GEOLOGICAL CONSTRAINTS ON MARTIAN ATMOSPHERIC PRESSURE IN THE RECENT PAST. Kreslavsky, M.A. Earth and Planetary Sciences, University of California - Santa Cruz, 1156 High Street, Santa Cruz, CA, 95064, USA, email: mkreslav@ucsc.edu

Introduction: Martian geological record accessible mostly through remote sensing observations is not an accurate record of the atmospheric pressure in the past. However, a surprising number of rough inferences can be made [1]. Here I focus on three different lines of observational evidence relevant for the most recent geological past, within thousands to millions of years.

Recent gullies: The term "recent gullies" has been applied to a wide range of different small-scale morphological features on Mars. Here I consider the most "classic" variety of gullies [2] that are observed at steep slopes in mid-latitudes and include sinuous channels (Fig. 1). Formation mechanism of these features had been a subject of debates, however, the evidence for necessity of the presence of liquid H_2O to carve the channels of the observed morphology is strong [3]. The original hypothesis of the groundwater source [2] is not supported for the majority of these objects [4]. The most probable formation mechanisms involve either (1) limited surface runoff of meltwater produced by *diurnal day-time* melting of transient seasonal snowpack at higher obliquity [5] or (2) debris flows initiated by *seasonal summer-time* melting of H_2O-rich permafrost at even higher obliquity [6].

In any case, formation of these gullies requires subaerial melting of H_2O ice, which can occur only under atmospheric pressure above ~600 Pa (~6 mbar), the pressure of H_2O triple point. A large number of the gullies are at high elevations [4], where currently the atmospheric pressure never exceeds 600 Pa. Thus, formation of these gullies requires a higher atmospheric pressure, at least by a factor of 1.5 or so. (The absolute accuracy of current pressure knowledge is insufficient for a more accurate estimate). The present-day residual south polar cap stores too little solid CO_2 [7] and cannot account for this pressure change. Recently, a thick layer of solid CO_2 has been discovered within the South polar layered deposits [8]. Probably, the gullies were active before this layer was formed and atmospheric inventory of CO_2 was greater.

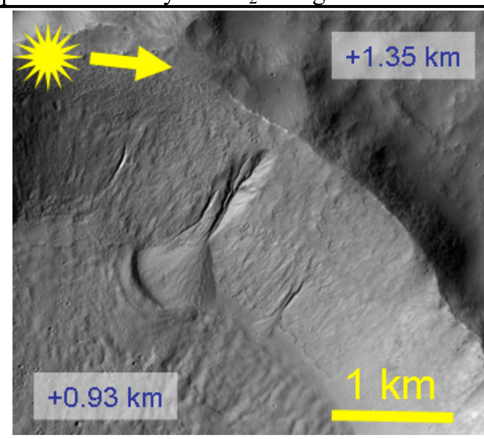

Fig. 1. Classic recent gully considered in [9]. Elevation of crater floor and surrounding terrain is marked.

For one recent gully considered in [9] (Fig. 1) emplacement of a set of small secondary impact craters was interbedded between fan deposits from different gully activity episodes. The formal 1.3 Ma model age of the primary crater produced that secondaries has been inferred from a population of superposed small

