Dike intrusions beneath grabens south of Arsia Mons, Mars

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[1] The existence of igneous dikes beneath grabens in Tharsis remains contentious due to conflicting observations of Martian geomorphology. We examine the topographic signatures of a Tharsis-radial graben array in 3 zones south of Arsia Mons. We identify dikes beneath grabens in all of the zones, with fewer dike-induced grabens closer to Arsia Mons. We infer that a single radial swarm of dikes outside the magmatic source area, central Tharsis, is unlikely. Our observations instead favor a long and varied magmatic history throughout Tharsis with several episodes of dike injection. **Citation:** Goudy, C. L., and R. A. Schultz (2005), Dike intrusions beneath grabens south of Arsia Mons, Mars, *Geophys. Res. Lett.*, *32*, L05201, doi:10.1029/2004GL021977.

1. Introduction

[2] A number of graben arrays that extend several thousands of kilometers away from Tharsis and distally cross-cut Noachian and Hesperian age highland units, but form contemporaneous or subsequent to Hesperian and Amazonian units close to Tharsis (Figure 1) [*Tanaka et al.*, 1992], have been suggested to result from a radiating dike swarm [*Wilson and Head*, 2002; *Mège et al.*, 2003]. Several observable characteristics, such as morphology, peak spacing, and vertical displacement, support graben formation by subsurface dike emplacement [*Tanaka and Golombek*, 1989; *Tanaka et al.*, 1991; *Mège and Masson*, 1996; *Schultz et al.*, 2004]. *Rubin* [1992] demonstrated the relationship between displacements on boundary faults with dike emplacement at depth by building on models that matched data from the Krafla rift zone in Iceland [*Rubin and Pollard*, 1988], as well as field and experimental data from *Mastin and Pollard* [1988]. In addition to documenting fault slip preceding a laterally propagating dike intrusion at depth, it was clearly demonstrated that grabens resulting primarily from a dike-controlled process have a characteristically unique topographic profile which differs from that of grabens resulting from the combined process of dike intrusion and faulting (Figure 2): a fault-controlled process produces a profile where two peaks are concave-up, and a volcanically-controlled profile has two peaks that are concave-down, with a much smaller uplift [*Rubin and Pollard*, 1988; *Rubin*, 1992].

[3] The Mars Orbiter Laser Altimeter (MOLA) profiles in the Tharsis region reveal both dike-controlled and fault-controlled graben formation [*Schultz et al.*, 2004]. *Schultz et al.* [2004] first identified the topographic signature characteristic of Martian grabens that are underlain by a dike. Our paper is motivated by, and follows the approach of *Schultz et al.* [2004] and *Rubin* [1992] in that topographic profiles are used to determine if grabens south of Arsia Mons in the regions of Icaria, Memnonia, Sirenum, and Thaumasia Fossae are underlain by dikes several thousands of kilometers away from the volcanic source area. We demonstrate that a single radial dike swarm is insufficient to explain the observations, and suggest an evolution sequence with at least three stages of deformation.

2. Method

[4] Grabens are located (Figure 3) in three zones south of Arsia Mons using digital elevation models (DEMs) constructed from MOLA profiles [*Okubo et al.*, 2004]. The MOLA Precision Experiment Data Record (PEDR), with a relative vertical precision of better than 1 m, is used to extract 224 orbital profiles [*Smith et al.*, 2003] over "narrow grabens" showing little sign of erosion for analysis based on the topographic morphology observed in the DEMs. The term "narrow grabens", as used herein, refers to linear, straight-walled depressions [*Golombek*, 1979], characterized by normal faults with throws up to hundreds of meters and dipping toward the center, and by a flat floor [*Wilson and Head*, 2002]. These grabens are long (tens to thousands of kilometers) and narrow (2–5 km wide) [*Mège et al.*, 2003]. Graben lengths are up to three orders of magnitude larger than their widths; however, due to their segmented echelon geometry (Figure 1), the grabens maintain a depth much smaller than 1 km, and therefore the displacement to length ratios are much smaller than might be expected if the total length is used to calculate the ratio instead of the more correct segment lengths [*Schultz*, 1997].

