Overview: One of the most dramatic characteristics of Ganymede’s groove terrain is the along-strike continuity of its individual ridges and troughs. Groove swaths can be nearly 1000-km-long, and individual grooves, which are generally linear, can often be traced along much of the swath’s length. Current models of groove formation neglect this critical aspect of groove morphology, instead simplifying the problem to a two-dimensional lithospheric cross-section. Here we describe preliminary 3D numerical simulations of groove formation on Ganymede, which will clarify the basic physical processes permitting the formation of linear ridges and troughs with along-strike continuity. Additionally, these simulations will permit further investigation of whether resurfacing on Ganymede occurred primarily through tectonism or required additional mechanisms such as cryovolcanism.

The groove terrain: Ganymede’s surface can be broadly divided into bright terrain units and dark terrain units. Although the morphology of the bright terrain is highly variable [1], much of it has an iconic morphology dubbed “grooved terrain” that consists of interwoven swaths of periodically spaced ridges and troughs [see 2 for an overview]. Ridge and troughs generally have amplitudes of a few hundred meters, and periodic spacing of ~10 km. The ridges themselves are generally linear, and can often be traced along-strike for hundreds of kilometers (Fig. 1).

The formation of Ganymede’s grooved terrain: In the post-Galileo era it has generally been accepted that Ganymede’s grooved terrain formed via extension of the lithosphere that deformed the surface into periodically spaced ridges and troughs [2,3]. The strongly periodic spacing of ridges within each groove set [4, 5] results from an instability during extension [6], which is enabled by the strong rheological contrast between the ice lithosphere and the underlying warm ductile ice. Dombard and McKinnon [7] used semi-analytical, infinitesimal strain models to demonstrate that the dominant wavelengths that develop, and rate of amplitude growth during such extension are sufficient to produce Ganymede’s grooves.

Numerical simulations of groove formation. Over the past decade, a succession of fully numerical, two-dimensional models have attempted to reproduce the morphology of Ganymede’s grooved terrain with mixed success [8,9,10], often struggling to reproduce the amplitude of the ridges [8]. However, the recent implementation of non-associated plasticity in these models [10] has resulted in simulations that reproduce both the amplitude and wavelength of Ganymede’s grooves at reasonable extensional strain (~10%). The success of this model has led to detailed investigations [11,12,13] of whether resurfacing on Ganymede can occur through tectonism alone (the so-called “tectonic resurfacing” hypothesis [14]). These advances have resulted in a more complete understanding of groove formation in two-dimensions.

The limits of 2D models: To date, all simulations of groove terrain have been performed, by numerical necessity, in two-dimensions. These 2D simulations were essential in establishing a foundational understanding of how strain is partitioned during extension to produce periodic, but large-amplitude tectonic structures. However, the grooved terrain is inherently a three-dimensional structure, and how strain localizes to form continuous, linear ridges from non-periodic initial topography remains unclear. In 2D, strain can quickly become localized within thinned regions of the extending lithosphere (e.g., topographic lows); however, strain localization in 3D is more complex. Previous modeling of extension and contraction in three dimensions have demonstrated that linear boudinage (in extension) or folds (in contraction) will self-organize from random small-scale preexisting topography under terrestrial conditions [15,16]; however, such modeling
has not been performed for an ice lithosphere. Nor has it been demonstrated that groove formation can completely disrupt preexisting, organized (i.e., non-random) surfaces in three-dimensions.

**Modeling groove formation in 3D, preliminary steps:** To better elucidate how strain localizes during groove formation, we have begun simulating the formation of Ganymede’s grooved terrain in 3D. Current, preliminary models use the finite element code *Tekton* [17] in a viscoelastic formulation. The model domain is 40 x 10 x 5 km with a resolution of 500 m, resulting in 18711 nodes and 16000 elements. The domain is long enough for periodic deformation to form, wide enough to evaluate effects in the third dimension, and deep enough to permit a strong rheological contrast to be imposed. In these models we use a simplified rheologic structure consisting of a high viscosity surface layer underlain by a low viscosity substrate. We initialize the simulations with low-amplitude (10 m) random topography. The model is fixed along the x and y=0 boundary, and extended along the long axis (Fig. 2).

The current 3D simulations do not reproduce groove-like deformation (Fig. 2). The pre-existing topography is essentially preserved over the small amount of extensional strain imposed. This strain is broadly distributed throughout the domain. The lack of localization is due in large part to the viscoelastic nature of the simulations, and the small strain imposed.

**Next Steps:** We are currently in the process of implementing plasticity (brittle failure) within the 3D version of *Tekton*. This will permit more rapid strain localization [10], and potentially the development of groove-like structures at small strains. Because *Tekton* is not parallelized, it is not well suited to 3D simulations. We are therefore exploring other finite element models, such as ASPECT [18], which may be better suited to our 3D study.

Additionally, we will utilize physical analog models of extension on Ganymede to document the real time growth and evolution of fault and fracture connectivity, lending confidence in understanding the mechanisms of fault network development. Analog model outputs for numerical models include (1) known starting geometries (e.g., fault nucleation sites); (2) temporal and spatial distribution of fault growth and linkage; (3) loading conditions (overburden, displacement magnitudes), and (4) cumulative strain (fault spacing and displacement). These parameters provide critical realism to the numerical modeling efforts.

Once the challenges of numerical implementation have been overcome, our 3D models will be used to fully evaluate the formation of Ganymede’s grooves in three-dimensions. The tectonic resurfacing hypothesis will also be assessed by imposing “real” topography on the initial domain that is consistent with the pre-groove surface of Ganymede (e.g., craters, ridges, etc).

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Figure 2: (Top) The initial 3D model domain. The surface is initialized with low amplitude (~10 m peak to trough) topography. (Bottom) The surface topography after 3% extension (out of the page). No periodic structures have developed.