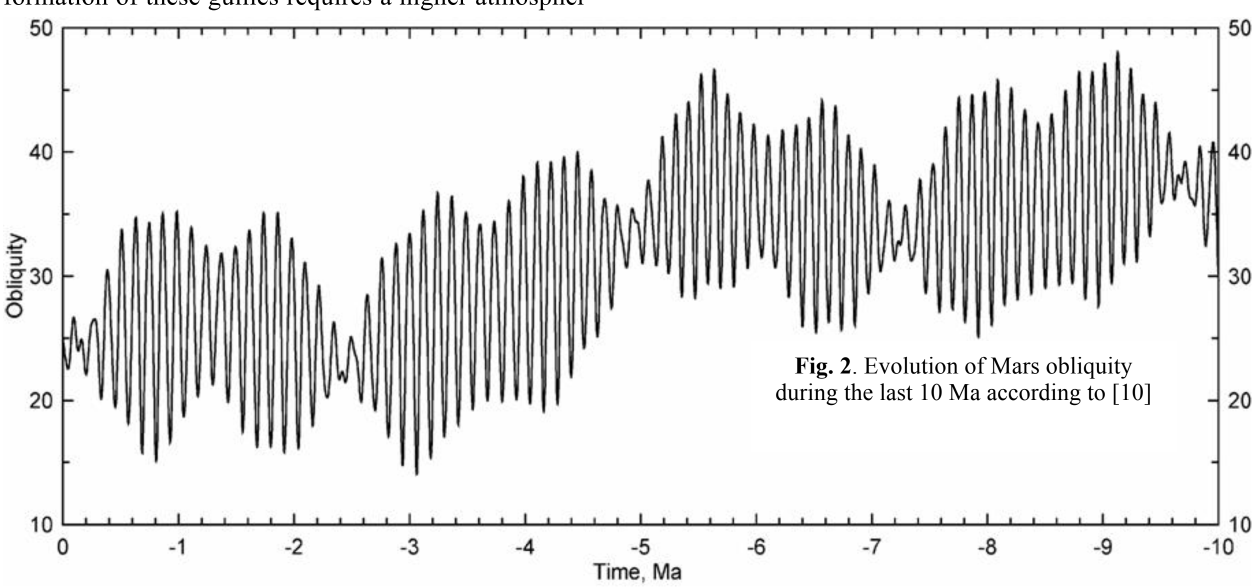

Fig. 2. Evolution of Mars obliquity during the last 10 Ma according to [10]

craters [9]. To make sub-aerial melting at that gully possible, the atmospheric pressure should be a factor of ~1.2 higher than now. Taken at face value, the model age of 1.3 Ma means that gullies form due to day-time melting (according calculated obliquity history [10], obliquity during the last 1.3 Ma ago did not exceed 35º (Fig. 2), which is perhaps insufficient for summer-time melting of permafrost [6]), and the pressure 1.3 Ma ago was still noticeably higher than now. The formal age of 1.3 Ma, however, assumes cratering rate that has been obtained through extrapolation of Ga-time-scale lunar cratering rate [11]; it is highly uncertain, especially for small craters. Estimates of the present-day observed small crater formation rate [12] being applied to the same population of craters yield >10 Ma age instead of 1.3 Ma. It is quite probable that the rate in [12] is underestimated and the true age is much less than 10 Ma, however, it is still possible that the latest activity in the gully occurred a few Ma ago, when obliquity exceeded 35º.

Carbon dioxide glaciers: Collapse of the atmosphere at low obliquity has been predicted long ago (as reviewed in [13]). Later it was shown [14] that under low obliquity condensed CO_2 would preferentially migrate to localized cold traps at pole-facing slopes at high latitudes, where it can form thick enough deposits and flow producing CO_2 glaciers. Morphological traces of such glaciers in the form of drop moraines (Fig. 3) have been found in three locations at high northern latitudes [15], which confirms that the atmospheric collapse indeed occurred and solid CO_2 indeed concentrated on cold steep slopes. There are two craters > 50 m superposed over the moraines left by CO_2 glaciers. It is somewhat too many. Formal lower boundary of the 90%-confidence intervals for the glacier age obtained by buffered crater count method [16] is marginally consistent with the 0.6 - 2 Ma age of the low-obliquity periods (Fig. 2), if we take the extrapolated cratering rate from [11] and inconsistent, if we take the rate from [12]. However, the case for the CO_2 glaciers is rather strong, and there is little chance that their traces could survive from much earlier periods prior to the calculatable ~20 Ma of obliquity history.

