AEOLIAN BEDFORMS IN THARSIS MONTES: RECORD OF WIND REGIME AND ATMOSPHERIC PRESSURE IN THE GEOLOGICALLY RESENT PAST.

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Introduction: On the Earth, the most reliable record of climate in the geological past comes from analysis of materials with modern highly advanced geochemical methods. Martian materials available for such studies are limited to a few poorly preserved samples with poorly understood provenance (martian meteorites). On the other hand, on Mars, the surface morphology preservation is much better than on the Earth, which enables its use as a geological record of climate change.

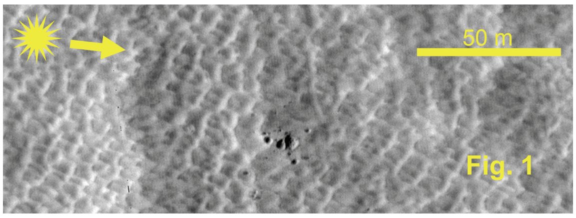
Here we focus on one small piece of evidence that comes from morphological observations: we analyze aeolian bedforms in Tharsis Montes, the four great volcanoes on Mars.

Observations:

Aeolian bedforms in Tharsis Montes were described in detail by Bridges et al. [2007, 2010]. The small-spacing bedforms of specific morphology drape a significant proportion of the surface in Tharsis. **Fig. 1** shows an example of such bedforms at Olympus Mons summit, close to the highest point on Mars. Details of their morphology and the dependence of spacing on elevation [Lorenz et al., 2013] suggest formation via saltation of sand-size particles. Those particles have been hypothesized to be aggregates of finer dust particles [Bridges et al., 2010], which would allow saltation under low atmospheric pressure at high elevations.

Saltation is a threshold process: it does not occur at all, when the wind speed is below the saltation threshold, and moves material very effectively, when the wind speed exceeds the threshold. Thus, the bedforms record only the most recent occurrences of winds that exceed the threshold. The threshold wind speed is higher for lower atmospheric pressure and hence, for higher elevation [Greeley and Iversen, 1985]. As noted by Bridges et al. [2010], the inferred wind direction on the volcano flanks is predominantly downslope, which is consistent with night-time katabatic winds [e.g., Spiga et al., 2011] being the strongest.

The small-scale aeolian bedforms in Tharsis are well distinguishable only in HiRISE images; other orbital images have insufficient resolution. We systematically studied a large subset of available HiRISE images in the region, selected those with well-expressed typical small-scale aeolian bedforms and quantitatively studied small (3 – 15 m) impact craters superposed over the bedforms (**Fig. 1**) and thus postdating the most recent saltation episodes.



Clusters of small craters. Some small craters form distinctive clusters (**Fig. 1**). This happens due to meteoroid breakup and fragment separation in the atmosphere [Ivanov et al., 2008]. The chance of breakup and the separation distance are generally higher, if the atmospheric layer is thicker, that is the surface pressure is higher. Thus, we would expect larger clusters and a higher percentage of impacts forming crater clusters rather than single craters at lower surface elevations, all other conditions being the same. Significant (in comparison to the atmospheric scale height) elevation variations in Tharsis allow us to check these predictions. On the other hand, if the atmospheric pressure were higher (lower) in the past, we would expect larger (smaller) and more (less) abundant clusters for older crater populations. Thus, analysis of clusters can give some information about surface pressure in the past. Here we report our results from analysis of cluster percentage. Analysis of cluster size is in progress.

Populations of small craters. All fresh craters larger than 3 m superposed over the aeolian bedforms can be reliably identified in the images, and sizes of craters larger than 4 m can be reliably measured. We performed systematic search for small craters in several (about 35) HiRISE images in Tharsis and analysis of their populations [Baskakova et al. 2013]. Technical details of this survey and data analysis will be published elsewhere.

If all pre-existing craters were erased by saltation, and then saltation ceased, we would observe "accumulational" population of impact craters. Craters in such populations (1) do not show morphological signs of prominent degradation; (2) their size-frequency distribution is steep and identical to that of newly forming craters; (3) their spatial distribution is indistinguishable form random. (For these criteria, each cluster of craters is considered as a single crater of some equivalent position and size). We excluded images with crater populations that obviously did not match these criteria (we, however, kept populations with minor signs of degradation in crater morphology). We found that in a number of images, populations of craters are consistent with crater accumulation. In these cases, the spatial density of craters can be used as a proxy for the age of the most recent saltation episode, taken statistical uncertainty into account. To avoid some biases we used only craters larger than 5 m for this, and use their density *N*(5m) as a measure of relative age.

