ANALYSIS OF THE FIRST-ORDER MECHANICS OF POLYGONAL FAULT NETWORKS ON UTOPIA PLANITIA USING BOUNDARY ELEMENT METHOD MODELING.

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Introduction: The giant polygons of Utopia Planitia, Mars are characterized by troughs tens of meters deep that define polygonal fault networks that have 1 to 30 km spacing between troughs [Figure 1]. A number of hypotheses for their origin have been proposed such as desiccation of water saturated sediments, thermal cooling and contraction in permafrost, cooling of lava, and tectonic deformation. Pechmann [1] has demonstrated that none of these terrestrial analogs would lead to a satisfactory description of the mechanisms and scales involved.

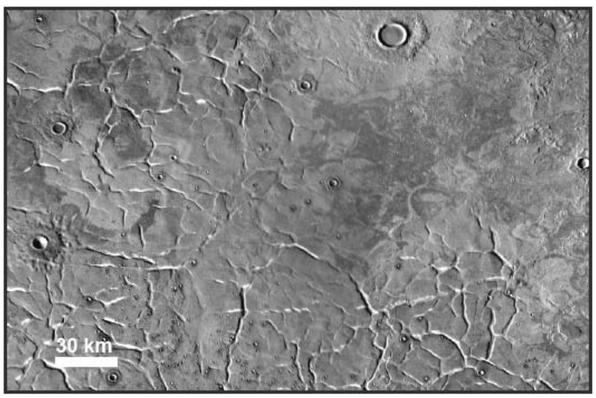

Figure 1: THEMIS Daytime Infrared Mosaic of a region in the Utopia Basin (Courtesy of Arizona State University).

Polygonal fault networks have been found in layers of mudrocks and chalks beneath oceans in sedimentary basins around the world [Figure 2]. These terrestrial polygons were first documented in Lower Tertiary mudrocks from the North Sea Basin by Cartwright [2]; 28 basins have currently been identified through 2D and 3D seismic studies to have extensive fault systems defining polygons with diameters up to 1 km. Earth polygonal terrains are located on passive margins in onlap fill units and are generally comprised of very fine-grained sediments [2,3,4,5,6,7,8]. The overlap in scale between the 1 km terrestrial polygons and the giant polygons of Mars suggests that they may have similar origins.

Geologic Background: A number of observations support a water-laid sedimentary origin for the materials where the giant martian polygons occur. Polygonal terrains occur in the lowest parts of the northern lowland, the most logical places for water to pond and sediments to accumulate if oceans or large lakes did occur [9,10,11]. Craters superposed on these terrains are dominantly characterized by fluidized ejecta, generally thought to be due to significant volatile content in the target material [12]. The upper elevation limit for polygonal terrain exposures along the south flank of the Utopia Basin occurs close to an elevation of -4350 meters [13], approximately coinciding with a topographic terrace along the flank of the Utopia Basin that has been interpreted to be a paleoshoreline [14]. Utopia Planitia is thought to be covered with sedimentary and volcanic material by Tanaka [15]. Luchitta et al. [9] support the material being of sedimentary origin deposited in a standing body of water.

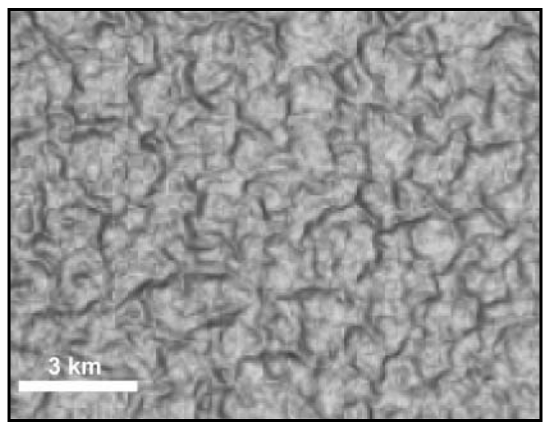

Figure 2: Seismic map of a polygonal network at the Base Quaternary horizon that is approximately 100m below the sea floor in sediments in the Lower Congo Basin [8].

