A MARTIAN GRABEN CHAIN MODEL MODEL USING BOUNDARY ELEMENT METHOD AND MOLA DATA

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Introduction: Determining the causes of the large numbers of fractures, graben, and pit crater chains on Mars is fundamental toward understanding the structural development of the planet's surface and the interaction of the mantle with the near surface and surface environment. Our objectives for the Alba Patera region were, thus, to understand the 3-D structures and processes related to graben and pit crater variability in size and distribution and to determine the effects of regional stresses on the development of groups of fracture systems. Our approach was to apply a 3-D boundary element code [4] to test which types of structures (i.e. normal faults, tensile cracks or dikes) beneath graben systems best fit the surface topography from the MOLA DEM by matching the elastic solution in half space.

Data and Modeling: The selected region spans 21.5^o to 24^o latitude and 265.6^o to 288^o longitude, south-east of Alba Patera. The Mars Orbiter Laser Altimeter aboard the Mars Global Surveyor provided 143 MOLA profiles passing through the selected region and 75629 shots in total. It gives range measurements along profile every ~300 m along MGS ground track. The resolution on MOLA groundtrack is 300 m with footprint of each measurement being 168m. Vertical ranging errors are between 0.23m to 10m (for slopes 1-30^o respectively). The MOLA profiles are available as Precision experiment data records (PEDRs) via NASA's Planetary Data System and they are used to generate a 2D gridfile with x-y resolution of 200 pixels/degree (~60km/grid spacing) via a standard GMT process [1]. The reason for choosing this region was the presence of a simple graben whose depth increases, first linearly then exponentially, in the along strike direction (Figure 2). These structures can be explained only by 3D analysis [2]. The DEM can be used for a 3D view of any area to decide the course of modeling to use, however for detailed fitting, the along-strike graben profile is given by the latitude-longitude-depth position of the deepest points in the graben system (assumed to be the graben's strike direction). Similarly, MOLA profiles considered for cross-graben profiles rather than extracting profiles to avoid spurious artifacts. East-west ramp of the area is removed by picking latitudinal profiles and detrending them.

Boundary element method is used to run forward models using POLY3D, which is a C language computer program that calculates displacements, strains and stresses induced in an elastic whole or half space by planar, polygonal-shaped elements of displacement discontinuity. The analysis was initiated using a simple graben modeled by two normal faults dipping toward each other with a dike intrusion at the base [3]. The dike is forced to have a tensile opening (uniform) while linearly increasing the hydrostatic stress at the rate of 8.162 MPa/km with depth. This calculation is done using simple hydrostatic pressure ($g = 3.71 m/s^2$) exerted by the magma chamber over a particular depth. Density of magma varies with depth but using the model from [5] a uniform density of 2200 km/m^3 is adopted. The normal faults have zero stress conditions. Although considerable insight into solution dependence on source parameters was achieved by

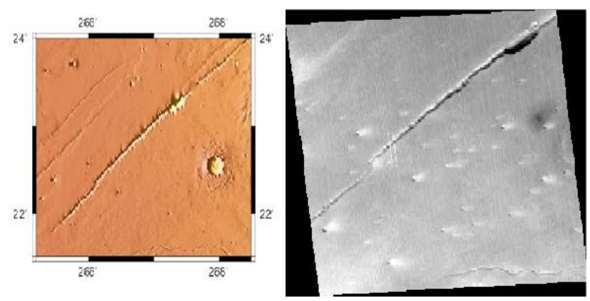

Figure 1: (a) GMT generated DEM and (b) a narrow-angle MOC image of the region of interest. The feature to concentrate upon is the graben with a slight offset at 266.15^{o}E and 22.3^{o}N perpendicular to its strike toward the west, widening and culminating in a large crater toward the east.

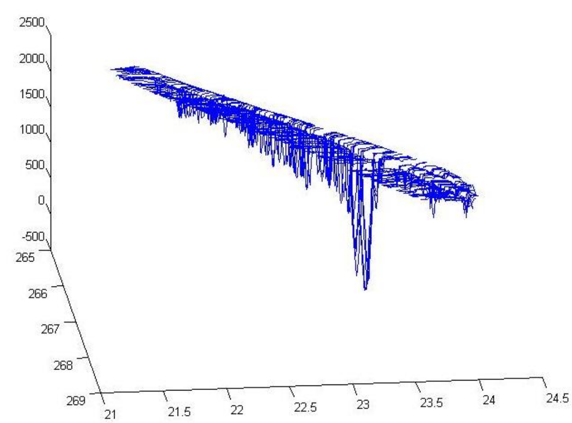

Figure 2: 129 MOLA profiles windowed within two parallel lines to constrain data within the graben system only. The depth profile of the graben via MOLA clearly shows an approximately constant depth for the first 25km-70km of the profile (where 1^o ~ 60km), then a linear increase and finally a culmination in a deep pit crater.

variation of dip, strike, stress conditions, source geometry and distances, none could explain the inherent asymmetry in the topography.

