# OBSERVATIONAL CONSTRAINTS ON ATMOSPHERIC PRESSURE ON MARS IN THE AMAZONIAN.

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**Introduction:**

Total atmospheric mass is an important parameter of the atmosphere models and has huge impact on the nature of the whole climate system. There are many reasons for atmospheric mass of Mars to change significantly at a wide range of time scales from years (e.g., in association with catastrophic events, like big impacts [1]) to Ga (e.g., secular loss). Here I review observational evidence of atmospheric pressure change on Mars, as it recorded in the geological record, which is readable from geomorphologic analysis with remote sensing data. I do not address "Early Mars" and focus on the Amazonian, roughly the last 3 Ga of the geological history. Here there are two distinctive time scales: short time scale, a few Ma and shorter, climate changes related to internal climate instabilities, astronomical forcing, and catastrophic events, and Ga time scale, climate change related to the unknown persistent obliquity state, secular planet degassing, and net volatile loss.

**Potential sources and sinks:** Exhaustive review of possible atmospheric sources and sinks is well outside the scope of this paper; I only try to illustrate that there is no reason to assume that the atmospheric pressure in the past was the same as now.

*Carbon dioxide* $CO_2$. A significant part of the present-day ~6 mbar atmosphere has been predicted to condense in polar areas, when obliquity is low. Low obliquity is the natural reason for a lower atmospheric pressure in the recent past. The residual south polar cap (RSPC), a perennial solid $CO_2$ deposit in the S pole, according to the most recent volume estimates [2] is equivalent to < 0.2 mbar, insignificant amount in comparison to the whole atmosphere. The amount of $CO_2$ adsorbed in the regolith is poorly known; according to [3] it can be as much as 70 mbar equivalent; a part of this amount can readily be desorbed, if the surface temperature increases. The polar layered deposits (PLD) are thought to form in response to recent climate change [e.g., 4]; they are made of $H_2O$ ice, but a significant amount of $CO_2$ can be hidden there unnoticed, up to 20 mbar, given the PLD volume [5] and assuming that 10% of it is clathrate hydrate. In summary, a total amount of $CO_2$ a few times of the present atmosphere might be accessible in the recent past.

For longer time scales, the accessible amount of $CO_2$ results from the balance of mantle degassing as a source and escape to space and carbonate formation as sinks. Although this balance is poorly constrained, recent analysis [6] predicts that in the Middle Amazonian the pressure was a few times higher than now due to generally higher volcanic flux (= higher degassing rate), while in the Late Hesperian - Early Amazonian it was lower, due to more intensive escape. Evidence for carbonate deposits was recently found [7,8], but the amount of carbonates stored in the crust is unknown; this amount can be huge. $CO_2$ from crustal carbonates can be (and certainly have been) released to the atmosphere in large impact events or by interaction with acidic fluids. If Early Mars was cold enough, there is a feeble possibility that a significant amount of $CO_2$ could be sealed in the crust in the form of clathrate hydrates and/or pore liquid and later released.

*Other species.* $H_2O$ is readily accessible at the surface and shallow subsurface in huge amounts (>0.6 bar equivalent); its atmospheric abundance is entirely limited by condensation and controlled by climate.

Volatile sulfuric species certainly have been released from the mantle by volcanism; they are photochemically unstable, though $SO_2$ can survive in cold atmosphere for a while. Huge amount of sulfur is stored in the crust as sulfates; some have been ejected back in the atmosphere by large impacts. In summary, $SO_2$ can be important as a minor component and may play a role in the climate system as a condensable and as a greenhouse gas, but only for geologically short periods; it does not rule the total atmospheric mass.

CO is in dynamic photochemical equilibrium with $CO_2$ [e.g., 9]; under cold climate conditions (when concentration of $H_2O$ vapor is very low) the equilibrium shifts toward CO + $O_2$; this perhaps determines the atmospheric pressure at very low obliquity (or in Early Amazonian under the fainter younger Sun) by converting condensable $CO_2$ to non-condensable CO and $O_2$. Up to a few mbar of $N_2$ might be gradually escaping during the Amazonian (see [10] for recent discussion); thus, $N_2$ can also control atmospheric pressure, if it was cold and almost all $CO_2$ condensed.

