WATER AS A CLUE TO THE EVOLUTION OF THE ATMOSPHERE AND CLIMATE HISTORY OF MARS: EVIDENCE FOR CIRCUM-POLAR/NON-POLAR ICE DEPOSITS, RUNNING WATER AND STANDING BODIES OF WATER IN THE HISTORY OF MARS.

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I. Introduction: Water is a key guide to understanding the history of the atmosphere and climate of Mars [1]. Geological evidence that illustrates the state of water (solid or liquid) and its distribution at various stages in the history of Mars is essential in documenting this history. In this analysis, evidence for the recent climate record in the polar cap is assessed, and non-polar ice deposits are tracked as a record of climate change throughout Mars history. Evidence for the presence and abundance of running water and standing bodies of water in past Mars history provide indications of when the atmosphere and climate were considerably different than they are at present. Together with mineralogical data and crater chronologies, a new picture of the history of the atmosphere and climate are emerging. A review, with selected references, is presented here.

II. Amazonian Polar and Circumpolar Deposits: 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. Recent analyses to assess the presence, age, and significance of non-polar ice deposits provide evidence of the history of climate on Mars and are clues to the current water cycle.

In 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]. Eleven examples of non-polar ice-related deposits are outlined that have implications for the atmospheric and climate history of Mars (Fig. 1).

(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]. Comparisons to Antarctic Dry Valleys polygons suggest that polygons at high latitudes on Mars are sublimation polygons and thus are underlain be significant quantities of ice [50]. Recent Phoenix results strongly suggest that remnant buried ice exists at these latitudes [51].

(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 glacier, 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.

(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].

III. Hesperian South Circumpolar Deposits:

(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 ~2.19×10^6 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.

IV. Evidence for Running Water:

(1) Late Amazonian Gullies: Gullies, perhaps recently active, have been reported [79] in several different Late Amazonian environments, are generally restricted to mid-latitudes, appear to be related to flow, and have been attributed to water flow as top-down melting of snow and ice, bottom up flow from groundwater, and dry granular flow [see review in 22]. The lack of clear consensus on the origin of valley networks precludes a direct understanding of their relation to climate, but some workers link them to recent climate change associated with latitude dependent layers, and glaciation [52], as well as favorable solar illumination geometry linked to obliquity cycles [19].

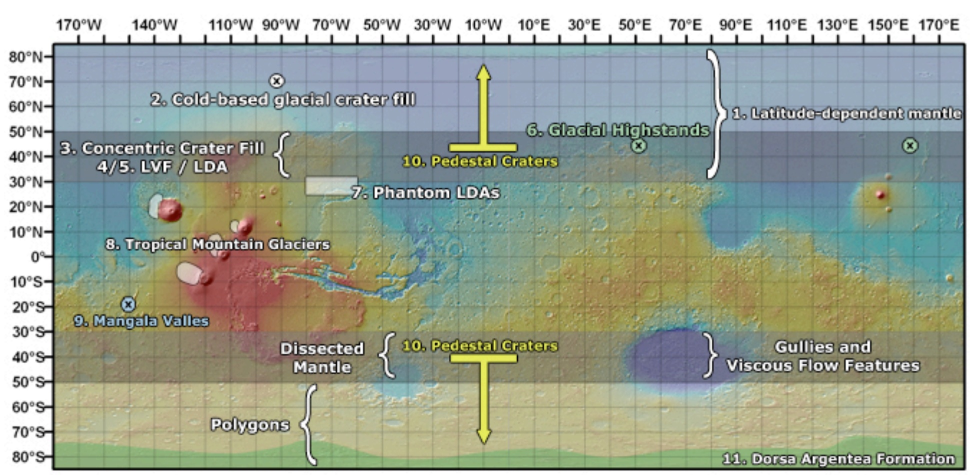

Figure 1. Major circumpolar and non-polar deposits and features interpreted to have been related to ice, glaciation and water (numbers refer to examples in the text).

(2) Late Amazonian Outflow Channels: Very recent outflow channels have been documented in the eastern Elysium region (Cerebrus and Elysium Planitia) [74] and evidence is seen for contemporaneous fissure-fed flows and massive groundwater release. These deposits are testimony to the continuing presence throughout the Amazonian of conditions that could lead to the release of subsurface groundwater by dike-emplacement events [75]. Such events serve to redistribute water from the subsurface to the surface water cycle, and to emplace huge quantities of water in a short period of time into non-equilibrium surface-atmospheric conditions. The nature of such events, their influence on the atmosphere, and the fate of the volatiles is currently poorly understood.

(3) Hesperian-Amazonian Valley Networks: Valley networks are traditionally associated with the Late Noachian, but several localized occurrences have been reported superposed on younger terrains. Several of these are associated with volcanoes in the northern mid-latitudes (e.g., Hecates, Ceraunius, Alba) [54,55,76] and may be related to magmatic heating and ground ice melting [53]. Another option is the association of some volcanoes and valley networks requires deposition of snow and ice on the summits during periods of climate change, and the contemporaneous magmatic activity to cause melting of snow and ice on the summit [54,55]. Thus, future correlation of these examples may provide evidence of periods on mid-latitude deposition of snow and ice, and thus clues to global climate change.

