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Dike indicators in the Hadriaca Patera–Promethei Terra region, Mars

Jarmo Korteniemi [a,b,*], Jouko Raitala [a,1], Marko Aittola [a,1], Mikhail A. Ivanov [c], Veli-Petri Kostama [a,1], Teemu Öhman [a,d,1], Harald Hiesinger [b]

[a] Division of Astronomy, Department of Physical Sciences, P.O. Box 3000, FI-90014 University of Oulu, Finland
[b] Institut für Planetologie, Westfälische Wilhelms-Universität, Wilhelm-Klemm-Strasse 10, D-48149 Münster, Germany
[c] Laboratory of Comparative Planetology, Vernadsky Institute of Geochemistry and Analytical Chemistry, RAS, Moscow, Russia
[d] Department of Geosciences, P.O. Box 3000, FI-90014 University of Oulu, Finland

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ABSTRACT

The eastern Hellas basin rim has been highly modified by a multitude of both volcanic and fluvial processes. It is covered by a large part of the Circum-Hellas Volcanic Province, consisting of the volcanic plains of Hesperia Planum and western Promethei Terra, as well as the two central volcanoes Hadriaca and Tyrrhena Patera and their associated lava flows. Large outflow channels of Dao, Niger, Harmakhis, Reull and Teviot Valles dissect the wrinkle ridged plains, postdating the major volcanic events. The origin of these outflow channels is still ambiguous, as the mobilization mechanism for the underground volatile reservoirs has yet to be revealed. Due to the proximity of the volcanic structures, many previous studies have suggested via models that the released ice or ground water was mobilized due to endogenic heating from magmatic activity in the region. To find evidence of this, we conducted a systematic search for any magmatic intrusions at 50 m/pixel resolution. This paper provides detailed mapping of several areas where we found features which we interpret to be dikes, and shows the overall distribution of such structures in the eastern Hellas rim region. The Hadriaca Patera volcano flanks exhibit a concentric pattern of linear ridges and fractures, indicative of a vast ring dike system. The dikes occupy mostly the area near the summit and the Hellas-facing flank, extending there for over 400 km away from the caldera. A Hadriaca-radial dike swarm pattern is observed extending southwards from the volcano, composed of isolated parallel linear ridge group outcrops and cut by the Valles canyons. An additional isolated dike ridge group exists south of lower Reull Valles, possibly controlled by the Tyrrhena Patera volcano some 1300 km away. All dikes within the study region are roughly Late Hesperian in age, either predating the Valles formation or being roughly concurrent with them. In total, 500 dike segments were identified, with a combined length of ~2500 km. Since ~90% of the dikes are ridges, they suggest that the entire region has undergone large-scale erosion of at least a few tens of meters to expose the dikes. The dike orientations were most probably controlled by the volcanic centers and possibly partly by a Hellas-concentric fracture pattern.

1. Introduction

Large Martian volcanic provinces, such as Tharsis (including Alba Patera) and Elysium, are surrounded by vast graben networks. Some of them are concentric to the regional volcanic centers while some radiate outwards extending up to thousands of kilometers away. These graben patterns have been extensively studied and many have been suggested and subsequently proven to be caused by intruding magmatic dikes (Tharsis: e.g. Carr, 1974; Mège and Masson, 1996; Wilson and Head, 2002, 2004; Mège et al., 2003; Gowdy and Schultz, 2005; Leask et al., 2007; Alba Patera: e.g. Scott and Wilson, 2002; Scott et al., 2002; Cailleau et al., 2005; Elysium Montes: e.g. Head et al., 2003; Russell and Head, 2003; Wilson and Mouginis-Mark, 2003b; Pedersen et al., 2010-this issue). Some nearby regions exhibit additional pit chains or apparent volcanic edifices resulting from dike-induced phreatomagmatic explosions (e.g. Wilson and Mouginis-Mark, 2003a; Mouginis-Mark and Christensen, 2005). Most of the above-mentioned studies interpret all these features as manifestations of giant dikes or dike swarms, which have been shown to exist on all major terrestrial planets (cf. review by Ernst et al., 2001). However, all these regions are relatively young and/or very long-lived volcanic centers, and only a few studies have tackled the question whether significant magmatic intrusions are observable in the older regions on Mars. Dikes in the southern highlands have been speculated to exist on the grounds of magnetic anomalies (Hood et al., 2007), and through analysis of the impact crater floors in the Hellas region (Korteniemi et al., 2005, 2006). A global survey and classification of ridges (Chicarro et al., 1985) indicated that many of the rectilinear

