PHYSICAL ANALOG MODELING OF MARTIAN DIKE GEOMETRIES AND SUBSURFACE DEFORMATION. D. Y. Wyrick, A. P. Morris, M. K. Todt, Department of Earth, Material, and Planetary Sciences, Southwest Research Institute® (6220 Culebra Rd., San Antonio, TX, 78238-5166, USA; dwyrick@swri.org)

Introduction: The Tharsis region of Mars is characterized by large volcanic and tectonic centers that have been active throughout Martian geologic history. Radial and concentric tectonic patterns correlate with at least five main episodes of activity concentrated around distinctive centers, dominated in the later stages by large volcanic provinces [1]. Many of these tectonic complexes exhibit distinct sets of grabens that extend radially for distances of hundreds to thousands of kilometers [1,2,3,4,5,6]. Formation of these grabens has been attributed to crustal extension [3,7,8] and/or dike propagation [6,9,10].

The dike-induced graben formation hypothesis stems from both numerical [11,12] and analog modeling [13] studies of terrestrial dike intrusion. In contrast to these models, many dike-intrusion models on Mars do not incorporate pre-existing faults and grabens, but rather rely upon dike injection as a graben formation mechanism [9,10,14]. The fundamental assumption of this interpretation is that the internal pressures within a dike cause significant structural deformation in the surrounding host rock, specifically that a vertical dike will allow for a graben to form above the tip of the dike.

In this study, we constructed and analyzed physical analog models of igneous injection as a primary mechanism for the production of grabens on Mars. In particular, our models were designed to explore the extent to which an igneous injection, under varying emplacement conditions, will induce near-subsurface and surface deformation.

Methodology: A series of physical analog models using layered sand and paraffin were constructed to test the magnitude and style of deformation associated with dike injection. Physical analog modeling is a well-established laboratory technique for reproducing the developmental sequence and overall geometry of geologic structures, and is commonly used in the investigation of geologic structures [15,16,17]. These models were specifically designed to study the deformation in the surrounding host rock in response to the injection of a magma. We used dry sand as an analog for Mars' brittle upper crust and liquid paraffin as a magma analog. The dry sand material (Oklahoma #1) deforms by faulting and folding and behaves as a time-independent material at the low strain rates interpreted for crustal processes. The paraffin was kept liquid at 150°F during the injection stage of modeling and solidified within seconds of emplacement. Paraffin wax was used in these experiments as it preserved the three-dimensional structure of both the intrusive body and the surrounding host rock.

Rubber tubing with a 20 cm long slit was secured to the model base by aluminum plates. This configuration was designed to produce a linear injection into the overlying model. Alternating colored, 1 cm thick sand was layered on top of the dike model setup. The total overlying sand thickness ranged from 6-10 cm in the models. This sand pack was then cooled with carbon dioxide (dry ice). Once the sand was cooled throughout, melted paraffin was injected under pressure (15-20 psi) into the rubber tubing. This caused liquid paraffin to inject upward into the overlying sand layers, cooling, and quickly turning solid. The model was then wet to allow for dissection. The model was sliced perpendicular to the dike injection at ~1 cm intervals to determine the style and magnitude of deformation in the sand layers surrounding the paraffin injection. During some models, the paraffin structures were dissected at the same intervals as the sand pack; in others, the sand pack was carefully dissected around the wax dike to preserve its structure intact. All models were photographed during experimentation and dissection to analyze strain patterns.

Results: A variety of dike, sill, and plug geometries were produced during experimentation, similar to previously modeled magmatic intrusions [18,19,20]. The paraffin wax injections preserved detailed morphology of these igneous intrusions. Although the purpose of these models was to discern deformation associated with vertical dikes, the deformation styles associated with other intrusive geometries are presented here to inform future interpretations of surface structure.

Vertical paraffin dikes produced no discernible deformation or offset of sand layers, either ahead of or above the intrusion. Several vertical dikes produced cup formations along their strike. These cups formed near the surface, transporting the sand layers above both vertically and laterally, creating uplift and reverse faulting directly above the cup.

Low angle (~45°) dikes occurred in models of higher overburden. These dikes induced reverse motion on overlying layers, expressed either as reverse faults or folds.

Many of the paraffin dikes in the models produced en echelon branching segments. These branches typically form ~30° rotated from the dike plane (Fig 1). In one model where the horizontal stresses were close in magnitude (i.e., $\sigma_2 \approx \sigma_3$), a fairly symmetrical spiral plug was formed, with branching segments rotated ~30° from the spiraling edge of the plug.

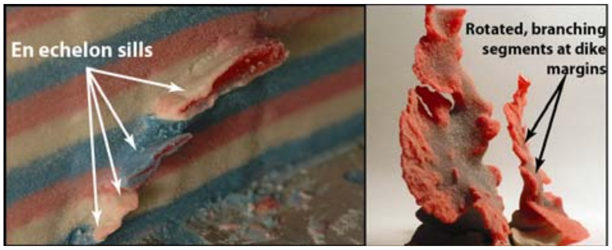

Fig 1. (A) A cross sectional view of en echelon sills reflects the rotated, branching segments of a much larger dike (B).

Plug formation typically occurred in models with more overburden and/or lower injection pressures. Plug formation at the model base led to the translation of overlying material vertically, producing reverse faulting at the plug margins.

A few complex morphologies were formed, such as a plug that developed vertical dikes at its margins. Dissection of this model suggested that reverse faulting developed above the plug first, then feeder dikes at the plug margin created steep anticlines on either side of the intrusion.

Discussion: In our models, surface deformation above and around the paraffin dikes primarily took the form of anticlines, folds and reverse faults (i.e., contractional strain) rather than graben and normal faults (i.e., extensional strain). Vertical paraffin dikes, absent a significant dip or base plug, produced no discernible deformation, either at the surface or in the subsurface. Experiments suggest that for cases of a non-vertical dike, the shallower the dip, the more reverse motion along the fault.

A variety of igneous formations were produced during experimentation, including dikes, sills, cups, and plugs; many with bladed "branches" that form at an angle to the main dike plane. However, in cross section, these branches often appear as separate en echelon sills, rather than the edges of a much larger igneous structure. These results suggest that estimates of stress orientation from en echelon segments may be missing the larger component of the dike, which may have a different orientation than the "en echelon" branches [21]. En echelon sills seen in outcrop may reflect the branching formation of an underlying, non-vertical dike, rather than conditions of sill emplacement.

The Tharsis radial graben systems are characterized by the "simple graben" morphology [3]: long narrow grabens bounded by normal faults, with a down-dropped flat floor unbroken by antithetic faults. Our analog models of dike injection did not produce this type of simple graben morphology. The primary result of our models was surface deformation in the form of compressional forces producing uplift at the surface rather than extension over the dike tip producing subsidence, similar to discrete element models of dike widening [22]. This study suggests that vertical dike intrusion does not produce significant extensional deformation in the near surface. If the dike dip is less than vertical, contractional folding and faulting develop adjacent to and above the dike. Evidence for this type of contractional deformation pattern has not been found in terrestrial field analyses or Martian data to date, which suggests that the Tharsis-radial grabens may not have formed solely in response to magmatic dike intrusion. The dike-induced graben hypothesis has been widely used to interpret underlying dikes and dike swarms and to help understand the volcanic history of the Tharsis region [6,9,23,24]. Understanding of the dynamic interaction between magmatic activity and the structural response of the host rock is crucial for understanding the volcanic and tectonic history of Mars and has implications for astrobiological research at past and present geothermally active sites [25].

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