The Plunging Model Solution: The along-strike asymmetry was modeled using a pair of normal faults which dipped toward each other and along plunged along-strike leading to a smoothly plunging graben with a dike intrusion at its base. This system is modeled using trapezoidal elements for the normal faults and the dike as opposed to rectangular elements in the symmetrical case. The geometrical controls for each trapezium are as follows: [1] Strike φ (width of the graben opening), [2] Dip ψ (Steepness of the graben), [3] Trapezium angle θ, [4] Plunge of the normal fault contact P, [5] Length of the trapezium sides L(asymmetry of plunge), [6] Depth at which the graben begins h, [7] Width of the graben W(surface horizontal extent of the feature). Out of the 4 angles, only 2 are independent and the relationship equations are derived as: $\cos(\psi) = \tan(\theta) * \tan(\varphi)$, $\sin(P) = \sin(\psi) * \cos(\theta)$ and $h = L * \sin(\theta) * \sin(\psi)$. Evidently, for any model, utmost 2 of the angles, one among h and L to determine the size of the fault sides and width of the faults (W for horizontal extent) can be specified.

To calculate the strike of the model, the data distribution is used which shows width of the graben to vary from 3km to 6km approximately over a graben length of ~150km i.e. strike ~1 degree. Since such a small value is giving rise to artifacts, strike is approximated to be 2 degrees. The data also shows dip of 70-80 degrees, hence as empirically proven, model dip should be higher, eventually selected as 85 degrees.

Results: The model (strike divergence of normal faults = 2 degrees, dip of faults = 85 degrees, plunge = 25.74 degrees) plunges from left to right and the deepest point is approximately at X=0, Y=150 km as shown in Figure 3. The strike is forced to match the width of the graben varying from 2.5km to 6 km. The vertical displacements caused by the plunging model do deepen but exponential decrease in topography is only possible if, at the deepest point of displacement solution, the tensile extensive stress is high enough to cause a pit crater to form. The tensile component of stress along the graben is calculated by adding the X-components of the 3 principal stresses. A scaled version is plotted as the black curve in Figure 5. The graben is along the Y-axis so the tensile opening will be along X. It is maximum toward the beginning of the

