THE ORIGIN OF PERENNIAL WATER ICE AT THE SOUTH POLE OF MARS.

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Introduction: The poles of Mars are known to have recorded recent ($<10^7$ years) climatic changes. While the South polar region appears to have preserved its million years old environment from major resurfacing events, except for the small portion containing the CO_2 residual cap, the discovery of residual water ice units in areas adjacent to the cap provides compelling evidence for recent glaciological activity. The mapping and characterization of these H_2O-rich terrains by OMEGA onboard Mars Express, which have supplemented earlier findings by Mars Odyssey and Mars Global Surveyor, have raised a number of questions related to their origin. We propose that these water ice deposits are the relics of Mars' orbit precession cycle and that they were laid down when perihelion was synchronized with northern summer; i.e. more than 10,000 years ago.

Perennial water at the south pole: The poles of Mars are covered with vast icy areas, the residual caps, whose composition, dimension and history differ significantly. The residual cap in the north grades into the underlying layered materials whereas the South Residual Cap (SRC) remains markedly distinct from the surrounding layered terrains. Remote sensing of the SRC surface indicates temperatures buffered all year at CO_2 phase change temperature (~140 K), providing evidence for a carbon dioxide composition [1]. In addition to CO_2 ice, recent observations made by the Mars Global Surveyor (MGS) and Mars Express (MEx) orbiters have revealed the existence of previously undetected portions of perennial water ice [2,3]. The OMEGA instrument (Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité) on MEx has mapped several of these water ice units:

- Unit 1 is found within the bright CO_2 residual cap and shows water ice mixed with CO_2 ice.
- Unit 2 forms a dark, CO_2-free, water ice strip, which outlines the scarps of the SRC and expands from underneath the thin and bright CO_2 cover of the cap.
- Unit 3 consists of isolated water ice portions which are free of CO_2 and which are located at some distance from the SRC.

The discovery of Unit 1 has confirmed the long-standing hypothesis that the SRC acts as a permanent cold-trap for water. Cold-trapping of water by CO_2 has however no direct role in the existence of the other units since only water ice is exposed there. Other modes of ice accumulation must be involved.

As stated in [3], locations of units 2 and 3 refer to the same geological unit (Af) of the USGS I-2686 geological map which was originally interpreted as partial CO_2 frost covered terrains. OMEGA data show that units 2 and 3 exhibit similar water ice/dust composition. The fact that polygonal sublimation features can be seen extending from inside the H_2O-rich Unit 2 terrains to below the CO_2 ice layer in a transition zone located at the border of the SRC suggests that Unit 2 is only the contour of a water ice layer residing under the CO_2 ice cap. Furthermore, the CO_2 veneer of the cap is probably not thicker than a few meters [3]. In such context, the formation of Unit 2 predates that of the SRC, whose age does not exceed a few centuries [*4*].

Past climate simulations: General Circulation Models (MGCM) have become useful tools for studying Mars' climatic response to known changes in its orbital parameters. Studies conducted to date have mostly focused on obliquity variations. Less is known about how the water cycle responds to changes in eccentricity and precession. However, precession and eccentricity force an asymmetry in the pacing of seasons and dictate which hemisphere is more likely to stabilize volatiles like water.

*Model description and simulation settings.*We use MGCMs developed at the Laboratoire de Météorologie Dynamique (LMD) [5] and at NASA Ames Research Center [6]. We first use the LMD model with a resolution of 5.625° in longitude and 3.75° in latitude. This model has been recently modified to reproduce the present-day water cycle and is in good agreement with MGS/TES observations [7]; clouds are radiatively inactive, but we represent the alteration of surface properties by setting the albedo to 0.4 whenever deposition of water ice exceeds 5 μm in thickness.

Our goal is to address the impact of precession on Mars water cycle and to determine if this cycle may have allowed water to accumulate in the South Polar Region in the recent past. To this end, we have chosen to run MGCM simulations using the orbital configuration that prevailed 21,500 years ago and which corresponds to the last time perihelion occurred during northern summer. We refer these simulations to as "reversed perihelion" simulations to indicate they are a mirror image (approximately 180° phase shift in the argument of perihelion) of the current orbital configuration. We chose this date because it represents a time when the contrast in summertime insolation between the poles is maximized and water transport favored the Southern Hemisphere for water accumulation.

