CLIMATE-DRIVEN MORPHOLOGICAL PROCESSES ON MARS IN THE LAST 2.5 MA.

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Introduction: Changing climate on Mars leaves a geological record that researchers strive to decrypt and understand. Success is slowly coming from comparison of observations and understanding of the physical nature of the processes. Here we summarize current knowledge of processes shaping the martian surface during last 2.5 Ma (when the spin axis obliquity oscillated around 25°).

Observed currently active processes:

- Formation of small impact craters [1].
- Aeolian bedform activity (movement of dunes and ripples) [2].
- Material transport in gullies, including channel incision. Most of this activity is caused by seasonal CO_2 sublimation [3], however, rare meltwater flows on "crocus day" causing incision cannot be ruled out at this point.
- Formation of "spiders" and similar features [4] due to seasonal CO_2-related processes.
- Spatial shrinking of the "Swiss cheese" CO_2-rich unit. [5]
- Mass wasting at steep cliffs in the north polar layered deposits (PLD) [6]

Dust lifting, changes of albedo due to dust removal and deposition [7], slope streaks [8], and recurring slope lineae (RSL) [9] are observed active processes that do not leave traces in topography.

Processes active during the last 0.3 Ma: This is the "current interglacial" period according to [10], when obliquity was almost the same as now, and climate change occurred due to the change of season of perihelion, internal climate instabilities, and reconfiguration of accessible volatile reservoirs at the surface.

In addition to the actually observed active processes listed above, there are processes that are not observable in real time now, but certainly have been occurring:

- Formation of small and larger impact craters, including ~5 – 50 craters larger than 1 km.
- Sand saltation and aeolian bedform activity, including areas where saltation is currently absent [11].
- Active erosion of sedimentary rocks in many tropical areas (including Opportunity and Curiosity working areas).
- H_2O ice ablation and deposition in the polar layered deposits (PLD), including infill of small craters. Net migration of H_2O from lower latitudes to the PLD might occur.
- Active processes in the high-latitude zones (from ~50-60° to PLD edges) that lead to formation of polygonal cracks, boulder movement, obliteration of small craters, quick infill and degradation of larger craters, etc. They are driven by H_2O ice-related processes with possible contribution from seasonal CO_2-related processes. Formation of active layer (seasonal permafrost melting) is not excluded during 1 – 3 short periods in the N high latitudes only [12].

It is possible that the "Swiss cheese" unit was absent very recently (~100 years ago, under the present-day spin/orbit configuration), and H_2O ice from SPLD was exposed during southern summers, which would lead to a much wetter climate, ground ice stability in dusty equatorial regions [13], and more intensive H_2O-related seasonal processes (gully incision with meltwater?). Repeating formation and disappearance of CO_2-rich units in both polar areas with significant climatic consequences is not excluded.

Mars 2.5 – 0.3 Ma ago: We do not see any signs of endogenic activity (volcanism, outflows, major tectonic displacements) during this period. Plenty of small craters, 50 – 500 craters larger than 1 km and 1 – 4 craters larger than 10 km (including Zunil) were formed; ejection of the majority of shergotites occurred in 2 – 5 impact events [14].

Net migration of H_2O from low- and mid-latitudes to the poles and deposition of the uppermost sections of the PLD during this period is likely, however, it is possible that the major parts of the PLD have been deposited before 2.5 Ma ago. If the thick CO_2-rich layer in the SPLD [15] formed during this period, the accessible CO_2 inventory, atmospheric pressures, and the efficacy of the seasonal frost-driven and wind-driven processes were higher before its formation. Climate-related processes were controlled by significant changes in obliquity.

Low-obliquity epochs. During these epochs, atmospheric collapse, formation of massive perennial CO_2 deposits at high latitudes, their concentration in craters and at the pole-facing slopes [16], and flow of CO_2 glaciers [17] occurred. Sand saltation, aeolian bedform activity, aeolian erosion were halted due to the low atmospheric pressure. Diffusive desiccation of ground ice and migration of H_2O form everywhere to the poles was going on. The onset of the atmospheric collapse depends on spring-time albedo of solid CO_2 deposits, which is controlled by spring-time H_2O deposition and therefore, by the presence of low-latitude sources of H_2O vapor; this means that the onset was different for different low-obliquity epochs.

