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Geological evidence for a migrating Tharsis plume on early Mars

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ABSTRACT

The Tharsis bulge is the largest magmatic/volcanic center on Mars and in the solar system, having a volume of ~3×10^8 km^3, with the majority of its mass emplaced more than 3.7 billion years ago. The igneous history of Tharsis has been implicated in the generation of an atmosphere and hydrosphere capable of clement conditions on early Mars. It has been proposed that an early plume migration from the southern highlands of Mars relative to a one-plate lithosphere led to the development of the Tharsis bulge in its current location along the Martian crustal dichotomy. We used geologic mapping, crustal magnetic data, crater age-dating and crater morphometry to detail a previously-unidentified path of putative plume migration. Our results indicate that extensive volcanic resurfacing occurred from a location near the present south pole to the equator around 3.8 billion years ago, obliterating older cratered terrains. The resurfacing path is manifest as smooth volcanic plains embaying ancient massifs and infilling large impact craters as well as a lack of a magnetic signature in this portion of the crust. Our results have significant ramifications for mantle dynamics and the early geologic history of Mars.

1. Introduction

Volcanoes in the Tharsis region of Mars were first identified from the Mariner spacecraft images returned in the late 1960s (e.g. Carr, 1974), and they have since gained recognition as the largest volcanoes in the solar system. However, it was not until topographic information was returned from the Mars Global Surveyor mission (Smith et al. 2001) that the extent of the massive Tharsis bulge was revealed. This feature covers one-quarter of the planet and has had a profound effect on the long-wavelength topography and gravity signatures of Mars (Phillips et al., 2001). Tharsis is centered approximately at the boundary of the crustal dichotomy, which is another tectonic and topographic feature of a hemispheric scale. The extensive igneous activity of Tharsis is thought to be a result of mantle plume upwellings and decompression melting (e.g., Mège and Masson, 1996). Mapping of associated tectonic structures (Anderson et al., 2001) and dried river valley azimuths (Phillips et al., 2001) suggest most of the load was emplaced in the Noachian epoch, prior to ~3.7 Ga, although surface lava flows continued to form on some volcanic constructs until a few million years ago (Hartmann, 1999; Robbins et al., 2010). Numerous models for the development of Tharsis have been proposed, including mantle plumes (Breuer et al., 1996; Carr, 1974; Harder and Christensen, 1996; Kiefer and Hager, 1989; Li and Kiefer, 2007; Mège and Masson, 1996; Roberts and Zhong, 2004; Wenzel et al., 2004; Zhong, 2009) and igneous intrusion into and extrusions atop a thin, weak lithosphere overlying an anomalously warm mantle (Solomon and Head, 1982).

Wenzel et al. (2004) and Zhong (2009) explored possible dynamic links between Tharsis and the crustal dichotomy. Wenzel et al. (2004) showed that the thickened crust in the southern highlands would induce mantle upwelling plumes beneath the thickened crust due to its insulation effects. However, Wenzel et al. (2004) could not explain the equatorial location of Tharsis. Zhong (2009), on the other hand, favored a Tharsis mantle plume source that formed and migrated under a lithospheric keel and the thickened crust from the southern highlands to the crustal dichotomy boundary. Spherical shell models of mantle convection on a one-plate planet were used to demonstrate that a unique mode of horizontal motion (rotation) of the entire one-plate lithosphere with respect to the underlying mantle, is readily excited for Mars by one-plume convection in the presence of lithospheric thickness variations (Šrámek and Zhong, 2010; Zhong, 2009). This causes relative motion of the plume with respect to the lithosphere, or apparent plume migration. The suggested mechanism explains the temporal and spatial patterns of Tharsis volcanism – in particular the apparent migration of the Tharsis volcanic center from southern latitudes (e.g., Thaumasia region) to the dichotomy boundary in the Noachian (Anderson et al., 2001; Frey, 1979; Johnson and Phillips,

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2005; Mège and Masson, 1996) – and offers a path to a unified model for the Tharsis bulge and the crustal dichotomy.

In this model (Zhong, 2009), the lithosphere in the southern highlands is assumed to be significantly thicker than near its equatorial margins (i.e. lithosphere keel), consistent with estimates for contemporary crustal thickness of the ancient highlands (Zuber, 2000), assuming that the thickened crust formed by partial melting of the underlying mantle; the keel thus represents the stiff (devolatilized) melt residue. Spherical shell models of mantle convection (Zhong, 2009) demonstrate that the lithospheric keel causes the one-plume upwelling structure to form below the keel (Fig. 1a). However, this configuration is dynamically unstable, causing relative motion of the plume with respect to the lithospheric keel and apparent plume migration as well as stretching of the upwelling structure into an elongated, ridge-like shape (Fig. 1b). The relative motion of the plume with respect to the lithosphere wanes after the plume reaches the crustal dichotomy boundary where the original crust, hence the lithosphere, is thin (Fig. 1c). Depending on inputs for mantle viscosity structures and lithospheric keel thickness, the relative motion of the plume with respect to the lithosphere ranges from 0.2°/Ma to 1.5°/Ma (Šrámek and Zhong, 2010; Zhong, 2009). We would like to point out that in a physically reasonable no-net rotation mantle reference frame, the lithospheric shell has a significantly larger rotation motions than the underlying mantle and mantle plumes (Zhong, 2009), and that our discussions in this paper emphasize the relative motions between the lithosphere and mantle.

