

THE ETCHED TERRAIN IN ARABIA TERRA, MARS, IS TILTED. B. M. Hynek¹ and R. J. Phillips², ¹Laboratory for Atmospheric and Space Physics, U. of Colorado, 392 UCB, Boulder, CO 80309 (hynek@lasp.colorado.edu), ²Department of Earth and Planetary Sciences & McDonnell Center for the Space Sciences, Washington U., St. Louis, MO 63130 (phillips@wustl.edu).

Introduction: Light-toned bedrock has been observed at the Mars Exploration Rover (MER) Opportunity landing site. These outcrops are rich in a slew of mineral and textural signatures that suggest likely formation within water, including probable evaporites [1-2]. Further, remote sensing data suggest that these outcrops are not a local phenomenon, rather, they are exposed across the entire hematite-bearing plain and well beyond (over an area $>3 \times 10^5$ km² spanning 20° of longitude) [3]. Recent results from the OMEGA instrument on Mars Express [4] show that the etched terrain mapped in [3] is rich in sulfates, thus corroborating the hypothesis that outcrops 100s to >1000 km from Opportunity are diagenetically related. Moreover, there are potentially correlative terrains (with similar morphologic, thermal, and mineralogic expressions) up to 5,000 km away; including deposits within the Valles Marineris, Aram Chaos, and isolated exposures across NW Arabia Terra. We are still trying to understand the full extent of these deposits but it is becoming increasingly clear that copious amounts of water acted over an enormous region of Mars.

Little is known about the timing of the putative sea and diagenesis of the layers. Hynek et al. [5] and Lane et al. [6] published absolute crater ages ranging from the Noachian/Hesperian boundary (~3.5 Ga) to the Early Noachian (>4.0 Ga), respectively. These results, however, are uncertain because of a complicated history of burial and exhumation and the potential inclusion of secondary craters in counts of smaller diameters [7]. The timing of valley network formation relative to these deposits is equally ambiguous. Superposition relations show that networks pre-date, post-date, and may even be coeval with the deposits. Regardless of these difficulties, understanding the timing and nature of these light-toned outcrops is of utmost importance to decipher the depositional environment, water budget, and geologic and climatic histories in this region of Mars. Detailed stratigraphic analyses can elucidate these important questions and assess whether this could have been a habitable environment favorable for the development of life.

Because of its sedimentary and apparent subaqueous origin, the etched terrain was likely emplaced as horizontal to sub-horizontal strata. In this study we test for horizontality of the etched terrain layers and interpret the results in terms of the geological history of this region of Mars.

Data Analysis: Although the etched terrain in Meridiani Planum is generally described as a single unit, there is complex stratigraphy within containing many layers of differing composition and thermophysical properties [3].

For this reason, we utilized 100 m/pix THEMIS-derived thermal inertia data for our stratigraphic analysis [3]. Areally extensive, continuous bedforms (horizons) within the etched terrain were identified and elevation data from the MOLA gridded product [8] were extracted along their surface exposure.

The sampled elevation range of all of the examined strata is ~1100 m. This is approximately the range in elevation of the regional topography of this part of Arabia. Thus if the entire stack of sediments is horizontal, then the regional relief observed in Arabia could be the result of post-depositional selective erosion of the stack. Alternative hypotheses are that (i) the sediments were not deposited horizontally, but instead strata boundaries are tilted, reflecting an underlying, preexisting slope, and/or (ii) an originally-horizontal stack has been tilted by subsequent tectonic events.

The elevation range within individual mapped horizons varies considerably, with a mean value of 164 m, and a standard deviation of 126 m (values range from 29 m to 483 m). It is possible that the layers are horizontal, and the elevation ranges represent samplings within the finite thickness of the same horizontal layer rather than its upper boundary; however we tried in earnest to sample the same section within a bedform. We evaluated potential error in our sampling technique as follows. If the samplings are random with respect to vertical within an individual stratum, then there should not be a coherent spatial relationship between the independently sampled elevations.

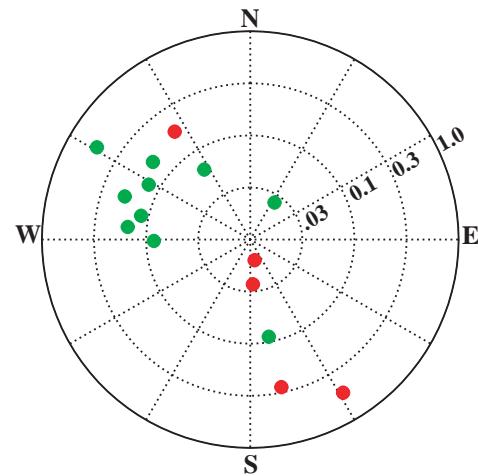


Figure 1. Polar plot of dip direction of fifteen sampled horizons of etched terrain. Radial axis is dip (in degrees) using a logarithmic scale. **Green** = H_0 is rejected; **red** = H_0 is not rejected.

