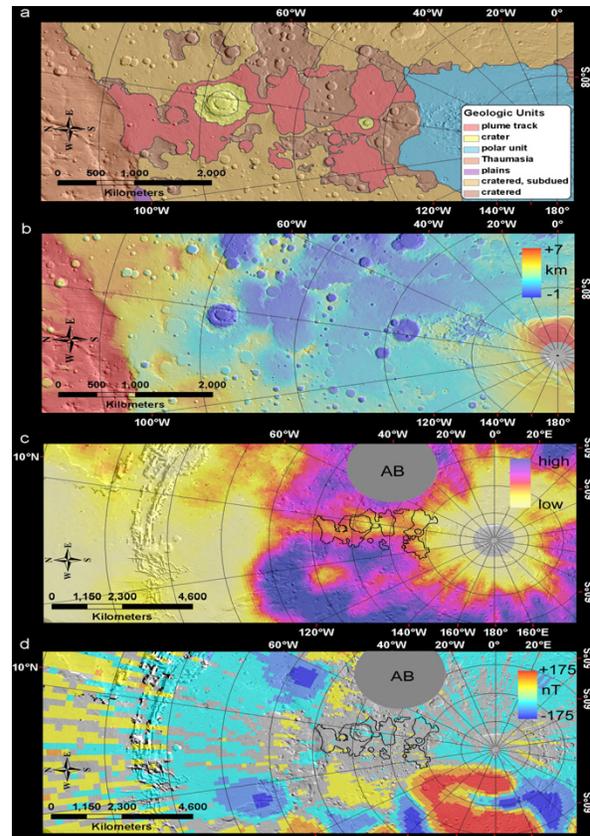


**GEOLOGICAL EVIDENCE FOR A MIGRATING THARSIS PLUME ON EARLY MARS.** B.M. Hynek<sup>1,2</sup>, S.J. Robbins<sup>2,3</sup>, O. Šrámek<sup>4</sup> and S. Zhong<sup>4</sup>, <sup>1</sup>Dept. of Geological Sciences, <sup>2</sup>Lab. for Atmospheric & Space Physics, <sup>3</sup>Dept. of Astrophysical & Planetary Sciences, <sup>4</sup>Dept. of Physics, all at UCB 392, University of Colorado, Boulder, 80309.

**Introduction:** The Tharsis Bulge covers 1/4 of Mars and is thought to be a result of mantle plume upwellings and decompression melting [1]. Zhong [2] favored a Tharsis mantle plume source that migrated under a lithospheric keel from the southern highlands to the crustal dichotomy boundary. Spherical shell models of mantle convection in stagnant-lid regime and with a single upwelling demonstrate that the lithospheric keel causes the one-plume upwelling structure to form below the keel [2]. However, this configuration is dynamically unstable, causing relative motion of the plume with respect to the lithospheric keel and apparent plume migration to the crustal dichotomy boundary.

This Tharsis plume model has specific predictions about melting and surface volcanism. No significant melting is expected 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. 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. When the plume moves to the Thaumasia region and further to the crustal dichotomy boundary where the lithosphere is thin, extensive melting occurs to give rise to the Tharsis bulge.

**Methods and Results:** To test the migrating plume/rotating keel model, we completed geologic mapping, analyzed impact craters [3], and used the remnant crustal magnetic field [4] to investigate potential crustal signatures of plume migration through this area during the Noachian epoch (Fig. 1). Geologic mapping of the region of interest (roughly one-third of the planet south of 40°S) was completed at ~1:5,000,000-scale and we identified seven major units on the basis of morphology and topography (Fig. 1). We used MOLA topography [5] and visible and infrared data [6] to delineate major geologic units south of the Tharsis bulge (Fig. 1a). 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 have subdued rims, indicative of significant fluvial erosion in the Noachian. Two plains units are also present – low-lying, aligned smooth units associated with the putative plume track and smaller, ridged plains that occur as isolated units throughout the southern highlands of Mars. The aligned plains' boundaries correlate well with smooth plains units from global maps [7] although they distinguished four units whereas we grouped these together based on consistent morphology, topographic expression, texture and embayment relationships throughout the region. The Thaumasia highland volcanic terrain was delineated. The south polar cap and associated deposits were mapped as one unit. Finally, the crater unit contains two very large, young, and fresh impact craters that superpose all other units and were excluded from the analysis to prevent their local resurfacing from affecting crater statistics.



**Figure 1.** (a) Geologic map south of Thaumasia. (b) MOLA topography of region [5]. Low-lying areas embaying older cratered terrains correspond to the inferred plume track in (a). (c) Crater density of craters with diameters >15 km and putative plume track (black outlines). (d) Radial component of magnetic field at 400 km (a proxy for remnant crustal magnetism) [4] and plume track. Geographic extent is the same in (a) and (b) and a broader extent is given in (c) and (d) for context. AB = Argyre Basin.