Atmospheric collapse means significant decrease in pressure. Although the inferred volume of the reconstructed glaciers is equivalent to less than 20 Pa, a much wider stagnant deposits of solid CO_2 certainly existed. Concentration in localized topographic cold traps [14] causes the pressure to be even lower than predicted by climate models assuming a spherical planet. The pressure, however, could not drop below ~30 Pa, the present-day inventory of incondensable atmospheric components, mostly N_2 and Ar. When H_2O vapor is the atmosphere is much lower than now (which was certainly the case at low obliquity), photochemical equilibrium shifts toward partial decomposition of CO_2 into incondensable CO and O_2 [17], which could lead to atmospheric pressure higher than ~30 Pa. The time scale of establishing this photochemical equilibrium is on the order of hundreds of years [V. Krasnopolsky, private communication], short enough to trace obliquity-driven climate change. It is interesting that the observed CO_2 glaciers occur at cold W- and NW-facing slopes, rather than on the coldest N-facing slopes. This can occur only if CO_2 is not the dominant component of the atmosphere.

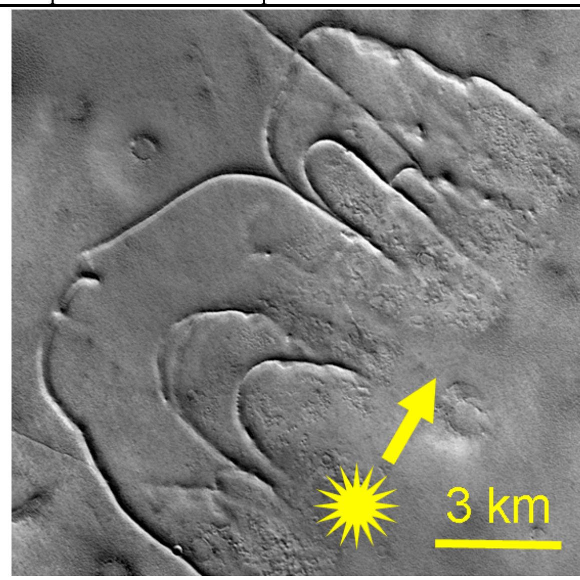

Fig. 3. Moraines left by carbon dioxide glaciers [15]

Aeolian bedforms on major volcanoes: Surfaces of the four major Tharsis volcanoes (Olympus, Arsia, Pavonis, and Ascraeus Montes) are covered with small-scale aeolian bedforms of specific morphology [18] (Fig. 4), hence, they formed by saltation of sand-like material under action of winds. The highest elevation where I observe indirect evidence for ongoing active saltation is 13.9 km above the datum on SW slope of Pavonis Mons, close its summit. Everywhere above this elevation and in may areas below it saltation is not active now: the surface bears sparse populations of fresh perfectly preserved small (5 - 15 m) impact craters superposed over the bedforms and not erased by sand movement (Fig. 4). Crater density gives estimates of time, when maximal winds were significantly higher than now and exceeded the saltation threshold.

A significant proportion of small impacts on Mars produce clusters of craters (rather than single craters) due to breakup of meteoroids in the atmosphere [19] (Fig. 4). Breakup of meteoroids is sensitive to the atmospheric pressure [20, 21]: thicker atmosphere would cause wider separation of craters within clusters and, to some limit, greater proportion of clusters. In this way the clusters bear potential information about atmospheric pressure in the past. Since the craters are accumulated from some moment in the past (the end of intensive resurfacing) till the present day, the information they can provide is some kind of effective average atmospheric pressure for the age of the population. Study of different populations provide some more detailed information about the evolution of the pressure.