Reversed perihelion simulations. According to our model, today's orbital configuration results in the formation of Unit 1 (according to OMEGA classification); i.e. water ice trapped within the South Residual Cap. The effect of a CO_2 cold-trap at the South Pole is modeled by forcing the surface temperature to be at the vapor-ice transition temperature of CO_2 (~140 K). The model predicts an annual accumulation of 400 μm of water ice over the SRC but no accumulation beyond the SRC limits. In the "reversed perihelion" simulation, the absence of a CO_2 cold-trap does not prevent water ice deposition. On the contrary, we find that a water ice layer permanently mantles the polar region at every longitude south of 80°S. (see Figure 1). The layer thickens at a rate of 500 μm/year and up to 1 mm/year in a small area located south of the west end part of the 85°S annulus. By extrapolation, a >6 meters-thick layer could have formed near the South Pole during the last excursion of perihelion argument in northern spring and summer.

A scenario for the formation of the water ice units. Elaborating upon model results, we may envision a scenario for the origin of the perennial water ice units observed by OMEGA in the South Polar Region. There is no clear geological signal for the age of these units. They likely formed before the permanent CO2 ice sheet (10^2 yrs) and after the PLD terrains (10^7 yrs). The fact that observed water ice boundaries exhibit striking conformity with those of the CO_2 cap, except for the isolated units that lie east and west, suggests there is a process linking the areal extent of the SRC to that of the water ice units. Here, we suggest the following sequence of events to explain these observations:

(1) During the "reversed perihelion" regime, which lasted more than 25,000 years between –34,000 yr and -10,500 yr, insolation and transport conditions were such that water ice was extracted from the north polar cap and accumulated near the South Pole. This eventually formed a circumpolar mantle which extended to approximately 75°S (i.e. far beyond the current boundaries of the units) and reached several meters in thickness.

(2) 10,500 yr ago, precession argument shifted into present southern spring/summer regime, reversing the north-to-south gradient of insolation between the poles. Following this change, perennial water ice became unstable at the South Pole and started to return to the North..

(3) With increasing southern summer insolation, sublimation intensified and the water ice mantle progressively recessed poleward (see Figure 2).

(4) Some 10^3 yr ago (according to estimates on the age of the SRC), some unknown process triggered the formation of permanent CO_2 ice slabs over the receding water ice layer. The presence of CO_2 ice imposes temperatures far below the condensation point of water vapor and thus creates a cold zone that artificially maintains the stability of water ice at latitudes where it would otherwise be removed by sublimation. The formation of the SRC subsequently protected water ice from further erosion.

A sketch of these events is displayed in Figure 3. According to this scenario, the water ice units mapped by OMEGA outside the SRC are the remnants of >10,000 yr old deposition events. It is possible, although very speculative, that in the absence of permanent CO_2 ice, these water ice units would have disappeared and that no water ice would now be exposed. The presence of outliers (Unit 3) is not well explained by the above scenario. However, they might reflect preferred deposition zones where erosion was reduced by some meso-scale stationary cold flow forced locally by the CO_2 cap.

A precession signal in Mars geological records?: The proposed explanation for the origin of perennial water ice at the South Pole is based on a precession-controlled mobilization of water between the poles. This mechanism may only operate at low obliquity (<35°) when insolation distribution favors storage of water in the polar regions whereas higher obliquities force accumulation to concentrate near the equator. Hence, the precession cycle should have affected the geology of the North Polar Region and the analysis of the north PLD stratigraphy suggests that it did. Extending the technique used in [8] to extract climatic signals from a sequence of layers exposed in a vertical section of the north polar cap, [9] have confirmed that the first 350 meters of the cap can be associated with the insolation variations of the last 0.5 10^6 yr. Since this orbital timeframe was mostly dominated by the fundamental 51 kyr period of precession, each of the 30 m-layer is interpreted as the result of changing style of water and dust deposition during each precession cycle. The South Polar Region has not experienced a comparable accumulation of layers. Analysis of the cratering pattern indicates that not more than 10 m of material have been deposited during the last 10^6 yr [10]. A thin layer similar to that predicted by the model (<10 m in thickness) may thus have exchanged several times between the caps during this period, while the associated resurfacing has been too moderate to leave visible marks on the surface. This further implies that every time water has been deposited in the South during the northern spring/summer phase of the precession cycle, it has totally sublimated during the following southern spring/summer phase. Otherwise a stack of layers would have progressively formed and would now be observed like in the North. This also means that a residual dust lag capable of shutting down the sublimation of the water ice sheet has not developed in the south polar region as it is thought to have developed in the north. However, this brings up the following conundrum: if only a thin layer (<10 m) has exchanged between the poles on Mars during the last precession-dominated 0.5 10^6 yr, then how could more than 300 m of material have accumulated over the north polar cap? This requires an additional exchangeable water reservoir in order to allow the north polar cap build up such thicknesses. This may be explained by exchanges with a tropical ice reservoir formed at times of high obliquity [Levrard et al., 2004] or Near subsurface water ice, as observed by Mars Odyssey [Boynton et al, 2002].