On Earth, the North Sea polygons form in a sequence of smectite-rich volcanic mudrocks produced from altered volcanic glass [7] and thus may be a possible model for the martian polygonal terrain materials. Sub-sea polygonal terrains on Earth occur in decoupled tiers associated with vertical and lateral lithological variations, with the largest fractures crossing multiple lithological units [2]. Major faults cut through two or more tiers and are widely spaced, suggesting a direct correlation of polygon width with layer thickness. The minor faults are confined within polygons defined by major faults, and thus are inferred to be younger [5].

North Sea polygons exhibit radial strain patterns in plan view with approximately 20% apparent areal extension within any one layer [3]. The deformation is layer bound and there is no evidence of extensional displacement transfer onto basement structures [3]. Cartwright and Lonergan [3,6] propose that volumetric contraction is the most reasonable explanation for the apparent extension. McGill and Hills [16] also required 20% extensional strain to produce the grabens in Utopia Planitia based on a 2D differential compaction model (desiccation shrinkage of wet sediments) with the scale of the giant polygons determined by the topography of the underlying surface. Using Fric2D, a Boundary Element Method (BEM) modeling code developed by Cooke et al. [17], Buczkowski and Cooke [18] have also shown that volumetric compaction is a feasible model for the development of faults within Utopia Basin. Volumetric contraction seems to accommodate the extensional faulting observed in earth polygonal terrains and the giant martian polygonal terrains.

Model: In order to understand whether volumetric contraction may have created the giant polygons, BEM models can be used to simulate the first-order mechanics of the faulting process. A BEM code based on the displacement discontinuity method of Crouch and Starfield [19] was used by Tuckwell et al. [20] to demonstrate that polygonal fracture networks can be created that resemble the North Sea polygons and the giant polygons of Mars. The models investigated map-view development of polygonal structures from an initial set of fracture seeds of different lengths that represented flaws within the models with different propensities to propagate. The elastic moduli, loading rate and fracture seed distribution were varied to study which parameters produced and controlled polygonal fracture networks [20].

To further investigate whether the earth polygonal terrains are an analog for the martian polygonal terrains, we are developing Fric2D cross-sectional models that use key martian parameters. The scale of the model is 1 km in height, a typical estimate of the thickness of materials within the polygonal terrain and 50 km in length to encompass typical diameters of the giant polygons [Figure 3]. Material properties for wet, fine sediment are applied to simulate a water-laid depositional environment. The model deforms under horizontal extension, which simulates volumetric contraction. Martian gravity is applied by reducing the density of the material by a factor of 0.38.

It has been inferred by earlier researchers that the underlying topography of the Northern Lowlands is similar to the topography of the older, Southern Highlands [16,21]. McGill and Hills [16] proposed that this underlying topography controlled the surface expression of the giant polygons in the Utopia Basin. Within the models, fracture seeds of variable lengths are evenly placed along the base of the model to represent the underlying uneven topography. Individual fractures grow by fracture propagation or linkage. Fractures propagate when the stress intensity at the fracture tip exceeds the fracture toughness of the material for an applied extensional strain. Within the model, fractures grow and propagate as opening-mode cracks. Although the grabens that form the polygonal terrain develop via normal faults that differ from the opening-mode cracks investigated here, the first order mechanics of propagation are similar. The overall patterns of grabens, composed of pairs of normal faults, are matched within the models where each graben is represented as an opening mode fracture [22]. Consequently, the spacing of opening mode fractures that reach the upper surface of the model can be compared to the spacing of grabens within the polygonal terrain on Mars. Models with seed spacing of 500m have been investigated to study the relationship between surface fracture spacing, the amount of strain and the strain rate (loading). Models compare slow and fast loading and vary the amount of extension to simulate high and low strain.

