NUMERICAL MODELING OF EXTENSIONAL NECKING INSTABILITIES: APPLICATION TO GANYMEDE'S GROOVED TERRAIN. M. T. Bland[1] and A. P. Showman[2], [1]University of Arizona (mbland@lpl.arizona.edu), [2]University of Arizona (showman@lpl.arizona.edu).

Overview: Ganymede's pervasive 5-10 km-wavelength grooves have been suggested to result from a necking instability during an epoch of lithospheric extension, but to date few quantitative studies of groove formation have been performed. We present two-dimensional numerical models of necking instabilities under conditions that are appropriate to Ganymede at the time of groove formation. Preliminary simulations indicate that extensional necking instabilities can occur under a range of conditions, many of which may be relevant to Ganymede. The form of the surface topography produced by these instabilities varies as a function of the strain rate, amount of extension, initial topographic perturbation, and rheological parameters.

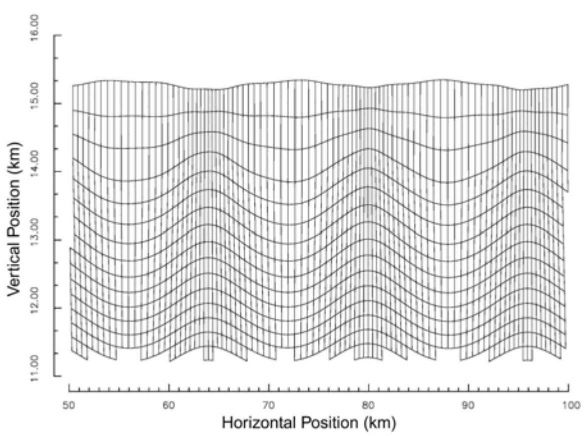

Figure 1: Enlarged view of the surface morphology produced by the formation of an extensional necking instability. The contours are material surfaces that were initially horizontal or vertical; extension leads to a necking instability, which produces pinch-and-swell morphology in the lithosphere and grooves at the surface.

Background: Voyager and Galileo images of Jupiter's moon Ganymede have revealed that its surface is composed of two types of terrain: dark, ancient, heavily cratered terrain and bright, young, tectonized terrain [1, 2]. Much of this highly tectonized surface consists of a distinct morphology termed grooved terrain. Grooved terrain is composed of sets of roughly parallel, evenly spaced, gently undulating grooves with amplitudes of several hundred meters [3]. Groove sets are typically hundreds to 1000s of km long and ten to one hundred km wide [4]. Grooves visible in regional scale voyager and Galileo images have wavelengths of 4 km to 17 km with an average of 8 km [5, 6]. While groove morphology varies from one set to another, there does not appear to be any global pattern of groove wavelength or orientation.

Based on the lack of identifiable compressional features on Ganymede's surface it has generally been accepted that the grooved terrain formed due to extensional surface processes during an epoch of global expansion [7, 8, 2]. However, the exact mechanism by which the grooves formed remains uncertain. Several authors have suggested that the grooves are the result of extensional fractures or repeated horst and graben that have been softened by viscous relaxation and mass wasting [7, 8]. While feasible, these mechanisms do not easily explain the strong periodicity seen in the grooved terrain. A more likely formation mechanism is that of an extensional necking instability as has been used to describe the formation of the basin and range province of the southwestern United States [9]. The necking instability mechanism assumes that the lithosphere is composed of a stiff, highly viscous surface layer underlain by a ductile substrate. As extension of such a domain occurs, any thickness perturbation in the layers will grow at a rate determined by the horizontal length scale of the perturbation and the details of the rheology assumed [9]. This results in a surface layer that is deformed into a series of periodic, undulating pinches and swells.

Using a linearized analytical model, Dombard and McKinnon [10] applied the extensional necking instability model to the formation of Ganymede's grooved terrain. They calculated growth rates of a necking instability as a function of wavelength and demonstrated that, under conditions of high heat flow, the fastest-growing modes have wavelengths and growth rates consistent with Ganymede's grooves. However, questions remain as to whether nonlinearities influence groove formation. Linearized methods must assume infinitesimal strain and can only treat the initiation of grooves. It is expected that as an instability develops and strains become larger, the role of nonlinear effects on instability growth will become significant. Furthermore, it is important to elucidate how such instabilities respond to finite surface topography.

The Model: We use the two-dimensional, finite-element code Tekton to simulate the extension of a stiff surface layer overlying a ductile substrate. Both Newtonian and power-law flow regimes have been explored. The latter case employs recent rheological laboratory data for both dislocation creep and grain-boundary-sliding flow mechanisms. The nominal domain size is 100 km long and 24 km deep, which allow us to span several long-wavelength grooves yet still resolve individual short-wavelength grooves. Free parameters in the model include the strain rate, temperature gradient, rheology, and initial perturbation.

