The Huygens-Hellas giant dike system on Mars: Implications for Late Noachian–Early Hesperian volcanic resurfacing and climatic evolution

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ABSTRACT

Two narrow, broadly arcuate, low ridges extend for 600–700 km in western Terra Tyrrhena, Mars, crosscut ancient Noachian terrain, and are associated with Early Hesperian plains, which cover ~30% of Mars. Geological relationships suggest that the ridges represent near-surface erosional remnants of subsurface dikes, solidified magma-filled cracks that were responsible for the volcanic emplacement of the plains. Ridge width and geometry are consistent with very high-effusion-rate flood basalt eruptions, emplacement events that would form smooth featureless plains and input significant volcanic gas into the atmosphere. Geological relationships suggest that the ridges were exposed by erosion (fluvial, sublimation, eolian) and partial removal of a regional volatile-rich dust layer.

Keywords: dike, Noachian, Hesperian, magma, Mars, eruptions.

INTRODUCTION

The melting of planetary interiors; segregation of melt products; ascent, intrusion, and eruption of magma; and outgassing to the atmosphere are among the most fundamental processes in the thermal and geological evolution of terrestrial planets. Commonly, much of the record of these processes remains in the subsurface, and deconvolution relies heavily on interpretation of surface deposits and exposures. Dike systems (solidified magma-filled cracks propagated from the source regions toward the surface) represent one of the key elements of the shallow subsurface manifestation of these processes, but are rarely exposed on planets with little differential uplift and erosion, such as the Moon, Mars, Mercury, and Venus. On Mars, the presence of linear volcanic vents, narrow graben (the surface manifestation of near-surface dike intrusion) (Wilson and Head, 2002a), and narrow linear ridges (the erosional remnants of near-surface dike systems) (Shean et al., 2005) represent the best evidence for the nature and distribution of dike systems. We report here on the discovery and documentation of a laterally and areally extensive set of narrow ridges that are interpreted to be the near-surface manifestation of a major dike system emplaced in the Late Noachian–Early Hesperian period of Mars history (~3.6–3.8 billion years ago; see GSA Data Repository[1]) and associated with one of the most widespread magmatic and volcanic events in the history of Mars.

HESPERIAN RIDGED PLAINS AND THE HUYGENS–NORTHERN HELLAS REGION

The nature and interpretation of the Hesperian ridged plains are best exemplified by the description of geological units for the global 1:15,000,000-scale geological maps of Mars (Scott and Tanaka, 1986; Greeley and Guest, 1987; Data Repository [see footnote 1]): The Hesperian ridged plains are described as ‘‘broad planar surfaces, rare lobate deposits, and long, parallel linear to sinuous mare-type (wrinkle) ridges.. . . Forms plains within and outside craters throughout plateau area and lowland plains.. . .’’, and interpreted as ‘‘Extensive lava flows erupted with low effective viscosity from many sources at high rates . . . ’’. The paucity of distinctive flow fronts that might confirm a volcanic origin, and the indirectness of secondary evidence to support a volcanic origin (such as the presence of wrinkle ridges), have led to some uncertainty in the origin of the Hesperian ridged plains (e.g., Gregg and Crown, 2005). Furthermore, in regions where volcanic edifices are observed (e.g., Hesperia Planum) there is evidence for pyroclastic activity, rather than effusive volcanic activity, playing a major role (e.g., Greeley and Crown, 1990). Because of their global distribution and significance in the history of Mars, we have undertaken a regional and global assessment of the Hesperian ridged plains as a means to assess evidence for the thermal, volcanological, and climatic evolution of early Mars (e.g., Head et al., 2002; Hiesinger and Head, 2004). In the course of examination of exposures of the Hesperian ridged plains in the area north and east of Huygens Crater, a 495-km-diameter impact crater on the northwest rim of the Hellas basin (Fig. 1), we discovered a series of linear ridges associated with Hesperian ridged plains. We used recent Mars mission data (see Data Repository) to trace the surface exposure of these ridges and characterize their nature and relationship to other units.