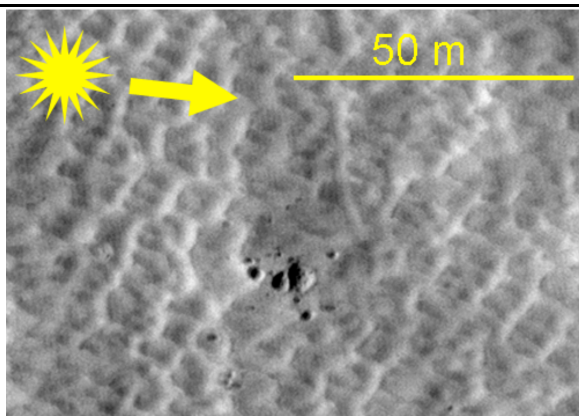

Fig. 4. Aeolian bedforms and a cluster of small impact craters near the highest point on Mars on Olympus Mons

Here I show some preliminary results of my attempts to extract this kind of information from the populations of small craters on the aeolian bedforms on Tharsis volcanoes. I searched 18 HiRISE images for small craters superposed over aeolian bedforms; totally I listed about 1200 craters; to ensure that there is no observational bias between better and worse preserved crater populations I disregarded all craters smaller than 4 m. Then, for each cluster, I calculated a diameter of effective equivalent crater [19]. Finally, I disregarded all craters / clusters with real / equivalent diameter smaller than 5 m; this gave me 192 individual craters and 57 clusters. The size-frequency distributions of these populations do not show any roll-off at smaller sizes, which indicates pristine populations. (If I included smaller craters, I would have better formal statistical uncertainties, but the distributions would indicate crater loss, which can vary from place to place and thus corrupt the results.) Fig. 5, left side shows formal 90% confidence intervals for the crater density (a proxy for age) plotted against elevation for each of 18 images.

The results (Fig. 5 left) show that there are statistically significant differences in ages among the study areas; the crater populations represent a luckily wide range of ages. At high elevations (summit area and calderas of Olumpus Mons), relatively younger terrains (dark blue in Fig. 5 left) have the same percentage of clusters as relatively older terrains (light blue). Hereafter I consider all high-elevation images together; their cumulative percentage of clusters is plotted against elevation as blue box in Fig. 5 right. At low elevations (flanks of Olympus Mons just above the scarp, orange in Fig. 5 left) the percentage of clusters differs between images, however, the difference is marginally statistically consistent with random fluctuations, and I also consider all these images together; their cumulative percentage of clusters is shown in Fig. 5 right as orange box. The age of high (blue) and low (orange) terrains is roughly the same, while the percentage of clusters is higher at lower elevations. This is exactly what we expect as a result of thicker atmosphere (higher atmospheric pressure) at lower elevations. This illustrates that the percentage of clusters, at least, at these high elevations, can indeed be used as a proxy for the mean atmospheric pressure.

Population of small craters in the upper caldera of Pavonis Mons (red in Fig. 5) is much older than the populations on Olympus Mons considered above. Elevation of Pavonis caldera is between the lower and upper populations on Olympus, however, the percentage of clusters (red box in Fig. 5 right) is lower than on the top of Olympus. This can indicate that the mean pressure during the accumulation of craters on Pavonis was lower than during the shorter time span of accumulation on Olympus. The deflection of Pavonis population from Olympus trend of cluster proportion vs. elevation is marginally statistically significant; better statistics (more images) are needed. If it is real, however, it means noticeably lower atmospheric pressure in some recent past.

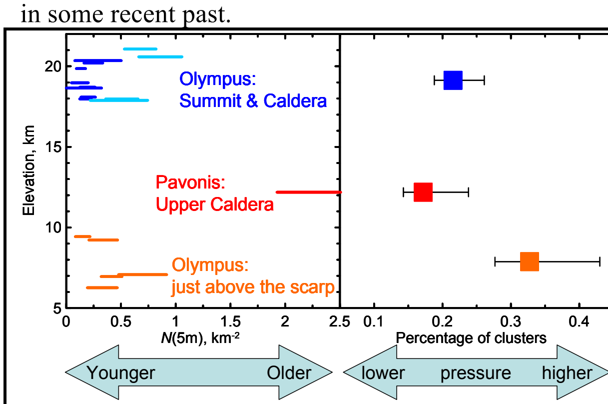

Fig. 5. Left: Elevations of surveyed areas and their with formal confidence intervals for crater density *N*(5m). **Right:** Mean elevations of three groups of surveyed areas and percentage of clusters in the combined crater populations in each group.