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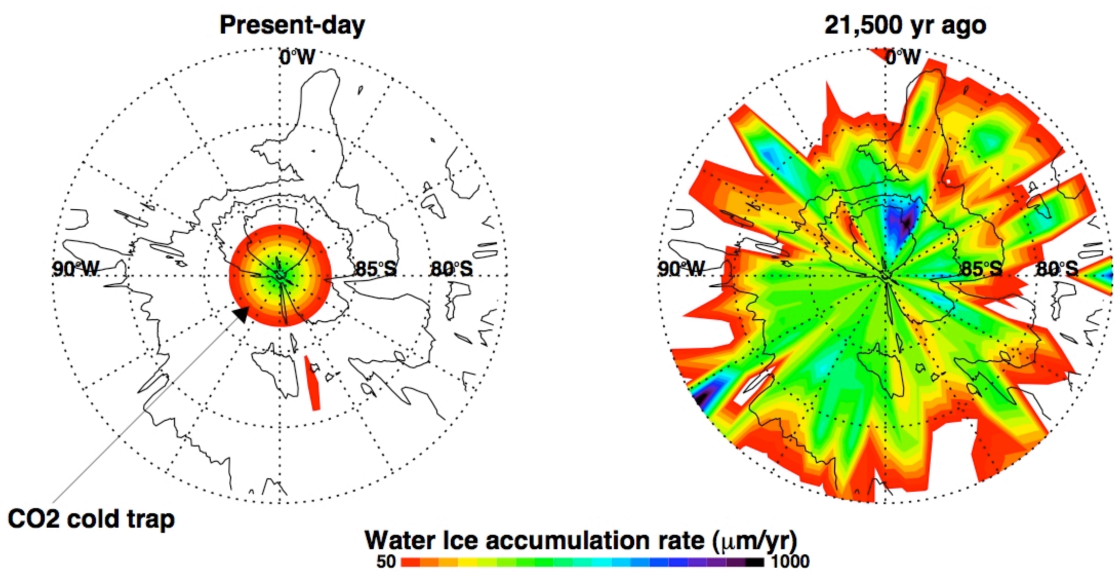

Figure 1: A comparison of water ice accumulation rates predicted by the model in the south polar region for the two perihelion configurations. Present-day map shows net accumulation only at the South Pole itself (equivalent to 1 grid-point in the model) where the prescription of a CO_2 cold-trap forces a local and permanent deposition of water ice. In the “reversed perihelion” simulation (right), the CO_2 cold trap has been removed and the pattern of accumulation is only controlled by a precipitation vs. sublimation positive balance on an annual average

