PHYSICAL ANALOG MODELS OF GANYMEDE'S GROOVED TERRAIN. D. Y. Wyrick[1] , M. T. Bland[2] and R. Patterson[1], [1]Southwest Research Institute (6220 Culebra Road, San Antonio, TX; dwyrick@swri.org), [2]U.S. Geological Survey (mbland@usgs.gov).

Introduction: The tectonic deformation observed on many outer planet icy moons is critical toward understanding the geologic evolution of these planetary bodies. A common tectonic style – grooved terrain – is still not well understood, and current numerical modeling approaches cannot yet capture the discrete faulting styles found on Ganymede and other icy moons. The goal of this research is to couple physical analog and finite element modeling approaches of grooved terrain development to leverage the strengths of one approach against the weaknesses of the other toward developing more geologically realistic models of icy moon tectonics. We are conducting a suite of physical analog modeling experiments to determine how icy lithospheres respond to localized extension, specifically the three-dimensional development of pinch-and-swell topography characteristic of Ganymede's grooved terrain. Analog model results are used to improve existing finite element models, including increased fidelity in fault nucleation as well as the temporal and spatial evolution of fault systems on icy moons. Physical analog experiments provide quantitative measures of strain partitioning (i.e., large-scale groove terrain faults vs small-scale intrablock faults) under scaled icy moon conditions, providing geologic realism with direct application to icy moon tectonism.

Ganymede's grooved terrain holds important clues to the style and magnitude of icy moon tectonics. Grooved terrain generally occurs as individual lanes and polygonal crosscutting swaths of bright terrain that cover about 2/3 the moon [1]. Within grooved terrain swaths, the ridges and troughs show generally similar morphology, size, and orientation, with ridge and trough amplitudes on the order of several hundred meters and groove spacing with wavelength from 3-17 km [2,3,4,5]. At larger scales, the grooved terrain gives rise to relatively long-wavelength undulations that may be a result of extensional boudinage, or "necking" [6,7,8]. Many authors have interpreted Ganymede's grooved terrain as the product of fault-accommodated distributed lithospheric extension, possibly accompanied by cryovolcanism [9,10,11,12,13,14,15].

One of the major hurdles in structural geology and geomechanics is the ability to accurately model the evolution of complex geologic structures in a reproducible and efficient manner. Whether modeling large-scale crustal deformation or outcrop-scale localized deformation, the ability to develop realistic, predictive models remains constrained by the limitations of the modeling approach. Typically, complex geologic problems have been characterized using one of two modeling approaches: physical analog modeling or numerical modeling [16,17,18,19,20,21,22,23]. Physical analog modeling is currently better suited to simulating three-dimensional structural complexity, including discontinuous deformation, such as faulting. However, analog modeling is limited in conducting multiple parametric analyses and is not amenable to extraction of quantitative stress information. In contrast, finite-element-based numerical modeling can record complex stress and strain fields during model evolution but still struggles with accurately capturing discontinuous processes, such as fracturing and faulting. Also, finite element models are often "too perfect" (e.g., lacking inherent flaws) to model natural geologic structures.

Physical Analog Models: Previous research laid the groundwork for physical analog models of Ganymede's grooved terrain [24,25,26]. These early experiments tested distributed extension of Ganymede's faulted brittle upper layers as a mechanism for grooved terrain development. These models were performed using a clay cake layer of varying thickness that was deformed through extension distributed by stretching of an underlying rubber sheet. [26] reported a high degree of geometric and kinematic similarity between model structures and grooved terrain observed on Ganymede, indicating that rotational half-graben brittle block faulting can explain at least some tectonics resurfacing and that 20% extension is sufficient to form grooved terrain. These analog modeling experiments were designed to test effects in Ganymede's brittle layer and did not model a ductile substrate. Therefore, the effects of extensional boudinage (e.g., [7]), which requires interaction between the brittle and ductile layers, were not explicitly simulated in these experiments.

These previous experimental data are being reexamined in light of more recent numerical modeling efforts [23] to gain a better understanding of how grooved terrain initiated and evolved over time. The analog modeling documents 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) model loading conditions (e.g., overburden, displacement magnitudes), and (4) cumulative strain (fault spacing and displacement). These parameters provide critical realism to the numerical modeling efforts and will lend confidence that the material constitutive behavior defined in the finite element models is replicating appropriate fracture characteristics. These inputs also serve as quality assurance that the strain accommodation in both modeling approaches is similar (e.g., displacement partitioned between large and small-scale faults) and that the amplitude and spacing of the topography is of a similar order of magnitude.

Future work: Recent advances in numerical models have, for the first time, reproduced the amplitude, wavelength, and average slopes of Ganymede's grooved terrain at modest strains (10%–15%) [23]. Current finite element modeling efforts are underway to investigate groove formation in the presence of large-scale topography [27]. These simulations lay the groundwork for the numerical simulations, however, these models, like all current geomechanical modeling, are limited by our understanding of the fundamental mechanical behavior of the strata and the mathematical (constitutive) relationships to describe them. Numerical models also have difficulty replicating the discontinuous and highly heterogeneous behavior of geologic systems. Results from previous and new physical analog modeling experiments will test and expand newly developed modules in the finite element Tekton2.3, including: (i) seeding weak zones to better mimic fault nucleation distribution, (ii) refine rheological parameters (e.g., brittle vs ductile ratios) to improve strain partitioning, (iii) validate existing non-associated plasticity module for dilation failure mode, and (iv) verify magnitudes and geometries of fault system development.

Data from the analog models will be used to validate initial numerical models at a 1:1 scale using only brittle deformation parameters to test the finite element modeling constitutive relationships. If the two modeling approaches are in fidelity in regards to model output, then confidence is gained in adding mechanical complexity in subsequent models.

Future work will include a comprehensive analysis of the complex strain patterns (which are not easily replicated by numerical methods) that are inferred to occur due to grooved terrain development and tectonic resurfacing on icy moons. Understanding the geologic processes occurring on icy moons, specifically the role regional and global scale stress fields play on the tectonic evolution, directly informs our understandinging of several icy moons processes, including both terrain brightening and crater destruction processes. The results of this project will improve our understanding of the development and sequential history of the grooved terrains on Ganymede, and will determine the extent to which tectonism can affect crater size-frequency distributions (and therefore inferred surface age). The improvements to current numerical models is timely, as project results will be available prior to the ESA JUICE and NASA Europa mission launches, providing the most geologic realistic predictive models prior to arrival at these icy moons.

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