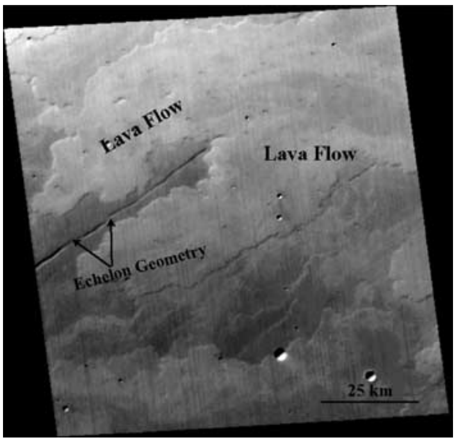

Figure 1. Typical graben south of Arsia Mons shown with echelon geometry. Many grabens in this area are interpreted as being covered by lava flows (M. C. Malin et al., wide angle FHA-00824, Malin Space Science Systems Mars Orbiter Camera Image Gallery, http://www.msss.com/moc_gallery/, 22 May 2000).

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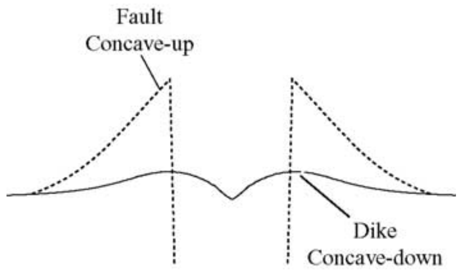

Figure 2. Characteristic concave-up surface topographic profile produced by two normal faults, and concave-down topographic profile produced by a dike intrusion.

[5] The PEDR tracks intersect each graben roughly at right angles to best characterize cross-strike topography. The slightly northeasterly regional slope (0.04° to 0.08°) is removed from each PEDR track by the use of trigonometric reduction of along-track elevation values. The PEDR profiles are analyzed based on morphology, i.e., concavity and dimensions. We differentiate between fault-controlled and dike-controlled topographic uplift, concave-up and concave-down, respectively, in the profiles, following *Schultz et al.* [2004]. Dikes that extend to depths of 20 or 30 kilometers produce tens of meters of topographic displacement; smaller dikes produce less vertical displacement. The width of a graben produced by a dike is on the order of a kilometer [*Schultz et al.*, 2004], and so where the vertical uplift is greater than tens of meters and/or the profile is concave-up, fault-controlled topography is inferred. Dike-controlled graben formation is interpreted based on a profile that shows small vertical uplift (a meter to tens of meters) and a profile that is concave down. Where the profile shows a vertical uplift greater than tens of meters but is concave down, a combined fault-controlled and dike-controlled mechanism is inferred, where a dike intrudes beneath an existing graben and fault slip occurs along normal faults in front of the dike due to emplacement [*Mastin and Pollard*, 1988; *Rubin*, 1992]. For each of the three zones south of Arsia Mons the topographic profiles are separated based on their concavity, i.e., dike-controlled versus fault-controlled graben formation.

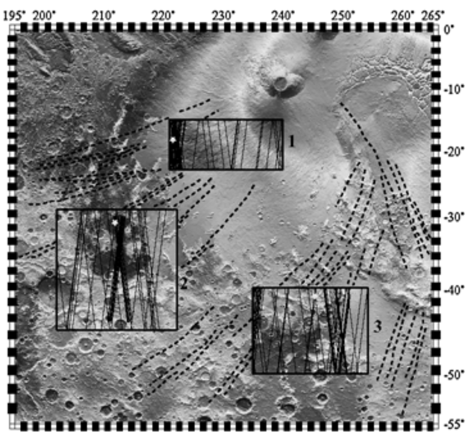

Figure 3. Three zones south of Arsia Mons used to locate grabens which were analyzed using 224 PEDR orbital tracks, shown with black lines. Yellow stars in each of the zones show the approximate locations of the PEDR profiles used in Figures 4, to 6. Dashed lines show the approximate orientations of grabens. See color version of this figure in the HTML.

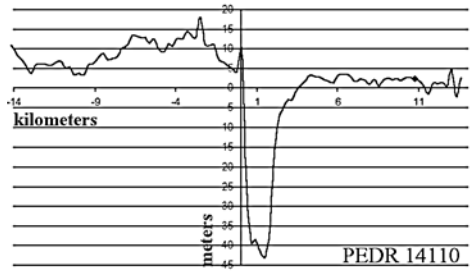

Figure 4. Based on the large vertical displacement and the concave-down profile, this PEDR profile, taken in Zone 1 south of Arsia Mons, is interpreted to show a volcanic vent.