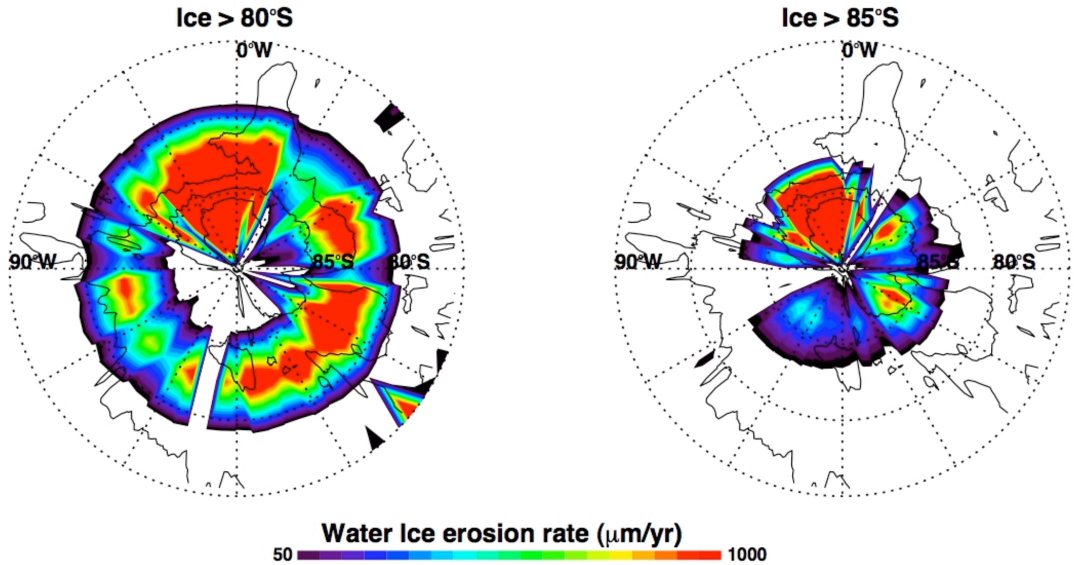

Figure 2: Annual erosion rate of a hypothetic water ice mantle located south of 80°S (left) and south of 85°S (right) predicted by the model under current climatic configuration.

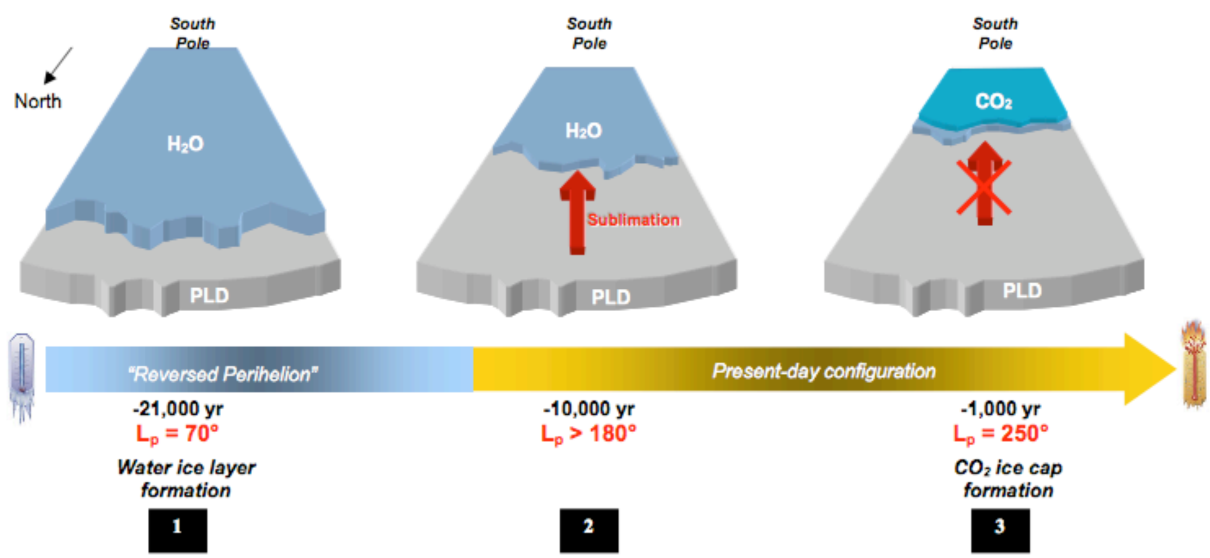

Figure 3: Illustration summarizing the sequence of events in the south polar region since the last “reversed perihelion” regime of the precession cycle. (1) At that time, water was extracted off the north polar cap and was deposited over the south PLD terrains thanks to a favourable summer insolation gradient between the poles. (2) The passage to present-day configuration, with perihelion argument now entering a northern spring regime, reversed the orientation of the insolation gradient and forced water to progressively return back to the North Pole. (3) In a third act, erosion process stopped as permanent CO_2 ice slabs formed and kept water from subliming further.