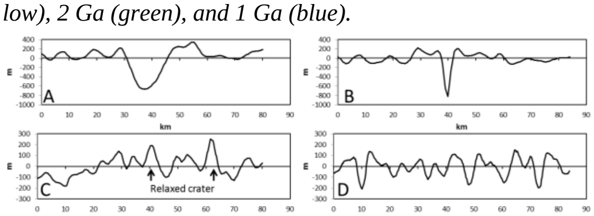

Fig 4: The initial topography (A: a deep crater; C: a relaxed crater) and final surface deformation (B,D) from finite element simulations of lithospheric extension (T_s=100 K, F=100 mW m^{-2}). The viscously relaxed crater is resurfaced tectonically. The deep crater is not.

References: [1] Parmentier E. M. et al. (1982) *Nature, 295*, 290-293. [2] Head, J. W. et al. (1997) *LPSC XXVIII*, 535-536. [3] Bland and McKinnon (2015) *LPSC* 46, #1540. [4] Patterson et al. (2009). [5] McKinnon W. B. et al. (2014) *GSA Ann. Meet.*, #259-5. [6] Schenk P. M. et al. (2001) *Nature, 410*, 57-60. [7] Head et al. (2002) *GRL 29*, 2151. [8] Bland et al. (2011) *LPSC 42*, #1814. [9] Singer et al. (2012) *LPSC 43*, #1659. [10] Dombard and McKinnon (2001) *Icarus* 154, 321-336. [11] Bland and McKinnon (2015). *Icarus* 245**,** 247-262. [12] Wyrick (2012) *GSA Ann. Meet.*, #131-6. [13] Showman et al. (1997) *Icarus* 129, 367-383. [14] Bland et al. (2009) *Icarus* 200, 207-221.