This plume model is only one of many hypotheses for Tharsis formation, yet it has specific predictions about melting and surface volcanism (Zhong, 2009). No significant melting is expected from the plume initially when the plume is below the center of the lithospheric keel (near the modern south pole) because the thick keel prevents the plume from rising to shallow depths (Fig. 1a). However, as the plume moves away from the center of the keel, it may rise to shallower depths to initiate melting and volcanism at the surface (Fig. 1 b–c). The initial phase of melting and volcanism could be rather moderate, depending on the lithosphere thickness. However, when the plume moves toward the crustal dichotomy boundary where the lithosphere is thin, extensive melting occurs and gives rise to the Tharsis bulge (Fig. 1c). The goal of this study is to test this plume migration model by using geologic mapping, crustal magnetic data, crater age-dating and crater morphometry in the southern highlands of Mars.

2. Methods and results

To test the migrating plume/rotating keel model, we completed geologic mapping, analyzed impact craters (Robbins and Hynek, 2010) and structural features, and used the remnant crustal magnetization (Whaler and Purucker, 2005) in the region south of the Tharsis bulge to investigate any potential crustal signatures of plume migration through this area during the Noachian epoch (Fig. 2). Geologic mapping of the region south of the entire Tharsis bulge (roughly one-third of the planet south of 40°S, totaling 5.6×10^7 km^2 in area) was completed at ~1:5,000,000-scale and we identified seven major units on the basis of morphology and topography (Fig. 2). We used topography from the Mars Global Surveyor (Smith et al. 2001) and visible images combined with a global daytime thermal infrared mosaic (Christensen et al., 2004) to delineate major geologic units south of the Tharsis bulge (Fig. 2a). Two types of cratered highlands are present — ancient, rugged massifs (cratered unit) and a subdued cratered unit that is still heavily cratered but the craters are infilled and with subdued rims, indicative of significant fluvial erosion in the Noachian (Craddock and Howard, 2002). The Thaumasia highland volcanic terrain was delineated and contains some of the oldest Tharsis materials (Anderson et al., 2001; Dohm et al., 2001; Johnson and Phillips, 2005). The south polar cap and associated deposits were mapped as one unit. The associated surrounding deposits are plains inferred to be resurfaced materials likely from the advance and retreat of the ice cap and contain topographically low plains with eskers and other diagnostic features of glacial activity (Head and Pratt, 2001). The crater unit contains two very large, young, and fresh impact craters, including Lowell, which superpose all other units and were excluded from the analysis to prevent their local resurfacing from affecting crater statistics. Two plains units are also present — low-lying, aligned smooth units and smaller, ridged plains that occur as isolated exposures throughout the southern highlands of Mars (similar to unit Hr on the global maps of Scott and Tanaka (1986) and Greeley and Guest (1987)).

The geographically extensive and aligned plain unit boundaries correlate well with smooth terrains from Scott and Tanaka (1986), although they distinguished four units whereas we grouped these together based on consistent morphology, topographic expression, texture, and embayment relationships throughout the region (Fig. 3). Specifically, the southernmost smooth plains unit we map corresponds to the Dorsa Argentea Formation, lower member (Scott and Tanaka, 1986), which is also prevalent around the south polar cap and extending north along the prime meridian to 60°S (Fig. 2b). We separated the southern plain unit from the rest of the Dorsa Argentea Formation unit on the basis of different expression, including the less rugged topography of the plain unit, the lack of chaotic/differentially eroded terrains that occur on the more southern units, and lack of eskers or periglacial features that are characteristic of this member. The central part of the plain unit correlates with an Npl2 unit from Scott and Tanaka (1986). While a number of other Npl2 units are prevalent in the region (particularly to the west) this unit has a much different character, including an expression of smooth plains with a dearth of craters (Fig. 2). Finally, the northernmost plain unit corresponds well with an Hpl3 unit —

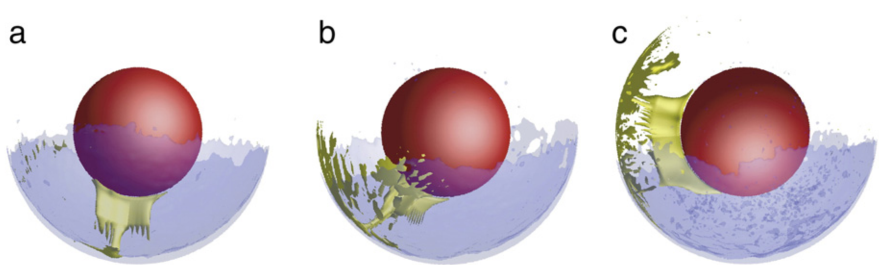

Fig. 1. Three time-series snapshots from the 3-D spherical shell convection model, modified from Zhong (2009). The transparent blue isosurface shows the lithospheric keel of roughly hemispheric extent, assumed to represent the high-viscosity melt residue left after the formation of the thicker southern highlands crust by partial melting. In yellow is the positive thermal anomaly which shows as a single upwelling. This upwelling initially forms below the center of the southern highlands (a) and subsequently migrates towards the edge of the thickened lithosphere, i.e. the dichotomy boundary (b). The upwelling then remains centered near the dichotomy boundary and at depth assumes an elongated, ridge-like shape perpendicular to the boundary due to shear stresses, from which several individual plumes may rise to the surface (c). These plumes caused extended volcanism along the original plume track and significantly more melt is present as the plume reaches the edge of the keel. The figure is presented with the lithosphere fixed to highlight the relative motions between the lithosphere and mantle plume. In a no-net rotation mantle reference frame, the lithospheric shell has a significantly larger rotation motion than the underlying mantle (Zhong, 2009).