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Dike-induced deformation and Martian graben systems

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ABSTRACT

The Tharsis region of Mars is characterized by large volcanic and tectonic centers with distinct sets of graben systems. Many of the radially oriented grabens have been inferred to form in response to intrusion of magmatic dikes. This interpretation is based primarily upon early physical and numerical (boundary element) models that were developed originally to understand surface deformation associated with dike emplacement on Earth. In this study, we constructed and analyzed two-dimensional discrete element models to test the hypothesis of shallow dike emplacement and widening 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—in the absence of regional extension or pre-existing faults—will induce near-surface graben formation. The use of discrete element models allows for the permanent deformation and material heterogeneity to be captured as opposed to boundary element models that are limited by an assumption of homogeneous elastic behavior. Our analyses consider both homogeneous materials as well as mechanical stratification. The results indicate that forcible widening of a dike alone is unlikely to produce grabens at the surface. Furthermore, estimates of subsurface dike widths and emplacement depths based solely on measurements of surface graben widths may significantly over- or underestimate actual parameters. Finally, the model results suggest that the ability to distinguish between fault-induced or dike-induced graben formation mechanisms may not be possible unless the subsurface mechanical stratigraphy can be well characterized.

1. 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 (Anderson et al., 2001). Many of these tectonic complexes exhibit distinct sets of grabens that extend radially for distances of hundreds to thousands of kilometers (Carr, 1974; Plescia and Saunders, 1982; Scott and Tanaka, 1986; Tanaka et al., 1991; Mège and Masson, 1996a, b; Anderson et al., 2001) (Fig. 1). Formation of these grabens has been attributed to crustal extension (Plescia and Saunders, 1982; Banerdt et al., 1992; Phillips et al., 2001) and/or dike propagation (Mège and Masson, 1996b; Wilson and Head, 2002; Scott et al., 2002). 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 (Mège and Masson, 1996b; Ernst et al., 2001; Wilson and Head, 2002; Mège et al., 2003; Schultz et al., 2004). Understanding of the dynamic interaction between volcanic activity and the structural response of adjacent and cogenetic faults and fractures is crucial to determining the evolution of the volcanic and tectonic history of Mars (e.g., Cailleau et al., 2003) and has implications for potential astrobiological research sites at past and present geothermally active regions (Schulze-Makuch et al., 2005).

The dike-induced graben formation hypothesis stems from numerical modeling by Rubin and Pollard (1988) and Rubin (1992) and analog modeling by Mastin and Pollard (1988) (Fig. 2). Rubin and Pollard (1988) and Rubin (1992) used boundary element modeling to describe the deformation that would occur above and ahead of a widening vertical dike intrusion on Earth. These models assumed slip along preexisting faults and fractures to determine the extent of graben subsidence due to dike intrusion during the 1977 Krafla, Iceland, eruption and help quantify the relationship between dike dimension and surface deformation (Rubin, 1992; Rubin et al., 1998).

In contrast, dike-intrusion models on Mars do not incorporate pre-existing faults and grabens and rely upon dike injection as a graben formation mechanism (Wilson and Head, 2002; Scott et al., 2002; Head et al., 2003). 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