**Recent epoch - observations.** Here I review morphological observations that put or possibly can put some constraints on variability of the atmospheric pressure in the recent ~3 Ma, mostly in association with astronomically forced climate change (e.g., due to change of obliquity).

*$CO_2$ glaciers*. Flow of $CO_2$ ice at low obliquity, when a significant part of the present-day atmos-

pheric $CO_2$ was permanently condensed, have been predicted [11] and morphological traces of such glaciers have been found in 3 locations at high N latitudes [12]. Although the inferred volume of the reconstructed glaciers is equivalent to less than 0.2 mbar, a much wider stagnant deposits of solid $CO_2$ certainly existed. Remarkably, the observed $CO_2$ glaciers occur at W- and NW-facing slopes, rather than on the coldest N-facing slopes. This can occur only if $CO_2$ is not a dominant component of the atmosphere, which indicates that the pressure could be the present-day $N_2$ + Ar (0.3 mbar) plus some CO + $O_2$ resulted from $CO_2$ photolysis.

*Recent gullies*. 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 that includes sinuous channels and occurs at steep slopes in mid-latitudes. Formation of these gullies has been argued to require liquid $H_2O$ [13]; the most probable formation mechanism is debris flows initiated by melting of seasonal $H_2O$ snow [13]. The latest flow events in such gullies are recent, at Ma time scale [14]. Some gullies of this type are at high elevations [15], where currently the atmospheric pressure never exceeds the $H_2O$ triple point, and melting of snow is not possible. Thus, formation of these gullies requires higher atmospheric pressure, at least by a few mbar. (The absolute accuracy of current pressure knowledge is insufficient for a more accurate estimate). The present-day RSPC [2] cannot account for this pressure change; perhaps, some $CO_2$ was adsorbed by the regolith and/or hidden in newly formed PLD layers since the most recent gully activity episode. Both higher pressure and formation and melting of seasonal snow are consistent with higher obliquity.

*Aeolian bedforms at high elevation.* Surfaces of all 5 great volcanoes (Olympus, Arsia, Pavonis, Ascraeus, Elysium Montes) are covered with small-scale aeolian bedforms of specific morphology [16], hence, they formed by saltation of sand-like material under action of winds. This saltation is not active now: there are populations of fresh perfectly preserved small (5 - 15 m) impact craters superposed over the bedforms. The age of these populations is on the order of a Ma (accurate crater counts are yet to be performed). The present-day pressure at the summits is below 1.6 mbar (<0.8 mbar for Olympus Mons). Saltation requires either higher pressure or unrealistically strong winds [16]. The latter might be caused by a large impact (e.g., Zunil impact ~ 0.5 Ma ago). A much better understanding of short-lasting effects of such impacts on the climate system is needed to understand, if such an impact indeed can cause saltation on Olympus. It is possible that saltation at high elevations was caused by the same period of elevated atmospheric pressure, as gullies formation. Detailed study of crater populations can potentially give better timing constraints on the latest saltation episodes. There is a chance, that the good timing will help to support or eliminate the impact hypothesis.

*Clusters of small craters*. A significant proportion of the present-day small impacts on Mars produce clusters of crater (rather than single craters) due to breakup of meteoroids in the atmosphere [17,18]. Study of statistics of such clusters in young surfaces can potentially give accurate information about the mean surface pressure during some recent Ma-scale-long periods. For example, wider scattering of fragments at the same elevation would indicate denser (in average) atmosphere. Such studies are laborious, require thorough consideration of possible biases and are far from completion, but look very promising. Especially interesting are the populations of craters on the major volcanoes mentioned in the previous paragraph. There are clusters of fresh craters near the highest point on Mars, on Olympus Mons. Simple scaling of break-up models [19] shows that this requires a denser atmosphere. However, more detailed modeling and data analysis are needed for robust and quantitative conclusions.

