PHYSICAL ANALOG MODELING OF MARTIAN DIKE-INDUCED DEFORMATION. D. Y. Wyrick, M. J Watson-Morris, and A. P., Morris, 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. Boundary element modeling was used to describe the deformation that would occur above and ahead of a widening vertical dike intrusion on Earth [11,12]. These models assumed slip along preexisting faults and fractures to determine the extent of graben subsidence due to dike intrusion [12].

In contrast, 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]. These models hypothesize that a dike propagating through the subsurface will reach a neutral buoyancy level, at which the dike will cease vertical ascent, but continue to propagate laterally and widen. The fundamental assumption of this interpretation is that the internal pressures within the dike cause significant structural deformation in the host rock surrounding the dike, and specifically that a widening 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 dike injection as a primary mechanism for the production of grabens on Mars. In particular, our models are designed to explore the extent to which a widening subsurface dike under varying emplacement conditions will induce near-surface and surface deformation.

Methodology: 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]. Crustal strata are represented in the models by table-top-scale analog layers such as sand or clay. These analog materials are selected to reproduce, at small scale, the geometric and kinematic features of natural geologic structures. To simulate development of geologic structures, the analog layers are deformed in a manner consistent with our understanding of tectonic models suggested by the observable geology.

Physical analog models using layered sand and paraffin were constructed to test the magnitude and style of deformation association with dike injection. These models were specifically designed to study the deformation in the surrounding host rock in response to the injection of a dike. We used dry sand as an analog for Mars' brittle upper crust. This material deforms by faulting and behaves as a time-independent material at the low strain rates interpreted for crustal processes. The dry sand used in the experiments is commercially designated as Oklahoma #1, which is a common constituent in ceramics. Faults and fractures produced in these analog materials are geometrically and kinematically similar to those observed in terrestrial fault systems [16,17].

Rubber tubing with 1 cm long slits cut at 1 cm intervals (45 cm in total length) was secured to the model base by aluminum plates. Alternating colored, 1 cm thick sand was layered on top of the dike model setup. The total overlying sand thickness was 6 cm. This sand pack was then cooled with carbon dioxide (dry ice). Once the sand was cooled throughout, melted paraffin was injected under pressure 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 ~1cm intervals to determine the style and magnitude of deformation in the sand layeres surrounding the paraffin injection. Three main feeder dikes were noted in the model, two remained in the subsurface while one erupted onto the model surface. Paraffin dike geometries were similar to previously modeled magmatic intrusions [18,19,20].

Results: Previous numerical modeling efforts have examined the role of a widening subsurface dike in the absence of regional extension and under various configurations of mechanical layered stratigraphy [21]. The results from [21] suggested that deformation was accomodated primarily by contractional fold development. The results of these new physical analog models indicate that injection of liquid paraffin into layered sand will produce primarily contractional features, consistent with numerical results.

The first appearance of a reverse fault occurred ~1 cm ahead of the leading edge of the rising dike. Immediately above the leading edge of the dike, a topographic high formed. The deformed subsurface layers indicate the development of an anticline. Further along the dike, reverse faults developed nearly to the surface and became slightly asymmetrical as the dike became more cup-like in geometry along strike (Fig. 1). The main paraffin dike developed two distinct smaller vertical dikes at the margins that produced anticlines above the dike tips. The upper most layers developed folds above the width of the dike. The folds translated to the surface as symmetrical topographic highs on the sides of the dikes with lower topography above the dike tip. It should be noted, however, that the elevation above the dike tip did not drop below the regional surface layer.

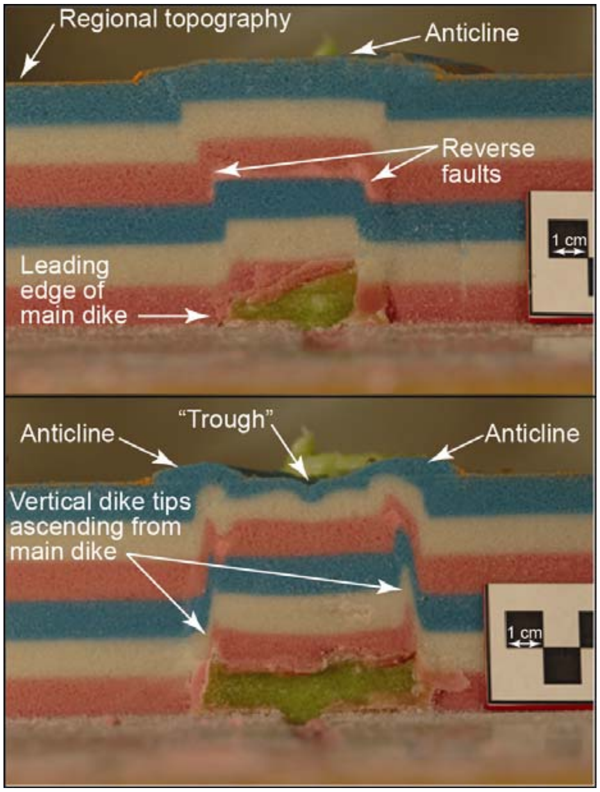

Figure 1. Model slices perpendicular to dike strike. Directly above the leading edge of the dike, reverse faults have developed. As the dike propagates to the surface, folds develop above the tip.

Implications: In our models, surface deformation above and around the paraffin dike took the form of an anticline rather than a graben. Formation of the "trough" was accomplished primarily through compression adjacent to the dike, causing contractional fold development at the surface. The model evolution indicates that the primary deformation style is via trough margin uplift rather than trough center subsidence, and that the most distinctive topographic signature of an underlying dike would be parallel ridges formed by contractional folding on either side of the trough. Variations in dike geometry do not appear to affect the overall style of deformation, but do influence the magnitude and location of deformation.

The Tharsis radial graben systems are characterized by the "simple graben" morphology [7]: 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. The signature style of dike-induced deformation in this study is contractional folding adjacent and above a 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 [6,9,22,23]. Understanding of the dynamic interaction between volcanic activity and the structural response of adjacent and cogenetic faults and fractures is crucial for understanding the volcanic and tectonic history of Mars and has implications for astrobiological research at past and present geothermally active sites [24].

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