FORMING GANYMEDE’S GROOVES: PRODUCING LARGE-AMPLITUDE, COMPLEX DEFORMATION. M. T. Bland1, W. B. McKinnon1, and A. P. Showman2, 1Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, Saint Louis, MO 63130 (mbland@levee.wustl.edu). 2Department of Planetary Science, University of Arizona, Tucson, AZ 85721.

Summary: We numerically simulate the extension of an ice lithosphere under conditions appropriate to the formation of Ganymede’s grooved terrain using a model that permits a decrease in the brittle strength of the ice as strain accumulates. The inclusion of such strain weakening results in increased localization of the surface deformation, producing large amplitude topography with complex deformation styles. These results mark the first time that truly groove-like morphologies have been produced by simulations of extensional tectonism in an ice shell.

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 [1]. At high resolution ubiquitous small-scale (100 to 200 m amplitude and ~1 km spacing) deformation is also observed. This relatively young terrain may have formed via unstable extension of Ganymede’s ice lithosphere during which perturbations in the thickness of the lithosphere became amplified into periodically spaced pinches and swells that correspond to Ganymede’s large-scale ridges and troughs [2,3]. Applying an analytical model of unstable extension to Ganymede’s lithosphere, Dombard and McKinnon [4] found that the fastest growing modes of deformation had wavelengths and growth rates consistent with Ganymede’s grooved terrain. However, numerical modeling of groove formation at finite strains have struggled to produce sufficiently large amplitude deformation during extension of an ice lithosphere. Maximum amplitudes in these simulations were ~70 m [5].

The model: We use the finite element model 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 an Poisson ratio of 0.25. 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) [6]. In general, dislocation creep mechanisms B, and C, and grain boundary sliding dominate the flow. Plasticity is modeled using a Drucker-Praeger yield criterion with a cohesion of 10 MPa and an angle of internal friction of 30°. Model domains were initially 24 km deep and 40 km long with square elements 167 m on a side. Domains were extended by 31.5% over $10^5$ years yielding a strain rate of $10^{-13}$ s$^{-1}$. A small (10 m) sinusoidal perturbation was imposed at the surface of the domain to allow instabilities to initiate. In these simulations we assume a cold surface temperature of 70 K (appropriate for the polar region and a faint early Sun) and a thermal gradient of 10 K km$^{-1}$.

Strain weakening. Plasticity is a continuum approach to modeling brittle behavior that assumes the lithosphere is pervasively fractured on a scale below the resolution of a single element, and that the cumulative behavior of these fractures can be treated as an addition to the viscous strain rate. Plastic behavior only occurs when the local stress (parameterized as the second invariant of the deviatoric stress) is greater than the yield strength of the material. Terrestrial models of tectonic deformation often assume that the yield strength of a material decreases as plastic strain accumulates. Thus a material “remembers” its strain history (i.e. material that has experienced more strain undergoes plastic failure more easily than material that has undergone less strain). Such strain weakening can lead to significant localization of strain and increased deformation amplitudes [e.g., 7]. In contrast to previous modeling [5] we have incorporated various strain weakening parameterizations into our models of groove formation (Fig. 1).

Fig. 1: Three heuristic models of strain weakening (i.e., the decrease in yield strength with increasing plastic strain).

Results: The inclusion of strain weakening in models of groove formation produces increased deformation amplitudes (Fig. 2). For some weakening parame-
ters average groove amplitudes are ~300 m, with max-
mum of near 500 m. Such amplitudes are consistent
with observations of Ganymede’s actual grooves. The
increase in deformation amplitudes is a direct result of
increased strain localization in the “pinched” regions of
the lithosphere. While strain localizes in these regions
even in the absence of strain weakening, almost all of
the deformation occurs in these regions when weaken-
ing is invoked, with little or no deformation occurring
in the intervening swells. The narrow regions of high
strain are strongly reminiscent of shear or fault zones
observed in terrestrial environments.

The degree and style of strain localization depends
only weakly on the heuristic model of strain weakening
assumed, but strongly on the “rate,” or gradient, of
weakening with plastic strain (Fig. 1). A rapid de-
crease in yield strength with increasing plastic strain
results in large deformation amplitudes but localization
in only a few regions of the domain. In contrast, a slow
decrease in yield strength with plastic strain results in
lower deformation amplitudes but more distributed
deformation with strain localizing in many regions.
Identical physical conditions (e.g., strain rate and ther-
mal gradient) can therefore lead to different types of
surface deformation if strain localizes with different
gradients in different regions of the satellite. Such dif-
fferences may explain Ganymede’s complex surface
morphology.

**Conclusions:** The inclusion of strain weakening in
numerical simulations of groove formation increases
deformation amplitudes by a factor of 4 to 6 over simu-
lations without weakening, producing grooves 200 to
500 m in amplitude. Such groove amplitudes are con-
sistent with observations of Ganymede’s actual
grooves. Additionally, as strain accumulates and local-
izes, we observe evolution from near harmonic undula-
tions to a more irregular (though still periodic) surface
topography, including in some cases fault capture and
evolution of the dominant wavelength. This may be a
better match overall to Ganymede’s actual surface, and
potentially offers an additional test of our models.
These results suggest that the inclusion of strain weak-
ening may finally allow groove formation “theory” to
match observed groove morphologies, while using real-
istic rheological parameters and temperature gradients.

**References:** [1] Pappalardo R.T. et al. (2004) in
*Jupiter: The Planet, Satellites and Magnetosphere* (F.
Bagenal et al., eds.) CUP, 363–396. [2] Fink J.H. and

**Fig. 2:** Second invariant of the deviatoric plastic strain
accumulated in each element during extension of the
domain for two cases: (Top) a simulation with no
strain weakening (amplitudes ~70 m) and (Bottom) A
simulation that includes strain weakening (amplitudes
~300 m). The trace of the surface deformation is
shown above each map.