*Size-frequency distribution of small craters.* The atmosphere affects the shape of size-frequency distribution of small craters (<30 m) [20] causing roll-over at smaller diameters. In an ideal world, comparison of the distributions for young surfaces of different ages could give constraints on evolution of the atmospheric pressure. In reality, this way is probably not tractable. Obliteration of small craters by surface processes is usually very effective, and few surfaces preserve the smallest craters well enough for such studies (the great volcanoes are exceptions). In addition, since these small craters are formed in strength (rather than gravity) regime, their sizes strongly depend on mechanical properties of the target material, thus accurate measurement of ages is problematic.

**Recent epoch - summary.** During periods of low obliquity the atmosphere collapsed, and pressure was perhaps less than 1 mbar, as predicted by simple climate models. Calculations of the obliquity history [21] tell that there were 5 - 12 such periods from 0.6 to 3.4 Ma ago, but not earlier, at least for 20 Ma more. Each period of atmosphere collapse lasted a few tens ka.

There are observational hints that for some time within the last few Ma the atmosphere was denser than it is now, perhaps in association with periods of higher obliquity. Extensive studies of young populations of small crater promise more robust and quantitative constraints on this.

**Longer time scale - the whole Amazonian.**

*North-south slope asymmetry and the absence of elevational zonality*. Steep slopes (~30°) are constantly produced on Mars by cratering (and also by tectonics). However, at high latitudes, steep slopes (steeper than 10 - 15° at 0.3 km baseline) are extremely rare, while in the equatorial zone they are plentiful and well preserved. The boundary between preserved and removed slopes is very sharp and occurs at ~40º latitude for pole-facing slopes and at ~48º latitude for equator-facing slopes, making a narrow zone of strong slope asymmetry [22]. Sharpness of the boundary suggests a role of a phase transition. These observations have been interpreted [22] through removal of steep slope by liquid water-assisted erosion during summers under very high obliquity, when at high latitudes insolation was sufficient to raise the day-average temperature above 0ºC. The asymmetry between pole- and equator-facing slopes is naturally explained by the difference in summer insolation at high obliquity (pole-facing slopes get more heat). The boundary between present and absent steep slopes does not feel topography. This indicates that there was no elevational zonality in the surface temperature; the latter is a function of insolation only. This means that the thermal coupling between the atmosphere and the surface is weak (like now, when no elevational zonality of temperature is observed), which in turn is possible only if the atmosphere is thin enough. Strong slope asymmetry in the mid-latitudes means the same: surface temperature is a function of insolation only. Thus, during the periods of very high obliquity, the pressure was not much higher than in the present epoch. Models of heat exchange between atmosphere and the surface are needed to quantify the pressure threshold above which elevation starts playing a role in temperature control.

The elevation range, where the absence of zonality is evident, is not wide (~-3 ... +3 km). The northern part of Hellas basin floor (-6 km elevation) is below 40ºS, but has no steep slopes. This can be a sign of the onset of elevational zonality, but also can be just a result of local geology.

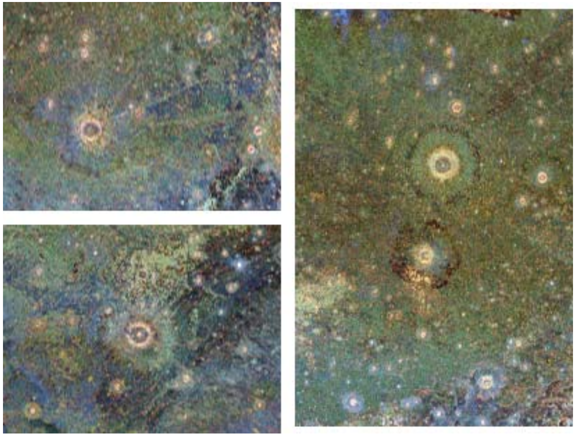

**Fig. 1.** Roughness maps [23] of large craters in the Northern Lowlands: (a) Mie (D~100 km), (b) Milankovič (D~120 km), (c) Lomonosov (D~150 km) and Kunowsky (D~70 km). Brighter shades denote rougher surface.

