EVIDENCE FOR NON-POLAR ICE DEPOSITS IN THE PAST HISTORY OF MARS.

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Introduction: The polar caps provide a record of the recent climate history of Mars [1]. Studies of the spin-axis/orbital parameter history of Mars provide a robust solution for the most recent ~20 Ma of martian history, but cannot be mapped further back into the past due to the chaotic nature of the solutions [2]. Thus, deconvolving the complex climate history of Mars requires analysis of the basic geological information, and interpretation of the depositional record of glaciation and glacial conditions at non-polar latitudes. These interpretations are assisted by an understanding of glacial and periglacial conditions in areas that are polar analogs to Mars (such as the Antarctic Dry Valleys) [3], and an understanding of the behavior of polar ice under different insolation conditions, using global climate models (GCMs) [4-5]. Finally, the availability of very high resolution images and topography (e.g., MOLA, MOC, CTX, HRSC, HiRISE) provide the ability to characterize and interpret these deposits. Here we report on recent analyses to assess the presence, age, and significance of non-polar ice deposits as evidence of the history of climate on Mars.

The Current Environment: Polar regions represent cold traps for planetary volatiles and analysis of these areas permits an assessment of the amounts and types of volatiles, their stability and mobility, and the long-term geological record of climate change. Present polar deposits on Mars consist of a thin residual ice unit (Api) overlying a thick sequence of layered deposits (Apl), and are of Late Amazonian age [6]. The individual layers in the current deposits are thought to be related to variations in spin-axis/orbital parameters [2]. These variations cause changes in insolation and climate, and corresponding variations in dust and volatile stability, mobility, transport and deposition [e.g., 7-8]. Recent analysis of the history of orbital parameters has shown that the current martian climate is likely to be anomalous, and that Mars may have spent much of its history at considerably higher obliquity than its present value [2]. We outline eleven examples of non-polar ice-related deposits revealed by new spacecraft data that have implications for the climate history of Mars.

(1) The Latitude-Dependent Mantle and Recent Ice Ages: Multiple lines of evidence have been presented on the basis of MGS instrument measurements and observations that show the presence of geologically very young and unusual features and deposits that formed as a result of recent quasi-periodic climate change [e.g., 9]. The observations span a wide range of scales (from meters to hundreds of km), are diverse in nature (topography, morphology and chemistry), and are strikingly consistent with models of current and past ground ice stability [10]. The observations all point to the presence of a succession of young, meters-thick latitude-dependent surface deposits that were ice-rich when formed, and whose deposition and removal were driven by spin-axis/orbital parameter induced climate change [e.g., 9]. MOLA-derived roughness shows preferential smoothing at sub-kilometer scales above ~30° latitude in both hemispheres, attributed to a young, superposed surface mantle deposit [11]. MOC data analysis [12] revealed the presence of many features that also showed a latitude dependence. Mustard et al. [13] showed the presence of a distinct pitted mantle texture between 30°-60° latitude in both hemispheres, interpreted to be the dissected remnant of a former ice-rich dust deposit. Poleward of 60° in both hemispheres, the terrain was characterized by bumpy polygon-like features interpreted to be different types of contraction-crack polygons, thought to mark the presence of shallow ice-rich deposits undergoing thermal cycling [e.g., 3,14]. Also documented within the deposit was the local presence of multiple layers [e.g.,15-17]. Features interpreted to be very recent water-carved gullies were observed to be latitude-dependent in their occurrence, concentrated at 30°-50° [e.g., 18-22]. Viscous-flow features, interpreted to be the result of the accumulation, mobilization and flow of ice-rich material [16], in local microenvironments [e.g.,23], occur in the same latitude band as the gullies. The global distribution of interpreted water abundance from Odyssey GRS/NS data [24,25] shows a remarkable correlation with the latitude-dependent deposits and features interpreted from MOLA and MOC data, confirming earlier predictions about the stability of near-surface ice in martian near-surface deposits [e.g., 10].

Latitude is the single variable with which all of these diverse observations correlate, and climate is the only process known to be latitude-dependent. The very strong correlation between the nature of the terrain smoothness, mantle continuity, high interpreted water content, and theoretical stability of ice in the near-surface soil, all compellingly point to climate-driven water ice and dust mobility, and emplacement during recent periods of higher obliquity [2]. Degradation and dissection of the deposit in mid-latitudes further point to recent climate change [e.g.,13], perhaps reflecting return of mid-latitude ice to polar regions during the recent phase of lower obliquity [e.g., 7,9].

(2) Northern High Latitude Cold-Based Glacial Crater Fill: Some northern high-latitude contain concentric ridges arrayed in lobate patterns that start at the crater rim, descend down the walls and across the crater floor, and separate around central peaks. These have been interpreted to be drop moraines, deposited during the advance and retreat of a lobate cold-based glaciar, originating on the crater rim [26].