The absolute ages that correspond to different crater densities in Fig. 5 left are poorly constrained, as discussed above. If we adopt cratering rate scaled from the Moon [11], all ages, including Pavonis caldera are within the last 0.2 Ma, when obliquity did not differ significantly from the present, and noticeable decrease of the atmospheric pressure is difficult to explain. The rates from [12] or factors of 2-3 higher put Pavonis population at ~ 1 Ma (with uncertainty) and allow inclusion of several obliquity minima into its lifespan (Fig. 1). To noticeably decrease the atmospheric pressure *averaged* over a million of years of so, the atmospheric collapse at low obliquity should be long, which would mean that the threshold of atmospheric collapse is close to the present-day obliquity and/or recovery from the collapse takes long time (tens of Ma).

Again, all these inferences should not be considered reliable at this point; more crater populations should be studied to get better formal statistics and to ensure that the same trends are reproduced in different places. The preliminary results presented here show that this work is promising and likely to give more reliable results.

Conclusions:

1. *Recent gullies* give strong evidence that a few Ma ago the atmospheric pressure was factor of ~1.5 of the present-day pressure or higher (at least, during obliquity peaks).

2. The observed traces of *CO_2 glaciers* confirm the prediction that during several low-obliquity periods 0.8 - 2 Ma ago atmospheric pressure dropped down to a few tens of Pa.

3. *Populations of small craters on Tharsis volcanoes* are promising for inferences about the mean pressure during the last ~1 Ma. They point to long period(s) of lower pressure, but more work is needed to assess this reliably.

References: [1] Kreslavsky M. (2011) 4th int. workshop on the Mars atmosphere: Modelling and observations, Paris, February 8-11 2011, available at: http://www-mars.lmd.jussieu.fr/paris2011/abstracts/kreslavsky_paris2011.pdf [2] Malin M. C. and Edgett E. S. (2000) *Science 288*, 2330-2335. [3] Mangold N., et al. (2010) *JGR 115*, E11001. [4] Dickson J. L. et al. (2007) *Icarus 188*, 315-323. [5] Dickson J. L. and Head J. W. (2009) *Icarus 204*, 63-86. [6] Costard F. et al. (2002) *Science 295*, 110-113. [7] Thomas, P. C., et al. (2009) *Icarus 203*, 352-375. [8] Phillips, R. J. et al. (2011) *Science 332*, 838-840. [9] Schon S. C. et al. (2009) *LPS XL*, Abstract #1677. [10] Laskar J. et al. (2004) *Icarus 170*, 343-364. [11] Ivanov B A. (2001) *Space Sci. Rev. 96*, 87 - 104. [12] Daubar I. J. et al. (2011) *EPSC Abstracts 6*, Abstract # EPSC-DPS2011-1649. [13] Kieffer H. H. and A. P. Zent (1992), in *Mars*, Univ. of Ariz. Press, 1180–1218. [14] Kreslavsky M.A. and Head J.W. (2005) *GRL 32*, L12202. [15] Kreslavsky M. A. and Head J. W. (2011) *Icarus 216*, 111-115. [16] Fassett C. I. and Head J. W. (2008) *Icarus 195*, 61-89. [17] Zahnle, K. et al. (2008) *JGR 113*, E11004. [18] Bridges N. T. et al. (2010) *Icarus 205*, 165-182. [19] Ivanov B. A. et al. (2008) *LPS XXXIX*, Abstract #1221. [20] Popova O. P., et al. (2007) *Icarus 190*, 50-73. [21] Chappelow J. E. and Sharpton V. L. (2005) *Icarus 178*, 40-55.