High-obliquity epochs. During these epochs, the climate was generally wetter due to more intensive summer-time H_2O sublimation, which caused expansion of the polar shallow ground ice stability zones toward lower latitudes, down to ~45°, and possibly to tropical dusty regions. Ground-ice-driven processes were more intensive and span wider regions. Ablation of the PLD (probably, minor in comparison to their total volume), migration of H_2O to lower latitudes, formation of icy mantles in midlatitudes and/or tropics were likely. Perched Zunil's secondary craters indicate that Zunil formed during a high-obliquity epoch, when a thin mantle existed in Easter Elysium Planitia. Higher seasonal temperature contrasts and possibly higher atmospheric pressure (due to release of some CO_2 from the PLD) favored sand saltation, activity of aeolian bedforms, and aeolian erosion. Formation of the transverse aeolian ridges [18] and intensive erosion of Medusa Fossae Formation material likely occurred during these epochs. Intensive dust lifting coupled with wetter climate favored formation of dust+ice mantles. High obliquity is favorable for intensive ground-ice-related and seasonal CO_2 frost-related processes.

"Normal"-obliquity epochs. These are periods between low- and high-obliquity epochs. All processes typical for the last 0.3 Ma may occur, however, recovery from low- and high-obliquity epochs (sublimation of massive CO_2 deposits or low-latitude icy mantles, respectively) may make climate conditions and morphological processes very different that now.

Liquid aqueous phases: Interfacial H_2O-rich films a few molecular layers thick [19] probably are ubiquitous on Mars; they possess some physical properties of water, however, they are not a liquid phase; they do not flow, and do not leave morphologically observed traces.

Night-time deliquescence [20] is routinely producing small amount of highly concentrated brines; since perchlorate salts are probably present everywhere in the surface layer, minor night-time surface wetting is likely to be common. Dry conditions under low obliquity halted deliquescence, while wet atmosphere under high obliquity is favorable. Deliquescence plays an important role in physics and chemistry of the surface layer (duricrust formation, etc.) and affects morphology through them. Deliquescence is a possible mechanism for RSL formation [21].

Day-time melting of ice. Day-time surface temperature is often sufficiently high for ice melting and formation of metastable (quickly evaporating) liquid water [22]. As a rule, ice is absent at the surface, where it would melt and evaporate during the day. An important exception is the crocus day melting, a situation, when H_2O frost is accumulating seasonally on the cold seasonal CO_2 deposit, and then melts as soon as the last portion of CO_2 sublimates. It is not excluded that the crocus day melting is responsible for some present-day activity in gullies [23]. High eccentricity and proper season of perihelion are pre-requisites for crocus day melting. The present-day spin/orbit configuration is very favorable for crocus-day melting in the S midlatitudes; only ~8% of time during the last 2.5 Ma are similarly or more favorable for this process. If crocus-day melting is indeed responsible for incision of gullies, gully incision punctuates through the geological history.

Day-time melting of hydrated salts. Day-time temperatures may be sufficient for melting of some hydrated salts to produce metastable concentrated brines that would evaporate and deposit non-hydrated or less hydrated salts that cannot melt anymore. This is another possible RSL formation mechanism. This kind of melting is only possible if there is a mechanism (erosion, mass wasting) progressively exposing suitable hydrated salt deposits.

Active layer formation. Unlike day-time melting at the surface, active layer formation is melting within the seasonal thermal skin, when the day-average surface temperature exceeds the melting point. Within the last 2.5 Ma, active layer formation might occur at very high latitudes during several short periods with favorable spin/orbit configuration [24,25]. In a manner similar to terrestrial permafrost, active layer formation leaves readily recognizable traces in surface morphology.

These guidelines provide a basis for reconstructing a sequence of potential processes during spin-axis orbital changes in the last 2.5 million years.

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