NATURE AND DISTRIBUTION OF THE LINEAR RIDGES

Over a dozen extensive exposures of narrow linear ridges comprising two major ridge systems have been detected (Fig. 1). Each ridge system is broadly arcuate to slightly sinuous in its surface pattern and remarkably consistent in character over its longitudinal extent, which, although discontinuous, can be traced for distances of 600 and 700 km, perhaps extending farther in the subsurface. The nature of the ridges is remarkably consistent over their length, as revealed in thermal emission imaging system (THEMIS) and high-resolution stereo camera (HRSC) data (Figs. 1B–1G; Data Repository [see footnote 1]). The width of the ridges ranges from ~500–1000 m but is typically ~700 m. The heights of the ridges, as revealed by analysis of Mars Orbiter Laser Altimeter (MOLA) PEDR profiles (see Data Repository), range from 6.2 to 24.3 m with a mean and median of ~14 m. In THEMIS images (visible—17.5 m/pixel; infrared—100 m/pixel), cross-sectional shapes appear rounded to sharp-crested (Figs. 1B–1G), but high-resolution (4.3 m/pixel) Mars Orbiter Camera (MOC) images (Fig. 1H) show that the central part of a typical ridge is sharp-crested and averages ~60 m across. The broad ridge seen in the THEMIS and HRSC images is caused by flanking erosional debris surrounding the central ridge. The ridge system does not change detailed character as a function of local topography. As ridge segments climb broad wrinkle ridges or descend into craters (Figs. 1E and 1F), their width and height remain virtually unchanged. The general shape of the ridge strike is linear, but in regional view it is broadly arcuate (Fig. 1A).

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[1] GSA Data Repository item 2006060, Mars stratigraphy, chronology, geomorphology, data sources, and volcanology, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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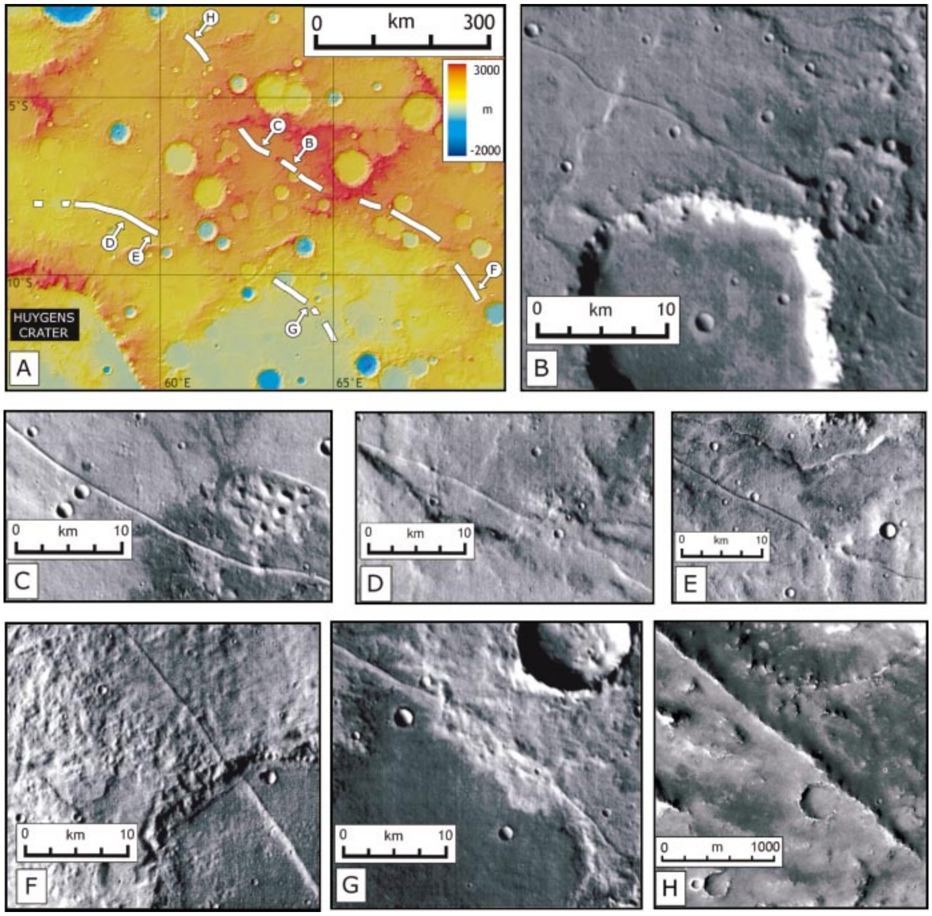