* Corresponding author. Address (until August 8th 2009): Lunar and Planetary Institute, 3600 Bay Area Boulevard, Houston, 77058 TX, USA. Tel.: +1 281 486 2100; (starting August 10th 2009): Division of Astronomy, Department of Physical Sciences, P.O. Box 3000, FI-90014 University of Oulu, Finland. Tel.: +358 8 553 1942; fax: +358 8 553 1934.
E-mail address: jarmo.korteniemi@oulu.fi (J. Korteniemi).
[1] Fax: +358 8 553 1934.

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ridge patterns in the eastern hemisphere may be dikes and are probably controlled by the Hellas basin. However, only one major magmatic dike system has been positively identified in the highlands, north of the Hellas basin (Head et al., 2006). Many scholars have nevertheless hinted towards specific magma–ground ice interactions occurring on the eastern Hellas basin rim in order to account for its extensive erosion and the mobilization of subsurface volatiles during the various stages of its evolution (Squyres et al., 1987; Crown et al., 1992; Leonard and Tanaka, 2001; Tanaka et al., 2002; Ivanov et al., 2005; Kostama et al., 2010-this issue). The neighboring vast plains of Hesperia Planum have been hypothesized to originate from fissure-fed eruptions (e.g. Scott and Carr, 1978; Greeley and Guest, 1987; Leonard and Tanaka, 2001; Ivanov et al., 2005)—even though no dikes or lava flows not related to the Tyrrhena Patera volcano have so far been found in the entire region, as pointed out by Gregg and Crown (2005) and Gregg (2008). Thus, positively identifying magmatic intrusions such as dikes in the (north)-eastern Hellas region would help to understand the extent and nature of the association between magmatic activity and the surface features we see today.

Our aim in this study is to systematically search the eastern Hellas rim region for any signs of magmatic dikes and to analyze their characteristics. Another goal is, if dikes or dike swarms do exist, to resolve what controls their distribution and orientation. This may help our understanding of the interaction of volcanism and fluvial activity in the region and will shed light on the regional geology. Our study area, spanning roughly 700 by 1200 km (25–45°S, 87.5–102.5°E, Fig. 1), covers much of the northern part of the Circum-Hellas Volcanic Province (CHVP: Williams et al., 2009, 2010-this issue), including Hadriaca Patera, the vast plains of both the Hesperia Planum–Hellas trough (Ivanov et al., 2005) and western Promethei Terra (Ivanov et al., 2010), the adjacent heads of Dao, Niger, Harmakhis and Teviot Valles, as well as several occurences of Noachian highland terrain.

1.1. Dike formation and identification

Dikes are more or less vertical intrusions into either massive or layered rock strata, with one lateral dimension being much larger than the other one. Terrestrial dike swarms typically aggregate 5–20% of the volume within the region they intrude (Walker, 1964; Crisp, 1984). In their purest form they do not penetrate to the surface and form vents, and thus many dikes in non-modified areas cannot be directly observed from remote sensing images. Thus we have to search for morphological surface manifestations of dikes (see also Mège, 1999). These can be categorized into six general types (Fig. 2): a) linear/en-echelon fractures or b) shallow graben on the surface above the dike result from the extensive pressure and tensile stress the magmatic dike body has exerted on the rock it intruded (e.g. Wilson and Head, 2002). c) Pit chains or maars are caused by dikes puncturing into a near-surface volatile-rich layer resulting in phreatomagmatic explosions (e.g. Wilson and Head, 1994, 2002). d) Fissure eruptions occur when a dike penetrates the surface; these appear as singular or lines of several small volcano-like features, spatter cones, diffuse halos with albedos different from the surroundings resulting from pyroclastic materials, and fissure-associated lava flows. e) Linear ridges are outcrops of the resistant dike body itself, exhumed by the erosion of the surrounding strata (e.g. Basilevsky et al., 2006; Head et al., 2006). f) If the stratum containing a dike is cross-cut and eroded by e.g. a fluvial channel, the dike will show up as a near-vertical lineation on the channel wall, providing a cross-section of the dike body. Each laterally continuous part (types a–e) is henceforth called a dike segment. These are usually solitary, but in some cases two or more segments are directly connected to each other: e.g. a linear fracture may continue as a linear ridge due to partial removal of the surrounding stratum and exhumation of the fracture-inducing resistant dike body. All the dike-indicative features are typically linear or slightly curvilinear over long distances, and they most often occur parallel to each other either in swarms of such segments or along the same line of strike. In the latter case several segments separated by spans of terrain follow each other in an obvious chain, forming what we interpret as a single, traceable dike. Furthermore, a good indication of a dike swarm is a radial pattern of segments, often roughly fan-shaped and focused on a volcanic center (Ernst et al., 2001), or a concentric system of segments on/around the volcano (e.g. Chadwick and Howard, 1991). If they are exhumed as resistant ridge outcrops, dikes tend to be among the oldest structures in the region, excluding the surrounding strata they intrude. Dikes can also be among the youngest features if they are still in the subsurface and form grabens, or reach the surface to form vents. These stratigraphic relationships, however, must be verified at each locality to clarify the distinction between the dikes in question and the host rock they intrude, as well as the youngest/overlapping units.