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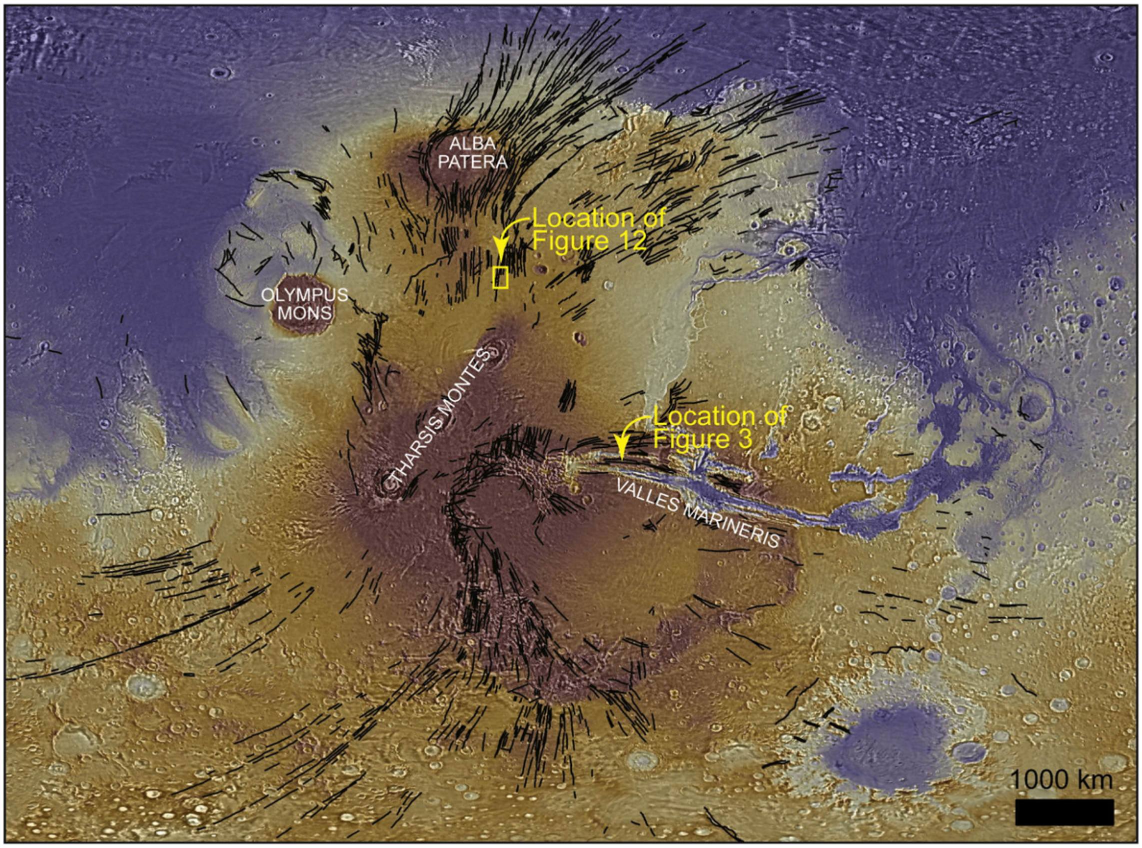

Fig. 1. Regional map of Tharsis with some of the major radial graben systems (fossae) shown in black (Skinner et al., 2006). Viking MDIM2.1 overlain with MOLA topography with reds representing high regions and blues representing low regions.

this interpretation is that internal pressure within the dike causes 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. For the purposes of this discussion, the terms graben and trough (which are often used interchangeably in the planetary literature) must be defined. In this paper, we define a graben as a down-dropped block bounded by a set of normal faults that is lower relative to the surrounding topography. We define a trough as a depression relative to the adjacent topography, i.e. the margins of a trough may be topographically higher than the regional elevation, with a central depression.

Mastin and Pollard (1988) constructed physical analog models to provide geomorphic details of small-scale deformation features associated with a widening subsurface dike (e.g., fractures along topographic highs, small thrust faults within the graben) that are not captured by boundary element modeling. Topographic variations in the analog models were noted and ascribed to dike-induced surface deformation. Important advances in our understanding of dike-induced deformation have been made using topographic data and boundary element modeling (Schultz et al., 2004; Goudy and Schultz, 2004; Okubo and Schultz, 2005a,b). Analysis of Martian graben morphology using Mars Orbiter Laser Altimeter (MOLA) topography data has been performed on selected grabens with variations along trend inferred to be the result of either dike-induced or fault-induced deformation (Schultz et al., 2004; Goudy and Schultz, 2004; Okubo and Schultz, 2005a,b), and these results have been supported by boundary element models to further distinguish between dike-induced and fault-induced morphologies on Mars (Goudy and Schultz, 2004; Schultz et al., 2004; Okubo and Schultz, 2005a,b). In these models, the flanks of simulated grabens show characteristic slopes, concave down for dike-induced grabens versus concave up for fault-induced grabens, which may indicate the presence or absence of subsurface dikes from topographic surface expression alone (Schultz et al., 2004; Okubo and Schultz, 2005a).

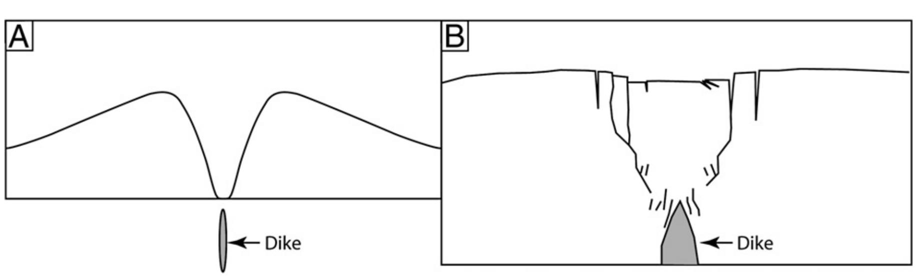

Fig. 2. Schematic illustrations of (A) surface deformation predicted above a subsurface dike modeled by the boundary element method (modified from Rubin and Pollard, 1988) and (B) surface and subsurface deformation from physical analog models (modified from Mastin and Pollard, 1988).