The results of the low strain, fast loading, 500m seed spacing model further supports the premise that spacing between grabens within the polygonal terrain reflects buried topography. Due to the low strain in the model, only the longest seeds propagated to the surface. The average surface fracture spacing in this model is ~23km, on the order of the trough spacing in the Utopia Basin.

To further investigate whether the uneven topography is the controlling mechanism of the surface trough spacing of the giant polygons, on-going models use MOLA tracks of the Southern Highlands to more realistically simulate the topography beneath Utopia.

Findings and Conclusions: BEM model results show that fracture seeds simulating uneven topography will produce martian and terrestrial scale spacing between fractures.

Regardless of loading rate, high strain produces similar populations of fractures and comparable surface fracture spacing. For the high strain models, the surface fracture spacing has a 1:1 relationship with the layer thickness (1 km) of the model. These models represent saturated systems where the layer thickness controls surface fracture spacing [23]. The level of strain required to reach fracture saturation depends on the length of the fracture seeds used within the model.

Material properties for fine, wet sediments that are analogous to earth sedimentary basin materials produce giant martian-scale polygonal fracture spacing (~23 km) in the model with low strain and fast loading. These low extension models produce undersaturated systems of fractures, where the longest fractures seeds are controlling surface fracture spacing. Consequently, the distribution of the longer fracture seeds controls the spacing of fractures that reach the surface of the model. For this reason, many realizations with different distributions of fracture seeds were used in order to explore the statistical robustness of the fracture spacing. The undersaturated model results highlight intriguing implications for Utopia where the underlying topography beneath the basin may control fracture spacing as the largest topographic irregularities will give rise to features that grow to the surface [16].

The extension required to produce martian scale polygons within this model is far below the 20% extensional strain proposed for the Utopia Basin and lower than the 20% radial bed-length extension implied for the North Sea [3,16]. However, the low strain implied by the model results is in order to produce surface fracture spacing only; the model does not address the strain required to produce troughs or faults with displacement. Furthermore, when shorter fractures seeds are used, greater extension will be required to propagate the fractures to the surface.

Present models are utilizing Southern Highlands topography to simulate the topography beneath the Utopia Basin. If terrestrial sedimentary basins are an analog for the giant martian polygons, fracture sets from multiple tiers on Mars may be present. Additionally, different material properties could influence the amount of extension required to produce surface fractures. Future investigations will include layered models to study spacing and tiers and other material properties.

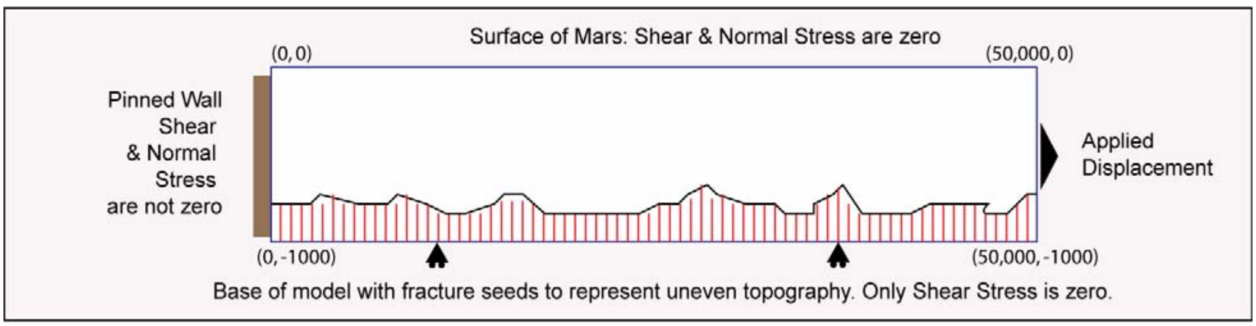

Figure 3: Conceptual Model (not to scale).

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