Results: Extension of the domain described above results in the formation of a necking instability (Figure 1). Surface morphologies produced by the growth of the instability are consistent with Ganymede's grooved terrain. However the growth of the instability is a strong function of the rheologic regime.

Newtonian Rheology. While the mechanical behavior of an icy lithosphere is not well described by a Newtonian rheology, modeling such a case provides an important baseline for comparison to more complex power-law rheologies. In these cases it has been found that at high strains, the surface morphologies produced are consistent with Ganymede's grooved terrain. After 30% extension of the domain, simulated grooves have amplitudes of 50 m to 450 m and wavelengths of 10 km to 30 km. Examination of the strain rate and temperature gradient parameter space has shown that both the dominant wavelength produced by the instability as well as the groove amplitudes are highly dependent on the temperature gradient and strain rate (Figure 2). Both the largest groove amplitudes and longest wavelengths are produced at high strain rates and modest temperature gradients. While no combination of strain rate and temperature gradient was found that would match both the amplitude and wavelength of Ganymede's grooves, the conditions that produce a surface with the most consistent morphology have strain rates of 10^{-14} s^{-1} and temperature gradients of 5 K/km (which have too long a wavelength) or 45 K/km (which have too low an amplitude). Notably the formation of the necking instability is independent of the initial perturbation imposed on the system.

Power-law Rheology. The growth of necking instabilities in a power-law flow regime is significantly more complex than in the Newtonian regime. As in the Newtonian case, at high strains the surface morphology produced is broadly consistent with Ganymede's grooved terrain. However, in the power-law flow regime the growth of the instability is strongly dependent on the initial perturbation assumed. Thus short wavelength perturbations produce short wavelength grooves while long wavelength perturbations produce long wavelength grooves. The reasons for this sensitivity to initial conditions remain unclear and are under investigation.

Conclusions and Future Work: Preliminary modeling of extensional necking instabilities produce surface morphologies that are consistent with Ganymede's grooved terrain. The extensional necking instability mechanism therefore appears to be a feasible process by which Ganymede's grooves may have formed. Significant work remains to fully characterize the growth of such instabilities. This work will include imposing perturbations consisting of multiple wavelengths, imposing a plastic rheology in the domain's surface layers, and including finite topography such as pits or crater rims in the domain. This work was funded by NASA PG&G

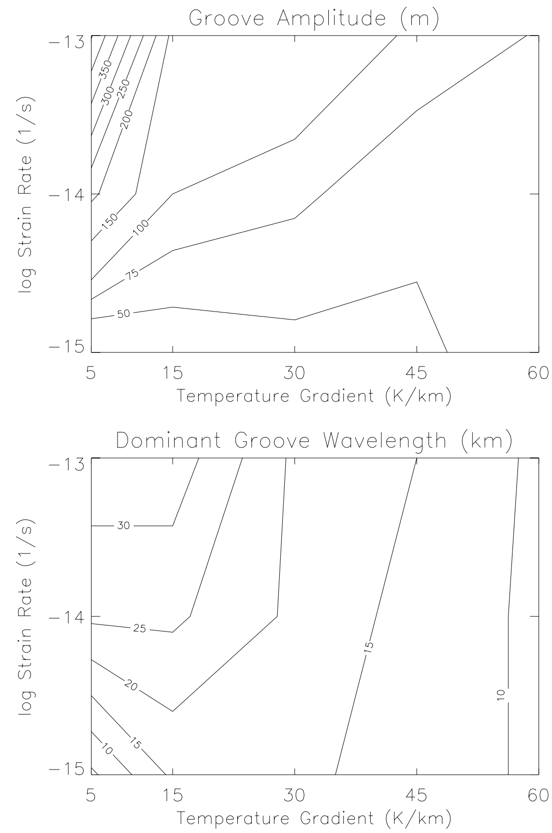

Figure 2: Contour plots of groove amplitude (top) and wavelength (bottom) as a function of strain rate and temperature gradient for a Newtonian rheology.

References:

[1] Smith, B.A. et al. (1979) *Science 206*, 927-950. [2] Pappalardo, R.T. et al. (1998) *Icarus 135*, 276-302. [3] Squyres, S.W. (1981) *Icarus 46*, 156-168. [4] Shoemaker, E.M. et al. (1982) *Satellites of Jupiter*, University of Arizona Press, 435-520. [5] Grimm, R.E. and Squyres, S.W. (1985) *JGR 90*, 2013-2021. [6] Patel, J.G. et al. (1999) *JGR 104*, 24057-24074. [7] Squyres, S.W. (1982) *Icarus 52*, 545-559. [8] Golombek, M.P. (1982) *JGR 87*, A77-A83. [9] Fletcher, R.C. and Hallet, B. (1983) *JGR 88*, 7457-7466. [10] Dombard, A.J. and McKinnon, W.B. (2001) *Icarus 154*, 321-336.