*Presence and absence of crater rays.* The map of topographic roughness [23] shows that a few large Amazonian age craters in the Northern Lowlands (Lyot, Mie, Milankovič) have long topographic rays, while other Amazonian craters of the same size range in similar geological settings (Lomonosov, Kunowsky) do not have rough rays, but have a smooth annulus (**Fig. 1**). Rays require ballistic delivery of ejected material and cannot form, if the atmosphere is too dense. It is natural to suggest that rayed craters formed when the atmosphere was thing enough, while smooth annulus is an effect of a denser atmosphere (might be similar to radar-dark halos on Venus). Detailed modeling of large impacts in the presence of atmosphere may help to quantify the pressure threshold for ray formation.

*Meteorites.* A few iron meteorites were found with rover Opportunity in Meridiani Planum. A few rocks are candidates for stony meteorites [24]. Calculations [25,26] showed that fall of irons is possible under the present atmospheric pressure, but only for a narrow range of initial entry conditions (to ensure that the meteoroid is decelerated but not disintegrated during the passage through the atmosphere). It is even more difficult to deliver stones. Thus, the presence of meteorites in Meridiani Planum suggests a somewhat denser atmosphere through a significant part of the Amazonian, while the meteorites were accumulating.

*Preservation of boulders.* Boulders can be destroyed by small impacts. Bombardment intensity depends on the atmosphere. Under the present-day atmosphere, the roll-over of the impact crater size-frequency distribution occurs at crater diameter of a few m [18]. In this case, the mean cratering rate in the Amazonian recalculated from the lunar cratering record [27] gives impact waiting time scale of ~1 Ga. This is the characteristic lifetime of a boulder. If the atmosphere is absent, a few m size boulders are grinded into regolith by abundant tiny meteoroids at ~100 - 10 Ma time scale.

In the Northern Lowlands above ~50ºN there is a population of subtle 100s m- to km-size circular features interpreted as heavily degraded impact craters. The size-frequency distribution of these features does not give a certain age, but for the larger end of the size range (~ 1 km) the age approaches the age of the lowlands (~3 Ga) [28]; for 300 - 500 m features it is on the order of 1 Ga. These used-to-be-craters have associated with them fields of 1 - 5 m boulders. In the general planform these fields are very similar to the boulder fields around fresh craters of the same size. If these boulders are indeed produced by impacts formed the used-to-be-craters, then many of them survived from at least ~1 Ga. This suggests that in average the atmosphere have not been much thinner than now. This conclusion involving the boulders is not robust: it is possible that the boulders were buried by ice for a significant time and this, not the atmosphere, helped them survive.

Calculations [30] showed that some small (cm) meteoroids can reach the surface even through the present-day atmosphere. They can split boulders and leave marks on their faces. Such phenomena have been documented [30]. Study of size-frequency distributions of boulders associated with the used-to-be craters in the Northern Lowlands can in principle give constraints on the number of such projectiles, and hence on the pressure. Marks left by small projectiles on boulder faces seem not abundant. If calculations [29] are correct, this may mean persistence of somewhat higher pressure through the Amazonian.

**The whole Amazonian - Summary.** The atmospheric pressure varied. The total duration of low pressure was not long. The mean pressure was probably somewhat higher than now. However, the pressure never exceeded the threshold of elevational zonality (at least under high obliquity).

**Conclusions.** Despite an apparent lack of quantitative accuracy, morphological observations give surprisingly much information about atmospheric pressure on Mars in the past.

The pressure certainly changed through the planet history. Any climate models that address past climate should explore a range of sizes of available $CO_2$ reservoir. It seems probable that the available $CO_2$ reservoir was typically somewhat larger than the present atmospheric inventory.

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