3. Results and Discussion

[6] Profiles analyzed from Zone 1, on the south flank of Arsia Mons (Figure 3), have morphologies that are interpreted as volcanic vents (Figure 4). Other volcanic landforms, such as collapse pits, small shield volcanoes, sinuous rilles, and lava flow complexes have been identified on this part of Arsia Mons in previous studies using MOC and THEMIS images, in addition to MOLA data [e.g., *Mouginis-Mark*, 2003]. These features have been interpreted as being associated with a volcanic rift zone in the NE-SW direction [e.g., *Crumpler and Aubele*, 1978; *Montési*, 1999]. In the 51 PEDR orbital tracks analyzed in Zone 1, only 4 grabens were found, and we interpreted all of them to be underlain by dikes, due to the concave-down profiles. Observations from the DEM and MOC images show that lava flows dominate the area, and these flows cover many grabens that would otherwise be observed (Figure 1).

[7] In Zones 2 and 3 the majority of the PEDR orbital track profiles analyzed show grabens having fault-controlled topography. However, 41% of the profiles observed in Zone 2 and 44% of the profiles observed in Zone 3 have a dike-controlled topography (Figure 5). Many of the profiles show that the cross-strike topographic profile of a graben differs from one side to the other, i.e., one side is concave-up and the other side is concave-down (Figure 6). This asymmetric profile is attributed to unequal fault dips and offset magnitudes on either side of the graben [e.g., *Rubin*, 1992; *Schultz et al.*, 2004]. These observations show that in Zones 2 and 3, which are thousands of kilometers away from the implied source area, as defined by *Mège and Masson* [1996], dikes exist beneath at least some grabens.

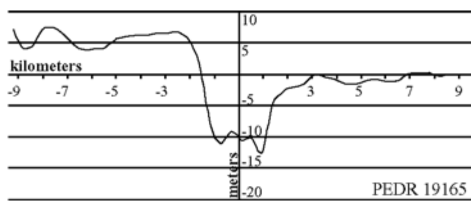

Figure 5. Zones 2 and 3, south of Arsia Mons, showing a typical PEDR profile of a dike-controlled graben.

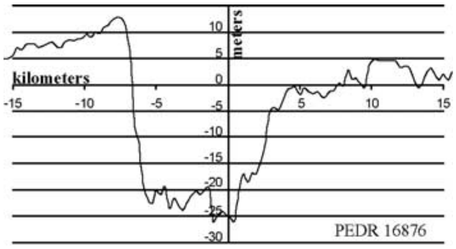

Figure 6. Cross-strike topographic profile in Zone 3 of a typical asymmetric graben consistent with 2 faults with unequal throws.

[8] Radiating dike swarms are thought to be associated with a systematic, monotonic transition with increasing distance from the source, from grabens closest to the source, to two parallel joint arrays at intermediate distances and finally to small cracks [*Mastin and Pollard*, 1988; *Ernst et al.*, 1995, 2001]. Our results do not support this simple progression from dike-controlled to fault-controlled topographic profiles with increasing distance from the center of Tharsis. *Ernst et al.* [2001] analyzed 163 fracture systems using criteria for radiating dike swarms on Venus, including the monotonic transition with distance from the magma source, and found 118 are clearly consistent with formation by dike emplacement, while the remaining 45 fracture systems result from purely tectonic uplift or a combination of more than one event. Our results indicate dike emplacement is a formational mechanism of at least some of the grabens south of Arsia Mons, but more than one dike injection episode is needed to explain the observations.

[9] We infer that a single formational event producing a dike swarm, radiating from a single magma source in central Tharsis, is insufficient to explain the observations. Graben formation occurred from the Noachian through the Amazonian [*Scott and Tanaka*, 1986; *Tanaka et al.*, 1992]. Our observations are consistent with models of long-lived volcanism in Tharsis [*Kiefer*, 2003] which had overlapping episodes of dike-controlled and fault-controlled graben growth in this part of Tharsis.

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