EPSC Abstracts,
Vol. 4, EPSC2009-525, 2009
European Planetary Science Congress,

The formation of Ganymede's grooved terrain

M. T. Bland and W. B. McKinnon

Washington University, Saint Louis, USA (mbland@levee.wustl.edu)

Overview

For nearly three decades researchers have suggested that Ganymede's ubiquitous grooves formed via periodic extensional necking of the ice lithosphere [e.g., 1,2,3]. While analytical and numerical models have indicated that the necking mechanism is feasible [4,5], successful models of groove formation that include large strains, random initial topography, and realistic lithospheric strength profiles have not yet been achieved. Here we present new numerical models of extensional deformation in an ice lithosphere that successfully produce periodic, large-amplitude, groove-like features under more physically realistic conditions.

Background

Covering nearly two-thirds of the satellite, Ganymede's grooved terrain consists of sets of roughly parallel ridges and troughs with peak-to-trough amplitudes of 200 to 500 m and strongly periodic spacings of 3 to 10 km. At high resolution, ubiquitous small-scale (100 to 200 m amplitude and ~1 km spacing) deformation is also observed (see [6] for a review).

Fink and Fletcher [1] first suggested that Ganymede's grooves may have formed via periodic necking of Ganymede's lithosphere. Dombard and McKinnon [4] used a linearized, infinitesimal strain model to show that deformation growth rates during necking of an ice lithosphere are consistent with the amplitudes and wavelengths of Ganymede's grooves. However, their analytical approach was formally limited to small strains and could not examine any non-linear interaction of multiple, simultaneously amplifying wavelengths. Later, Bland and Showman [5] produced numerical models of groove formation at large strains. While these models never produced large amplitude deformation they demonstrated that periodic deformation (such as is observed on Ganymede) can result from the extension of an ice lithosphere with semi-random initial topography. Bland et al. [8] then showed that models that include strain weakening (i.e., a decrease in the yield strength of the ice as plastic strain accumulates) result in deformation amplitudes of 200 to 500 m if simple sinusoidal initial topography (10 m amplitude) was used. While these models were successful, they neglected the influence that realistic surface topography may have on localizing strain. Additionally, for numerical stability the models in [5,8] used a plastic cohesion an order of magnitude larger than that measured for ice [9]. Here we present numerical models of groove formation that include more realistic conditions: large strains, random initial topography, and a weaker ice lithosphere.

The Model

We use the finite element code Tekton (v2.3) to simulate the extension of an ice lithosphere. The model includes the elastic, viscous, and plastic deformation of ice. We assume a Young's modulus of 10^{10} Pa and a Poisson ratio of 0.325. The model utilizes a composite power-law rheology that accounts for dislocation creep (regimes A, B, and C), diffusion creep, and grain-size-sensitive creep (grain boundary sliding and basal slip) [7]. Plasticity is modeled using a Drucker-Praeger yield criterion that includes strain weakening such that the yield strength of the ice decreases as plastic strain accumulates [see 8,10]. Model domains were initially 24 km deep and 40 km long with a maximum resolution of 167 m. Domains were extended by up to 31.5% over 10^5 years yielding a strain rate of 10^{-13} s^{-1}. Small amplitude (maximum 15 m), semi-random initial topography was imposed at the surface of the domain to allow instabilities to initiate. We assume a cold surface temperature of 70 K (appropriate for the polar region *and* a faint early

EPSC Abstracts,
Vol. 4, EPSC2009-525, 2009
European Planetary Science Congress,

Sun). The lithospheric thermal gradient was varied from 5 to 30 K km^{-1}.

Results

The final surface deformation (extrapolated into a third dimension) and the distribution of plastic strain at depth are shown in Fig. 1 for four simulations with rates of strain weakening ranging from ϵ=3 (rapid weakening) to ϵ=10^4 (no weakening). The simulations show that, even when weakening is rapid, large amplitude periodic deformation results from extension of the lithosphere. Fourier analysis of each simulation indicates that the deformation has a dominant wavelength near 7 km, the wavelength expected for a thermal gradient of 10 K km^{-1} [5]. In this case however, the large-amplitude deformation is less periodic than when the weakening is slow; the later produces periodic but low-amplitude deformation. Additionally, when weakening is rapid the form of the final deformation is sensitive to the initial topography. Strain preferentially localizes where the initial topography has troughs that are deeper or broader than average. Our models of groove formation suggest that groove terrain morphology depends on the interplay between the lithospheric thermal gradient (which sets the dominant wavelength), the rate at which strain weakening progresses, as well as details of the initial topography.

The simulations described above continue to include an unrealistically strong ice lithosphere (i.e., large cohesion). Simulations that include a realistically weak ice lithosphere are currently being conducted. Initial results suggest that necking occurs more easily when the lithosphere is weak. While a strong layer often facilitates necking, including a weak lithosphere leads to lower stress at the brittle-ductile transition and thus permits the ice to deform via less viscous dislocation creep B or grain-boundary-sliding mechanisms. As these simulations become finalized we will gain a more comprehensive understanding of groove terrain formation.

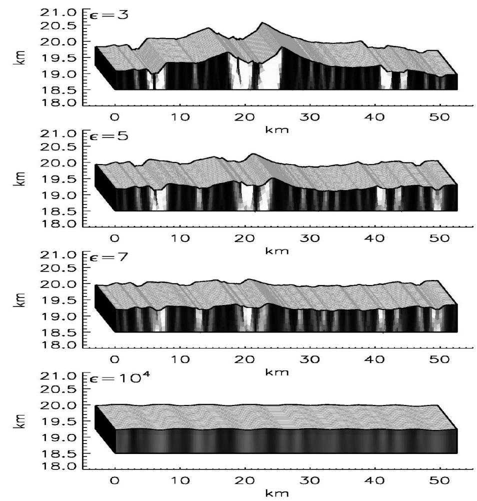

Figure 1: The surface deformation and distribution of plastic strain in the upper portion of our model lithospheric domain. White regions indicate large strains, dark regions indicate small strain. Each simulation is identical (thermal gradient of 10 K km^{-1}, semi-random initial topography) except for the rate at which strain weakening occurs, parameterized by a value ϵ. Small values of ϵ result in "rapid" weakening, large values of ϵ result in "slow" weakening.

References

[1] Fink, J.H. and Fletcher, R.C (1981) *LPSC XII*, 277.
[2] Pappalardo, R. T. et al. (1998) *Icarus*, 135, 276-302.
[3] Collins, G. C. et al. (1998) *GRL*, 25, 233-236.
[4] Dombard, A. and McKinnon, W. B. (2001) *Icarus*, 154, 321-336.
[5] Bland, M. T. and Showman, A. P. (2007) *Icarus*, 189, 439-456.
[6] Pappalardo R.T. et al. (2004) in *Jupiter: The Planet, Satellites and Magnetosphere* (F. Bagenal et al., eds.) CUP, 363–396.
[7] Durham W.B. and Stern L.A. (2001) *AREPS 29*, 295-330.
[8] Bland, M.T. et al. (2009) *LPSC XL*, 1690.
[9] Beeman, M. et al. (1988) *JGR*, 93, 7625-7633.
[10] Bland et al. (2009) *Icarus*, submitted.