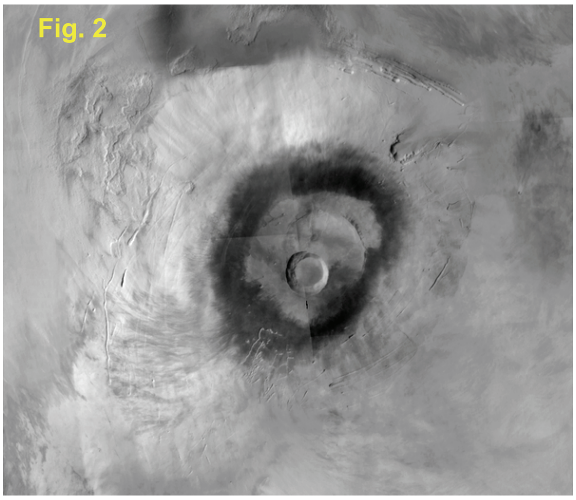
Absolute ages derived from *N*(5m) are inherently poorly constrained. It is possible that cratering rate is not constant and changes significantly at time scales of ~10^5 years. Because of deceleration and breakup of the meteoroids in the atmosphere, the rate may slightly depend on elevation. The same meteoroid may make a larger crater in the soft sand in comparison to typical rocks, which can significantly change effective cratering rate for craters of given size.

The martian absolute cratering rates can be estimated in two principally different ways. One is recalculation of the long-term lunar cratering rate [Ivanov, 2001], the other is observations of the present-day impacts [Daubar et al., 2013]. The later estimation gives only a lower boundary of the cratering rate, which turned out an order of magnitude lower, than the result of [Ivanov, 2001]. Taking all uncertainties into account, it is reasonable to assume that the rate of formation of craters larger than 5 m in Tharsis is bracketed between 2.5 and 25 $km^{-2}Ma^{-1}$. In other words, crater density of N(5m)=1 km^{-2} corresponds to an age bracketed between 0.4 Ma and 40 ka. As a "nominal" rate, we use 4.36 $km^{-2}Ma^{-1}$, so that N(5m)=1 km^{-2} corresponds to 0.23 Ma. This "nominal" rate comes from an assumption that the age of Zunil impact is the same as the ejection age of of martian meteorite EETA79001, 0.75 Ma, without any corrections for elevation and target material.

Inferences:

Current wind regime. In many areas in Tharsis we see populations of pristine craters superposed over the aeolian bedforms. This means that saltation does not occur in the present epoch and the wind speed does not exceed the saltation threshold.

Active saltation does occur within the dark collar of Pavonis Mons (seen in MOC WA mosaic in **Fig. 2**). Tharsis in general is bright (has high albedo in the visible). The dark collar (Fig. 2) is still significantly brighter than dark martian terrains (like Syrtis Major), but it is darker than any surface within Tharsis. The contrast of the dark collar changes seasonally. Apparently, inactive surfaces in Tharsis are covered with bright fine dust, which is continuously deposited from the atmosphere. Saltation within the collar removes the fresh dust veneers and exposes darker bedform-forming material. HiRISE image PSP_009646_1795 clearly shows the absence of small superposed craters within the collar, and rather dense (*N*(5m) = 1.5 km^{-2}) population of pristine superposed craters above the collar. In the uppermost 1 – 2 km of the dark collar, we see several highly degraded craters. This indicates that the upper edge of this active saltation collar is shifting upslope in the present epoch.



In addition to the Pavonis dark collar, superposed craters are absent in a few more HiRISE images at intermediate elevations on Olympus, Arsia and Ascraeus Montes. It is possible that these volcanoes posses the active saltation collars similar to Pavonis, but with less prominent albedo expression. It is also possible that saltation there has ceased recently (*N*(5m) < 0.1 km^{-2}) or it occurs not every year. Significant albedo changes on Arsia reported by Veverka et al. [1977] favor the latter interpretation.

There is a great variety of low-contrast albedo markings in Tharsis (see **Fig. 2**). Most of them are not associated with active saltation (have pristine craters superposed over the aeolian bedforms).

Direct quantitative comparison of the wind speed predicted by circulation models with the observations of the saltation threshold is difficult, because the latter is poorly known, and because the models do not adequately capture the details of the boundary layer wind profiles. The lucky fact that the present-day winds exceed saltation threshold only in the narrow collar(s) gives the possibility to calibrate the saltation threshold in terms of *modeled* wind speed and then compare the models for slightly different climate conditions with the observations.

Past episodes of stronger winds. We do not observe dense populations of the small superposed craters in any HiRISE image with aeolian bedforms. This means that some time ago winds exceeded the saltation threshold everywhere in Tharsis. The highest measured crater density in our survey is *N*(5m)=2.2 in the northern part of Pavonis Mons caldera, which correspond to the "nominal" absolute age of 0.5 Ma (90 ka – 0.9 Ma admissible range). Thus, it is quite possible that the latest pervasive saltation in Tharsis was associated with one of the most recent spin axis obliquity peaks (0.38 Ma or 0.51 Ma or 0.63 Ma ago). **Fig. 3a** shows the recent obliquity variations; time axis is aligned with *N*(5m) axis assuming the "nominal" cratering rate. Note, that this plot can be significantly stretched or shortened in the horizontal direction in comparison to the the N(5m) axis of Fig. 3b.