The plume track units are widespread in the region south of the Tharsis bulge, where heavily cratered ancient highland inliers are embayed by a roughly linear series of smooth plains between Thaumasia and the south polar ice cap (Fig. 1a,b). These plains have lobate margins, constant and low elevation surfaces, onlap relationships with surrounding higher-standing older units, evidence for overtopping and infilling large impact basins, and morphologies consistent with low-viscosity volcanic extrusions. Given these characteristics, we infer that the plains formed by flood volcanism and are a surface manifestation of the migrating Tharsis plume across the southern highlands. While plains units occasionally occur within the southern highlands [7], they are much smaller in area and thickness, show a more random

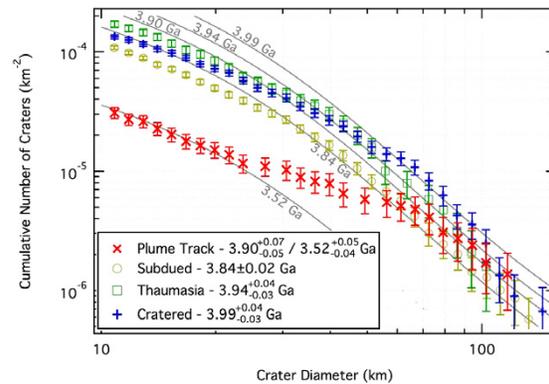
distribution, and are not spatially aligned like those found in this region.

Crater age determinations were completed on all geologic units. We used a global crater database [3] that contains ~500,000 impact craters and is statistically complete to ~1-km-diameter (Fig. 2). The cratering absolute chronology from [8] and the crater production function of [9] were used to estimate absolute ages. The cratered highlands date to >3.90 Ga, as does the Thaumasia unit that represents some of the earliest magmatism on the Tharsis bulge (Fig. 2). The plains unit representing the surface signature of the inferred plume dates to a similar age when using craters larger than ~65 kilometer diameter, mimicking that of other cratered units. Between 65 and 20 km diameter, there is a downturn in the slope of the crater size-frequency distribution (SFD) (Fig. 2). This can most easily be explained by a significant resurfacing event that removed all craters smaller than 65 km around 3.8 Ga and then subsequent crater production on the new surface at smaller diameters has occurred since 3.52 Ga. These two surface age estimates from the plume track unit effectively bracket the timing of plume migration and finality of surface volcanism in the region. Indeed, a map of all craters >15-km-diameter shows a low density region that corresponds with the putative plume track (Fig. 1c). This is in contrast to the rest of the global southern highlands, which show densities similar to the mapped cratered units.

We find that the average crater depth in the putative plume track is significantly shallower than in the cratered unit for diameters ( $D$ )>50 km and also much shallower than in the subdued unit for  $50 < D < 70$  km. These results are indicative of extensive, presumably volcanic, infilling of the plume unit's larger craters. The cratered unit appears to be a good representation of the southern hemisphere in terms of crater depth versus diameter [3], supporting the comparison.

Mars has remnant crustal magnetization across much of the southern highlands created by thermal magnetization from an active dynamo [4]. The dynamo is thought to have operated prior to 4.0 Ga, since large impact basins, including Argyre Basin, that formed since that time have no magnetic signature. The inferred plume track spatially correlates to crust lacking a magnetic signature while surrounding units are magnetized (Fig. 1d). We argue that plume-related magmatism and volcanism effectively removed any previous crustal magnetic signature in this area by both extrusive and intrusive volcanism as it migrated through the region after the dynamo shut down.

**Discussion:** Collectively, the mapping, crater analysis and lack of a magnetic signature are consistent with migration of a mantle plume and below we develop a conceptual model to support the observations: Between 3.9-3.5 Ga, a mantle plume migrated under the lithospheric keel from near the present south pole (*i.e.* the center of the thickened crust and highlands), roughly along the 85°W meridian, to the geographic center of the Thaumasia region. Model calculations indicate that this took between 33-250 Ma [10]. The surface manifestation consisted of significant flood volcanism that created the plume track plains, which embayed surrounding cratered highland terrains and impact craters and also obliterated craters <65-km-diameter. We estimate that the flood lavas are on average ~3-km-thick, given that they



**Fig. 2.** Crater size-frequency distributions of selected geologic units identified from mapping. Note the downturn of the plume track unit starting at ~65 km to smaller diameters.

infilled craters <65 km, and the depth-diameter ratio for fresh Martian craters in that size range is about 1:20 [3]. This explains the old age of the plume track's surface at big crater diameters and reduction of craters with  $D < 65$  km (Fig. 2).

The youthfulness of the Tharsis plume unit's surface age relative to the Thaumasia igneous center at smaller crater diameters (Fig. 2) (roughly 300 million years younger) can be attributed to residual melt and volcanism from decompression melting as the plume moved northward. Models show that during migration from the center of the lithospheric keel, shear stresses cause the plume at depth to assume an elongated, ridge-like shape perpendicular to the dichotomy boundary from which several individual plumes may rise to the surface, causing long-lived volcanism along the plume track. This is manifest in the plume unit as a downturn in its SFD of craters <65 km (Fig. 2). The Thaumasia highlands represent an uplifted and partially resurfaced region evident from pervasive tectonic deformation and in some places the retention of remnant crustal magnetization. We infer that plume migration toward the thinner edge of the lithospheric keel in this region is the mechanism for uplift and resulted in the cratered, tectonically deformed and volcanically modified highland terrain present today.

Our model provides a source and pathway of the enormous mantle plume ultimately responsible for the formation of the Tharsis bulge. We hypothesize that starting 3.9 billion years ago, a plume migrated from near the current south pole of Mars underneath the lithospheric keel roughly 4,000 km toward the crustal dichotomy boundary near the equator. This caused significant extrusive volcanism at the surface that buried an older cratered terrain. Our results have significant implications for mantle dynamics and resultant magmatism as well as the volatile inventory and climate history of early Mars.

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