Figure 1. A: Distribution of ridges northeast of Huygens crater (495 km diameter, lower left) superposed on northern rim of the Hellas basin. Thick lines show locations where the two linear ridge systems have been mapped, and lettered arrows show locations of images B–H. MOLA topographic base map. B–H: Images showing characteristics of the ridge system developed primarily in Npld (Noachian dissected terrain; Greeley and Guest, 1987). B: Slightly wavy nature of ridge in 40-km-long segment where it crosses rim of an ancient 18 km rectangular crater. Note the interruption by superposed crater chain adjacent at northeastern corner of crater rim. Portion of THEMIS image I08199013. C: Typical character of a 37-km-long portion of ridge system showing its narrow and linear behavior as it crosses smooth mantling material to west and north, and pitted, dissected material in southeast. Portion of THEMIS image I08224016. D: Linear 30-km-long ridge segment cutting across wrinkle ridges and displaying a superposed impact crater with a pedestal-like elevated ejecta deposit. Portion of THEMIS image I07214002. E: Linear 37-km-long segment showing knobs and associated flow-like lobes. Portion of THEMIS image I01272001. F: Linear 35-km-long ridge segment showing lack of deflection as ridge passes across crater rim crest and down onto crater floor in southeast. Terrain in western part of image appears mantled and pitted. Portion of THEMIS image I0309002. G: Broadly arcuate ~38-km-long ridge segment with central portion of ridge covered by lobate ejecta from the 10.5-km-diameter crater in upper right. Ejecta from crater appears to have banked up against ridge, overtopping it and then flowing down into adjacent low, which has been filled with Hesperian ridged plains. Portions of ridge at its extreme southeastern exposure appear to be partially covered by a mantle deposit. Portion of THEMIS image I08174015. H: Mars Orbiter Camera high-resolution (~4.3 m/pixel) image of the linear ridge. Note sharpness of ridge crest and material along sides of ridge, responsible for making it appear broader in the lower-resolution images (compare to Fig. 2). Note highly subdued texture and mantled nature of surrounding topography and craters. Portion of image E0500492. North is up in all images.

Locally, the ridge can curve slightly (Figs. 1B, 1C, and 1G), but there is no evidence to date for multiple ridges, braiding, bifurcation, sinuosity, or tectonically disrupted patterns along strike.

The ridge system is in contact with several southern upland geological units (Greeley and Guest, 1987). For the majority of its strike, the ridge system is situated on ancient Noachian dissected terrain (Npld), described (Scott and Tanaka, 1986) as heavily cratered uneven surfaces highly dissected by small channels, channel networks, and troughs, and interpreted to be ancient cratered terrain highly eroded by fluvial processes. Patches of the Hesperian smooth unit Hpl_3 and Hesperian ridged plains are superposed on the Npld and are interpreted to be composed of lava flows ponded in low-lying regions and perhaps some interbedded sediments. The ridges are seen to be both superposed on and crosscutting these plains units and to be embayed by them (Figs. 1D, 1E, and 1F). Impact craters and their ejecta are superposed on the ridges (Figs. 1D and 1G) as well as cut by them (Fig. 1F). In some cases, there is evidence that lateral emplacement of ejecta took place subsequent to the ridge formation, as ejecta is preferentially piled up in the vicinity of the ridge (Fig. 1G). The ridge systems are approximately parallel to, but much smaller than, the broad crustal magnetic anomalies detected in this region by Mars Global Surveyor (e.g., Connerney et al., 2001).