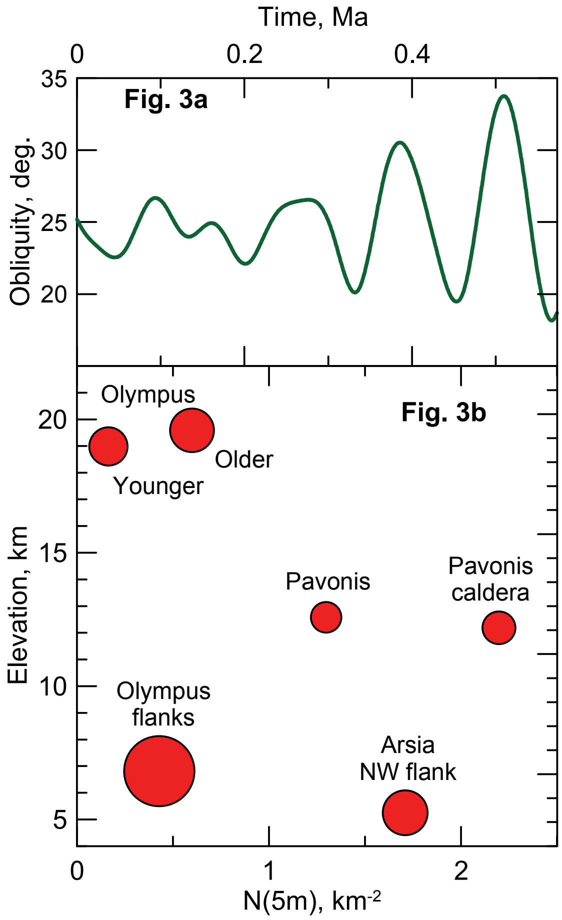
For images with accumulational populations of craters, the measured crater densities differ significantly. The observed populations certainly do not record the same latest strong wind episode. The absolute number of craters within each image is not large (from a few craters to a hundred), and associated formal statistical uncertainty in $N(5)$ is high. Thus, it is impossible to distinguish, if there were a few distinctive wind maxima, or there were only a few distinctive strong wind episodes.

For images surveyed so far, the minimal number of windy episodes consistent with formal statistical uncertainties is 4. At least 2 windy episodes are needed to explain the span of crater densities $N(5) = 0.08 - 0.8$ km^{-2} young ages observed through Olymus Mons. Since for these low densities the statistical uncertainties are large, it is impossible to suspect any specific age consistency between different images. Anyway, the inferred absolute ages are younger than 0.2 Ma, which means that the windy episodes occurred well after the latest obliquity peak 0.38 Ma ago. Thus, these windy episodes might be related to rare episodes of severe weather (e.g., exceptional dust storms), different seasons of perihelion, changes of sufrace albedo in or around Tharsis due to changes of dust coverage, episodes of higher atmospheric pressure. The latter is unlikely, because the observed accessible solid CO_2 reservoir (the Southern residual polar cap, aka Swiss Cheese terrain) is too small to be responsible for significant pressure changes.

We do observe a group of crater densities about $N(5) = 1.7$ km^{-2} (~0.4 Ma "nominal" age). Such densities are observed in 3 HiRISE images widely scattered on NW lower flank of Arsia Mons, in the region of extinct glaciers, as well as in one locations on Pavonis Mons. The most recent obliquity peak is a possible candidate for the latest saltation episode in these terrains, but other options are not excluded.

Coverage of Tharsis with HiRISE images is too sparse, and no meaningful maps of crater densities / ages can be produced. In addition to mentioned very sparse or absent craters in the collars, we see that the calderas tend to have higher crater densities than the surrounding summit areas.

Lower atmospheric pressure in the past? The proportion of clusters in the superposed crater population that we try to use for analysis of atmospheric pressure has very high formal statistical uncertainties. To reduce them, we combined several images located at similar elevations and having statistically indistinguishable crater densities and thus similar ages. The obtained 6 data points are shown in **Fig. 3b**, where the mean elevation is plotted against the mean crater density, and the diameter of each circle is proportional to the percentage of the clusters in the population; the latter varies between ~20% for Pavonis above the collar and ~65% for Olympus just above the scarps. If we consider the younger populations (Olympus) and the older ones (Pavonis and Arsia) separately, we clearly see the elevational trend: the lower the elevation, the higher the percentage of clusters. This proves our suggestions that the percentage of clusters is sensitive to the atmospheric pressure.



If we compare younger and older populations with each other, we see that the older populations have systematically lower cluster percentage than the younger ones, if interpolated to the same elevation. This suggests a lower atmospheric pressure in the past. Possible physical interpretation of this can be prolonged atmospheric collapse [e.g., Kieffer & Zent, 1992] associated with the most recent periods of low obliquity.

This conclusion about a lower atmospheric pressure in the recent past is not reliable: the observed trend in proportion of clusters can have other explanations, e.g., changes of the meteoroid populations. Despite our precautions, we also cannot exclude an observational bias in identification of clusters in sparser and denser populations.

Conclusions. The presented results on the maximum winds exceeding the saltation threshold can be effectively compared against mesoscale models of present and recent climate on Mars.

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