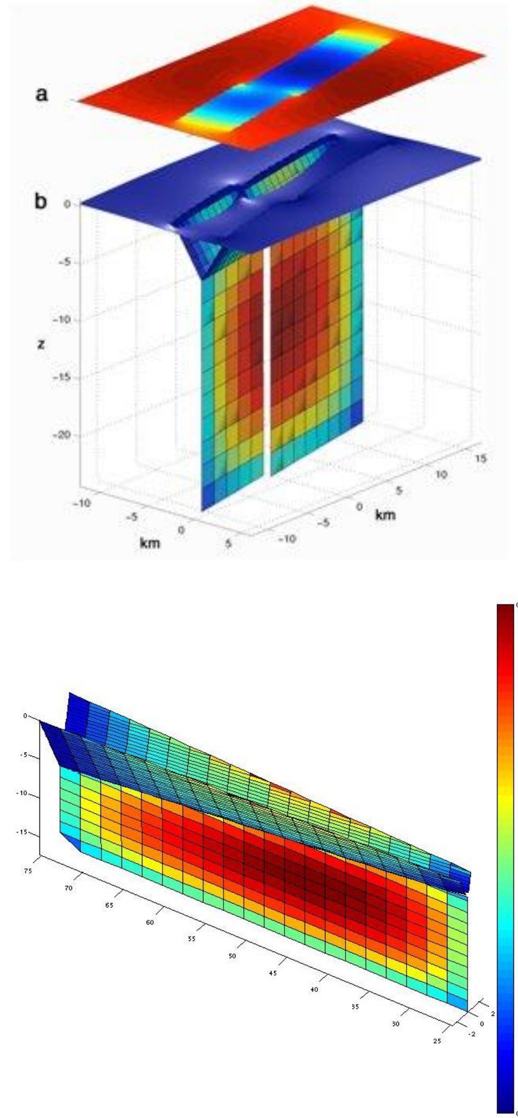

Figure 3: (Top) Example of a Poly3D solution for a dike-graben pair with small offsets between the two graben and dikes. In this case, the nearer dike is 10 km long, and the far dike is 15 km long and this model explains the offset in our data perpendicular to the strike. A unit pressure opens each dike with no ambient (external) stress field. The faults dip at 60°, are free of shear tractions, and remain in contact. (a) Vertical surface displacements. (blue, negative; red positive displacement). (b) Crack relative displacement magnitudes (blue, minimum amount, to red, the maximum amount; for the dikes this is mostly opening, and for the graben mostly downdip slip). (Bottom) The plunging model with parameters specified in text explains the linearly deepening graben.

profile where vertical displacement is maximum, i.e. the point at which the dike is closest to the ground surface. This increase in extensive tensile component due to the plunging model may lead to the formation of a

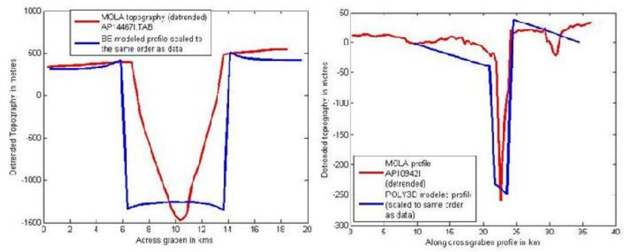

Figure 4: (Left) Comparison of a cross-graben profile of Martian topography data and the plunging model vertical displacement solution. The dike is almost 90 degrees hence the profile is symmetrical. (Right) Cross-graben asymmetry is brought about by modeling the dike dipping at 75 degrees. Cross-strike asymmetry varying along the graben, implies a varying dike dip and offset.

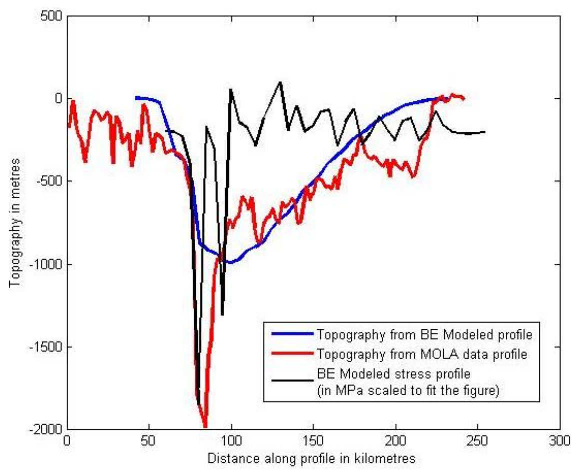

Figure 5: Comparison of a along-graben profile of Martian topography data and the plunging model vertical displacement solution. The model plunges from left to right as shown in Figure 3c it explains the deepening graben while the principal tensile stress (max: -12MPa, scaled to fit figure) calculated along the same profile shows a large increase at the deepest part. This extensive stress could be the cause of the pit crater/hole formation.

large pit crater at the deepening end of the graben, as seen in the data. Further along the strike, the tensile stress component decreases hence the depth of the pit craters decrease. This is clearly seen in the MOC image in Figure 1. Asymmetric across-strike profile is attributed to unequal fault dips and offset magnitudes on either side of the graben as shown in Figure 4.

The offset between the two grabens as seen at 266.15^{o}E and 22.3^{o}N in Figure 1, can be explained by a segmented fault-dike system as shown in Figure 3. The system to the west of the offset does not seem to be a plunging system because the depth of the graben along that segment is uniform (corresponds to the central segment in Figure 2). The system to the east of the offset is proven to be a plunging system from east to west, as described earlier, with varying dike dip and offset to explain the variation in cross-graben asymmetry. As the graben continues eastward, the extensive (negative) stress increases in the cross-graben (along X-axis) direction and beyond a particular point causes pit crater to open up. We see this in the DEM topography as a deepening graben culminating in a very deep pit crater. The formation of this structure relieves the strain considerably and the pit crater chain following along the same strike, decreases in depth toward the east.

The work is initiation to the approach of intertwining Poly3d modeling and data from MOC, THEMIS and MOLA in order to explain the formation of the structures at Alba Patera beginning with a simple candidate site. More such sites when selected and similarly modeled will help suggest a pervasive mechanism for the formation of the Tharsis graben and pit crater chains.

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