Reevaluating Groove Formation on Ganymede: Forming Larger Amplitude Grooves at Smaller Extensional Strains

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Walk-By Summary...

Inclusion of a more-realistic model of brittle continuum behavior (i.e., plasticity) in simulations of groove formation on Ganymede results in the formation of large-amplitude (300-500 m), periodic, groove-like structures at relatively small strains (10%), for cold (polar) surfaces. These strains are 3-10x smaller than in previous models, and are more consistent with strain estimates on Ganymede.

Ganymede's Grooved Terrain

Groove morphology:
- Roughly-parallel, periodically-spaced ridges and troughs
- Amplitudes ~100-500 m (peak-to-trough) (Fig. 1, and [1,2])
- Groove spacing 3-10 km [3,4].

Our New Simulations...

- Visco-elastic-plastic simulations of the extension of an ice lithosphere.
- Includes relevant rheological mechanisms for ice I_
- Uses realistic non-associated plasticity (see below)
- Examine a range of plausible heat fluxes and strain rates.

Deformation is Consistent with Grooves...

Figure 2: Cartoon of the model. $\varepsilon = \text{strain rate}$, $C = \text{cohesion}$, $\theta = \text{angle of internal friction}$, $\varepsilon_y = \text{yield strength}$ $C' = \text{Drucker-Prager moduli}$ $a = \text{Drucker-Prager modified}$ $\rho = \text{density}$ $\psi = \text{Poisson's Ratio}$ $E = \text{Young's modulus}$, $x = \text{strain}$, $\gamma = \text{heat flux}$, $z = \text{depth}$, $T_m = \text{maximum temperature}$, $d = \text{ice grain size}$

Figure 3: Comparison of the groove amplitudes as a function of strain for simulations with associated and non-associated (dilation angle $\phi = 5$) plasticity. Simulations used a heat flux of 100 mW m$^{-2}$, strain rate of $10^{-5}$ s$^{-1}$, and surface temperature of 70 K. Contrasting element dilation results in greatly enhanced topographic amplitudes (see Fig. 4).

The Basic Result...

Extension of the lithosphere results in periodic ridges and troughs with maximum amplitudes of 300-500 m after 10% strain (and cold surface).

Role of Strain Localization...

- Including strain weakening can modify the morphology of the surface deformation, resulting in the formation of graben-like structures.

Figure 7: As in Fig. 4A (heat flux = 100 mW m$^{-2}$, strain rate = $10^{-5}$ s$^{-1}$) but including strain weakening with (A) $\sigma_{II} = 10$ (moderate weakening) after 5% extension, and (B) $\sigma_{II} = 4$ (relatively rapid weakening) after 8% extension. Rapid weakening results in the formation of graben-like features with imbricate faulting, rather than ridge and trough-like features.

Deformation is Consistent with Grooves...

Does Groove Formation Depend on Latitude?

Figure 8: Maximum groove amplitudes at strains of 2% (squares), 5% (diamonds), and 10% (circles) as a function of surface temperature for simulations with $E = 10^{11}$ s$^{-1}$, and no strain weakening. Temperature range is consistent with current equalitarian and polar temperatures (assuming annularly averaged radiative equilibrium). Forming grooves is difficult at current equatorial temperatures (see [11]).

How Much Strain is Required?

Answer: ≤10% strain
- Previous simulations had maximum amplitudes of ~70 m after ~33% strain [8], or 150 m after 20% strain if strain weakening mechanisms were included [9].
- The new, lower strains are more consistent with strain estimates on Ganymede [10].

Take-Aways...

- Simulations of groove formation can produce large-amplitude (300-500 m) periodic structures with only 10% extensional strain (for cold surfaces).
- Simulated surface deformation is quantitatively consistent with Ganymede's observed groove morphology.
- The increase in surface deformation (relative to previous work) results from the use of non-associated plasticity, which limits element dilation during plastic failure.
- Strain weakening is not required, but promotes the formation of graben-like (rather than ridge-trough) structures.
- Groove formation is less effective at current equatorial surface temperatures.

References