ORIGIN OF THE LINEAR RIDGES

What processes might be responsible for the ridges? The ridge-like nature of these features suggests the possibility of sedimentary processes, such as exhumed stream channels, but the linear nature, overland trace, and the lack of tributaries argues against this interpretation. Subglacial esker-like features can often form irrespective of localized topographic gradients, and evidence has been cited for their occurrence on Mars (e.g., Head and Pratt, 2001), but the extreme length and linearity of these features is unlike that of any eskers seen to date. The linear nature suggests that fault-related processes might be a factor in their origin, but the ridge-like nature is not typical of normal faults, and reverse faults generally show the wrinkle-ridge-like nature of low-angle folds and thrusts typical of many parts of the Hesperian ridged plains (e.g., Watters, 1993). Dike emplacement events, caused by the propagation of magma-filled cracks in the crust, form long linear fractures filled with magma that solidifies and can leave a surface ridge following exhumation (e.g., Ernst and Barager, 1992). Dikes are generally vertical or nearly vertical in nature, cross terrain irrespective of topography, are in the range of meters to hundreds of meters in width, are extremely linear and often broadly curving, and can extend in the near subsurface for thousands of kilometers (e.g., Ernst and Barager, 1992; Ernst et al., 1995; Wilson and Head, 1994, 2002a). On the basis of the characteristics of these ridges, we interpret them as the surface manifestation of magma-filled cracks (dikes).

Commonly, when a dike is emplaced, it rises to the near surface along most of its length, and the top stalls at a depth of a few meters to a few hundred meters, depending on local crustal density distribution, stress levels and orientations, magma overpressurization levels, and gas content and exsolution patterns (e.g., Rubin, 1992; Mastin and Pollard, 1988). Of-

Figure 2. Perspective view of an eroded dike (~2–7 m wide) showing narrow crest of exposed dike and very broad flanking erosional aprons (compare to Figs. 1B–1H). Ship Rock, New Mexico, USA, looking north-northwest; photo by Paul Logsdon.

ten, a small portion of the dike intersects the surface and creates a short-duration ‘‘curtain of fire’’ eruption and a longer-duration centralized vent (e.g., Wilson and Head, 1988). The majority of dike emplacement events do not result in eruptions, and much of the length of one that does result in an eruption remains below the surface and solidifies in the shallow subsurface, and must be exhumed to be exposed (Fig. 2). It is highly unlikely that any major portions of the ridges documented here represent hundreds-of-kilometers-long surface eruptions forming ‘‘curtains of fire’’ and rows of cones to create the ridge, as the morphology of such features is beaded (cones), and flanking flows are commonly observed (Data Repository; see footnote 1). It is much more likely that the ridges represent exposures of the top of the dike intruded to shallow near-surface crustal levels; in order for the ridges to be currently exposed, they must have been exhumed. Well-known similar examples occur on Earth (Delaney and Pollard, 1981) and show the prominent linear ridge representing the dike outcrop and the very broad flanking aprons of erosional debris (Fig. 2). Knowledge of typical depths to the tops of dike intrusions suggests that the dikes were emplaced to within a few hundred meters of the surface (e.g., Wilson and Head, 1994; Mastin and Pollard, 1988). This implies that a minimum of several tens to a few hundred meters of material was once on top of the ridges and has since been largely removed. Analysis of similar linear ridges interpreted to be remnants of dikes emplaced in piedmont glaciers on Mars (Shean et al., 2005), and associated theoretical studies of dike emplacement in terrestrial ice-rich deposits (e.g., Wilson and Head, 2002b), suggest that this configuration (sharp ridge crest and broad flanking erosional material) differs from primary extrusive cones (see Data Repository) and is consistent with dike emplacement in volatile-rich deposits, and subsequent exhumation.

MODE OF EMPLACEMENT OF THE LINEAR RIDGES

The geometry and extent of the ridges provides important constraints on the nature of the dikes and the eruption conditions that might have accompanied their emplacement. The broad ridge in lower-resolution images is typically $\sim$700 m across, and the details revealed in high-resolution images suggest that the surface exposure of the ridge crest is $\sim$60 m wide. This implies that the actual width of the dike at depth might range up to $\sim$200 m. This range of values indicates that the depth from the original surface to the top of the dike would range from zero (the part that erupts) to as much as several hundred meters (Wilson and Head, 2002a), depending on the actual width of the dike (Data Repository; see footnote 1). If, for example, an eruption was active along a 5-km-long segment of the dike (less than 1/100 of the total dike length), the rise speed of mafic magma in a dike $\sim$100 m wide could be up to 20 m/s, and the volume flux (velocity $\times$ width $\times$ length) could be up to 10×10^6 m^3/s (Wilson and Head, 1994; Data Repository). Flows erupting from such vents would travel over flat to gently sloping terrain for hundreds to thousands of kilometers (Wilson and Head, 1994), or in rougher topography, pond in local to regional lows such as craters, burying the vent and the associated eruptive products in the process. In summary, on the basis of models of the ascent and eruption of magma on Mars and the structure of its crust (e.g., Wilson and Head, 1994, 2002a), dike widths of this magnitude are likely to involve very high-effusion-rate and high-volume eruptions, in the range of those typical of flood basalts on Earth (of order 10^5 m^3/s). These models are consistent with the patchy nature of Hpl$_3$ and Hesperian ridged plains in the cratered uplands and the dearth of individual flow fronts.