(3) Mid-High Latitude Concentric Crater Fill: Concentric crater fill (CCF) was initially observed in Viking data [27]; new data show details of morphology and structure that support the role of ice in CCF formation [28]. Recent image data suggest that CCF craters may have been ice-filled and that CCF formed as a part of more regional glaciation [29].

(4) Mid-Latitude Lineated Valley Fill (LVF) and Plateau Glaciation: Earlier studies emphasized the role of vapor-diffusion-assisted emplacement of ice in slope-related talus, causing talus lubrication and plastic flow of the debris [27]. New data strongly support some earlier interpretations [30] that significant ice was involved and that debris-covered glacial flow formed regional valley glacial landsystems [31,32].

(5) Mid-Latitude Lobate Debris Aprons (LDA): Earlier thought to represent ice-assisted creep [27], the intimate association of LDA with LVF [33], and LDA internal structure and morphology now point to a debris-covered glacier mode of origin for many LDAs [34].

(6) Evidence for Mid-Latitude Ice Highstands: New data show evidence for highstands of ice (e.g., perched lobes in high-standing box canyons, trimlines, moraines) suggesting that almost a kilometer of ice has been lost from LVF [35].

(7) Low Mid-Latitude Phantom Lobate Debris Aprons: New high-resolution data show evidence for the former presence of ice-rich deposits surrounding massifs at latitudes even lower than the LDA, interpreted as representing the presence of former ice lobes [36] at even lower latitudes (<30°) than the LDAs.

(8) Tropical Mountain Glaciers: New data suggest that the fan-shaped deposits on the NW flanks of the Tharsis Montes and Olympus Mons represent huge tropical mountain glaciers [37-42] formed during periods of high obliquity [43] during the Late Amazonian.

(9) Near Equatorial Outflow Channel Rim Deposits: The graben at the origin of Mangala Valles outflow channel (18°S) contains glacial-like features on its rim, suggesting that the climate earlier in the Amazonian was cold enough in the near-equatorial regions to cause glaciation, rather than runoff [44]. The lack of evidence of melting of these glacial features suggests that the outflow of water did not radically change the climate.

(10) Pedestal Craters: Recent analysis of pedestal craters has shown more clearly their latitudinal distribution [45] and revealed strong evidence for significant thicknesses of ice below pedestal protective veneers [46].

(11) South Circumpolar Ice Cap: The Hesperian Dorsa Argentea Formation: The set of Hesperian-aged south circumpolar deposits represented by the Dorsa Argentea Formation [DAF; 6,47-48] has been interpreted to be a volatile-rich polar deposit representing more than twice the area of the present Amazonian-aged layered terrain and residual polar ice, which it currently underlies. This huge polar ice-related deposit makes up about 2% of the surface of Mars and has undergone significant evolution since its emplacement. The deposit characteristics (e.g., smooth, pitted and etched deposits, pedestal craters, sinuous ridges interpreted by some as eskers, fluvial channels around the margins, and marginal plains thought by some to be remnants of ponds and lakes, etc.) have been interpreted to indicate that the DAF contained significant quantities of water ice, and that it represented an ancient circumpolar ice sheet [48]. These data also suggest that the circumpolar ice sheet subsequently underwent meltback and liquid water sub-ice-sheet drainage, ponding in adjacent valleys, and ultimately draining, through surface sub-aerial channels, down into the Argyre basin more than 1000 km away. Estimated volumes are ~2.19 x 10^6 km^3 for the present deposit (equivalent to a global layer ~15 m deep), and perhaps twice as much for the original deposit (equivalent to a global layer ~30 m deep) [48]. The current estimated volume of the DAF is ~1.2-1.8 times the size of the current Amazonian north polar layered deposits, and ~1.6 times the size of the current Amazonian south polar layered deposits [48], approximately the same size as the Greenland ice cap and ~7% of the Antarctic ice sheet. If the atmosphere was thicker during the Noachian and Hesperian eras than today, then conditions at the south pole may have been very different. For example, above a few hundreds Pascals, surface temperature distribution would behave much more like on Earth, with high altitude regions significantly colder than lower plains because of adiabatic cooling of the atmosphere [49]. Within this context, it is likely that the high southern latitudes would have become a cold-trap where ice would tend to accumulate and form a large ice cap, both because of their latitude and their altitude.

Summary: Together, these data provide insight into the climate history of Mars; they suggest that the climate of Mars has been similar to that of today for much of the Amazonian, with climate variations being driven largely by changes in spin-axis/orbital parameters [2] and that obliquity was above 45° for part of the Late Amazonian. The Hesperian-aged DAF suggests that conditions were different in this important transitional period, with the possibility of a thicker atmosphere producing the huge south-circumplolar DAF. These observations provide an important context for the assessment of the Noachian climate history of Mars.

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