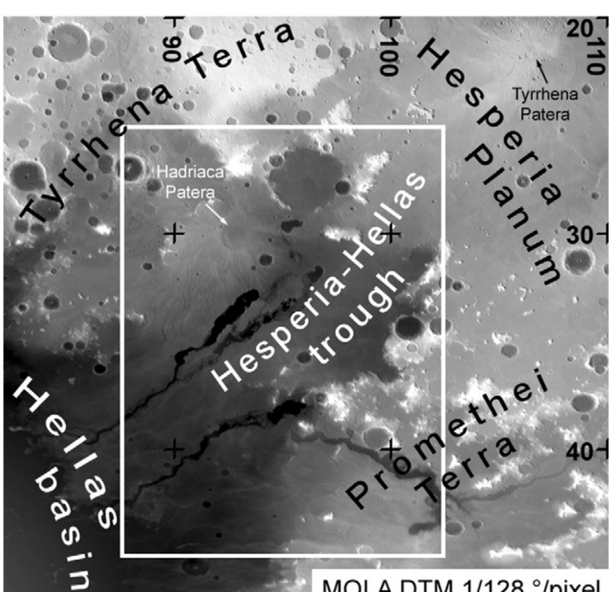

Fig. 1. The study area (white rectangle, see Fig. 3) shown in regional context on a greyscale topography map (black = low, white = high elevation). The names of the main features discussed in the text are also given (the Hesperia-Hellas trough is adopted from Ivanov et al. (2005)).

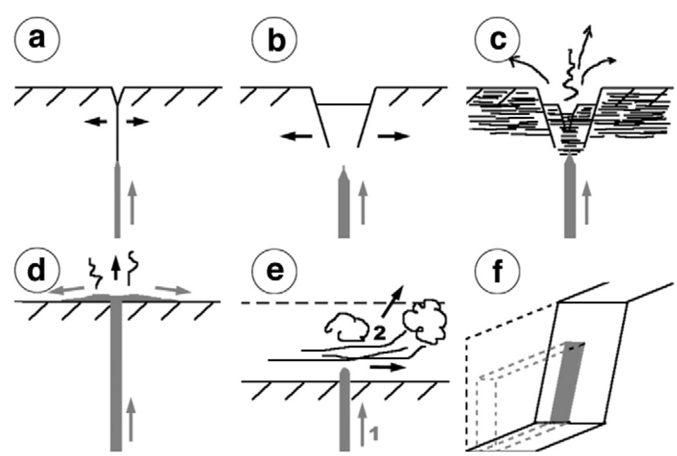

Fig. 2. Profile sketches of surface manifestations of dikes: (a) fracture, (b) shallow graben, (c) pit chain, (d) fissure vent, (e) eroded surface with remnant ridge with numbers indicating sequence of events, (f) partly eroded surface with a lineation on the wall. Dikes and other magmatic materials are shown in grey, dashed lines represent original surfaces of now-removed materials, horizontal layering in (c) corresponds to volatile-bearing materials, and arrows show material movement directions.