What processes might be responsible for the exhumation and current exposure of the dikes? The striking continuity and width of these ridges across different terrain types (Figs. 1 and 2) suggest that the shallow crustal material removed to expose the upper parts of the dike tips must have been very homogeneous in its properties and easily removable. Dike geometry suggests a thickness of removed material of up to several hundred meters. The morphology of the unit (Npld) in which the ridges predominantly occur suggests a major role for volatiles in the emplacement and loss of the removed layer. Grant and Schultz (1990) described widespread inverted relief craters and valleys of similar age in Electris and near Isidis that they interpreted to be eroded and exposed by wholesale deflation of loess-like airfall deposits. In the south circumpolar Hesperian-aged Dorsa Argentea Formation, deposits interpreted to be ice-dust mixtures up to 500 m thick have been almost completely removed in extensive regions around armored crater ejecta (e.g., Head and Pratt, 2001; Bleacher et al., 2000). Fluvial erosion in the region in the form of valley networks (Greeley and Guest, 1987), sublimation or melting of ice in a mantling ice-dust cover, or a combination of these, could thus explain the observations.

The timing of emplacement of the dikes and removal of the material appears to be near the Noachian-Hesperian boundary, as suggested by the association of the regional dissection with valley networks, and dike crosscutting of, and embayment by, Early Hesperian plains. Association with the valley networks (largely Late Noachian but extending into the Early Hesperian; e.g., Carr, 1995; Scott and Dohm, 1992) may suggest a causal relationship. It is well known that widespread phases of volcanic activity can place significant volatiles into the atmosphere (e.g., Phillips et al., 2001; Jakosky and Phillips, 2001), producing climatic conditions conducive to atmospheric and surface warming and potential pluvial or surface sublimation and melting/runoff conditions. Thus, we speculate that emplacement of the Late Noachian and Hesperian plains through dike-fed flood basalts may have altered the atmosphere sufficiently to cause removal of hundreds of meters of a volatile-rich unit, exposing the top of the dike.

SUMMARY AND CONCLUSIONS

Two major low, narrow, broadly arcuate linear ridges in the region of western Terra Tyrrhena northeast of Huygens crater cross Noachian terrain for distances of hundreds of kilometers irrespective of topographic and geological unit changes. The longest of these is more than 700 km in length and is remarkable in its continuity and consistent nature, and in its exposure relationships. We find that the most plausible origin of these ridges is that they are the surface manifestation of near-surface magmatic intrusions (dikes). The consistent width, vertical orientation, linear continuity, broad linear-arcuate nature, and similarity to examples of exhumed dikes on Earth (Fig. 2) are all consistent with dike emplacement. Detailed, along-strike stratigraphic relationships show that the ridges cut some Hesperian ridged plains but are embayed by others. We thus interpret these features to be associated with the emplacement of the nearly globally distributed Early Hesperian ridged plains. Hesperian plains have previously been interpreted to have been emplaced volcanically, but the lack of clearly identifiable flow fronts and the presence of mantling sediments has often led to alternative hypotheses. The width and geometry of these dikes is consistent with very high-effusion-rate, high-volume flood basalt eruptions, emplacement events that would result in the volcanic flooding of rough Noachian terrain topography, leaving little evidence of flow fronts. The current nature and consistent exposure of the ridges strongly argues that they have been exhumed, with overlying material several to over a hundred meters thick being removed. The present topographic relationships imply that exhumation was a very efficient process, and we suggest that the removed layer may have been very volatile rich and fine grained, and susceptible to sublimation, possible aqueous erosion, and eolian redistribution. The close linkage in time of the valley networks characterizing the dissected terrain and the emplacement of the volcanic plains suggests that volcanic degassing into the atmosphere may have changed the climate sufficiently to cause erosion of a volatile-rich cover.

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