We tested this in the simplest possible way, by seeing how well a plane fit the data for each stratum sampled. For each horizon, we converted data in the latitude-longitude system to a simple x - y Cartesian system. We fit a least-squares plane to each data set and calculated an f statistic [9] for the significance of the fit. Specifically, we tested the null hypothesis, H_0 , that the regression (fit of the plane) was *not* significant. H_0 was rejected if $f > f_\alpha(2, N-3)$, where N is the number of data points. We picked $\alpha = 0.10$, partly because of the typically small number of samples, but, still, there is only a one-in-ten chance of a Type I error resulting (rejection of H_0 when it is true). There were fifteen horizons used, and in Figure 1 we show a polar scatter plot of dip direction (azimuth) versus dip.

The null hypothesis is rejected for ten of the fifteen strata. Of these ten, eight have dip directions clustering between NW and W, with dips between 0.1° and 0.3° . Thus some of the elevation range observed in the sampled strata is apparently due to tilting of the etched terrain layers in a consistent direction.

Discussion: With these results, we explore the alternative hypotheses stated above in the context of Tharsis-induced deformation. The regional topographic slope in Arabia, and elsewhere on Mars, reflects the sum of the pole-to-pole slope and lithospheric deformation due to Tharsis loading [10]. The pole-to-pole slope, the long wavelength expression of the global dichotomy, formed extremely early and may have its genesis in primordial crustal fractionation [11], whereas the Tharsis component of the slope formed sometime before the end of the Noachian [10]. Influence of underlying slopes on sediment dip occurs in various depositional environments on the Earth (e.g., continental shelves). The putative shallow marine sequence that formed the expansive etched terrain [1-4] may have followed the slope of the underlying bedrock. If so, the etched terrain formed after much of the Tharsis load was in place, possibly in the Late Noachian. Further, the body of water from which the deposits evaporated must have been at least ~ 100 m deep (typical elevation range we mapped) and extended at least ~ 100 km (typical geographical range of elevation samples within a horizon). This is a testable hypothesis and we are using bed morphology to examine its plausibility.

Alternatively, the etched terrain was deposited pre-Tharsis, and a portion of observed tilt was induced by Tharsis loading. This hypothesis has two branches. In one scenario, etched terrain deposition conformed to the dip of the preexisting pole-to-pole slope (in which case the water, again, must have been at least ~ 100 m deep). Subsequent east-west tilting in Arabia induced by Tharsis loading would have produced a northwest tilt to both western Arabia and the etched terrain strata. This is the case for the observed broad-scale topography of western Arabia (Figure 2A) as well as model results for Tharsis loading [12]

with a pole-to-pole slope, spherical harmonic coefficient J_1 , added to the results (Figure 2B). (The model behavior itself is unconnected to the pole-to-pole-slope.) In the second scenario, pre-Tharsis etched terrain strata boundaries were horizontal (did not conform to the J_1 slope). In this case, there appears to be no geometrical constraint on water depth. Subsequent tilting by Tharsis would have produced a westerly tilt to the strata, as can be seen in the loading model results without the addition of the J_1 term (Figure 2C). Interestingly, dip directions cluster between NW and W, as noted above.

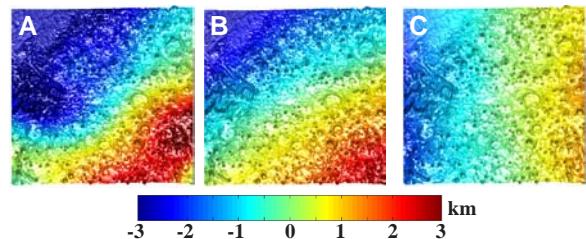


Figure 2. (A) Observed degree 10 topography in western Arabia Terra. (B) Topography from Tharsis loading model [12] with pole-to-pole slope, J_1 , added. (C) As in (B) but without J_1 . Topography values are in color overlaying $\frac{1}{4}$ degree relief map of observed topography. All maps are $80^\circ \times 80^\circ$ centered on $0^\circ, 0^\circ$ and the etched terrain lies near the center.

Conclusions: The sulfate-rich etched terrain observed at the Opportunity site is exposed 100s to 1000s of kilometers beyond the landing site as gleaned from remote sensing data [3]. We analyzed the 3-D stratigraphy of benchmark horizons within the etched terrain to understand their spatial relations and to shed light on the timing of formation and subsequent geological history. The horizons are indeed tilted and most follow the model topography of Tharsis-induced loading coupled with a contribution from the pole-to-pole slope. Thus, two hypotheses are likely: (i) formation of horizontal or sub-horizontal layers very early in martian history with subsequent tilting related to the growth of the Tharsis mass, or (ii) formation of the layers on a preexisting Tharsis-induced slope. Further investigation of the etched stratigraphy should help discriminate the hypotheses and constrain the timing, and possibly the depth, of the alleged sea.

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