(4) Outflow Channel Formation: It is generally accepted that outflow channel formation resulted from relatively catastrophic release of vast quantities of groundwater [1], perhaps related to dike and sill formation. Critically related to the formation of outflow channels, however, is 1) the origin of the groundwater that produced the elevated hydrostatic head necessary to create the outflow channels, and 2) the fate of the effluent released to the surface and likely ponded in the northern lowlands. Buildup of the hydrostatic head [80] may have important implications for climate history; one model suggests a south polar basal melting source and global aquifer interconnections [56] while another suggests that the combination of snow and ice deposition in the Tharsis summit region during early periods of enhanced geothermal flux may have caused basal melting and direct vertical groundwater recharge [57]. Further, the emplacement of significant volumes of outflow channel effluent certainly increased the amount of water available to the surface water cycle, and may also have created standing bodies of water, potentially changing the atmosphere and climate, perhaps for relatively long geologic periods [58]. The fate of the outflow channel effluent (if released into the current environment) may have been to freeze rapidly and to sublimate, being redistributed into regional and global cold traps [59]. Thus outflow channel formation processes hold very important, clues to the nature of the atmosphere, climate history, and the surface and subsurface water cycle.

(5) Valley Network Formation: Dendritic valley networks have long been cited as evidence for a "warm and wet" early Mars, with possible rainwater and runoff [1, 77]. Recent analyses of the ages of valley networks have shown that they cluster in the late Noachian, around the Noachian-Hesperian boundary [60]. There are many unknowns, such as 1) whether valley networks represent top-down precipitation and runoff, 2) whether any such top-down precipitation was liquid water or snow and ice, 3) whether the valley networks could have a groundwater/sapping origin, and 4) whether late Noachian valley network activity represents a peak occurrence (with attendant implications for the nature and evolution of the atmosphere) or 5) whether it represents a winding down and preservation of conditions that prevailed throughout the Noachian.

(6) Open-Basin Lakes: Analysis of valley network systems and the topography along their paths has revealed the presence of over 200 open-basin lakes [61]. Closed-basin lakes are those in which a valley network component enters a depression but there is no evidence of an exit channel. Open-basin lakes are depressions, commonly craters, in which components of valley networks both enter and exit the depression, implying that water once filled the depression to a sufficiently high level to breach the downslope side and exit the depression. These environments provide important evidence for the volumes of water involved in valley network systems, and the processes responsible filling and breaching the basins [62]. They demonstrate that valley network activity was sufficiently prolonged to form standing bodies of water on the scale of Lake Baikal and the Caspian Sea on Earth [61].

V. Other Factors in the Evolution of the Atmosphere: Water can be emplaced into the atmosphere by several other processes, and these process can further influence the nature and evolution of the atmosphere in terms of its composition and the amount of solar radiation reaching the surface (icehouse/greenhouse conditions).

(1) Impact Cratering Processes: An important factor in the earliest history of the atmosphere is the relationship of the atmosphere to impact cratering processes: in theory, individual large impacts can blow of large percentages of the atmosphere [73], and their role in both the earlier Noachian, during periods of peak bombardment, and later in the Noachian, when the impact flux was waning, needs much more analysis. Impacts could serve to put fine-grained, high-temperature material in the atmosphere, together with water, radically changing insolation, and causing pervasive chemical and mineralogic alteration of the ejecta material [63].

(2) Volcanic Processes: Extrusive and explosive volcanism can served to emplace magmatic and remobilized crustal volatiles, as well as particulate matter (tephra), into the atmosphere and influence the basic atmospheric composition as well as its ability to reflect, filter and modulate solar radiation [64]. Volcanism very generally scales with the thermal evolution of the planet, with higher levels of activity in earlier history, lower levels later on, and certain periods of punctuated activity caused by internal convective reorganizations. For Mars, the formation and early evolution of the crust, and the earliest stages of the building of the Tharsis rise, are interpreted to have emplaced huge quantities of volatiles into the atmosphere [65]. A near global phase of volcanism in the early Hesperian (the Hesperian ridged plains) [66] is thought to have involved huge quantities of flood basalts and is characterized by localized centers of phreatomagmatic activity, both strongly influencing the atmosphere [64,67,68]. Analysis of eruption conditions during this period [64,69], combined with atmospheric general circulation models, has show that tephra can be very widely dispersed and that its influence on the atmosphere can depend on the location of the vents [68]. In the future, more detailed mapping and characterization of the styles, abundance [78], and distribution of volcanic deposits in space and time will provide important input to understanding the nature and evolution of the atmosphere.

VI. Evidence for Chemical Alteration of the Surface and the Evolution of the Atmosphere: One of the most remarkable findings in the last decades of Mars exploration has been the acquisition of high spatial and high spectral resolution information on surface mineralogy that has permitted the analysis of atmosphere–surface alteration in a geologic context and the definition of distinct phases of surface alteration and atmosphere-surface weathering environments [70]. These proposed periods strongly imply a Noachian environment with pervasive water-related weathering, an Amazonian period dominated by cold, hyperarid weathering conditions, and a transitional Hesperian environment where sulfur played a significant role. One of the major challenges of the next decade is the testing of this model and the development of an understanding of specific regions in which the geological and mineralogic record can be related to the evolution of the atmosphere.

VII. Summary: Together, these data and processes provide insight into the history of the atmosphere and 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-circumpolar DAF. These observations provide an important context for the assessment of the Noachian climate history of Mars, where there is significant evidence for running water and standing bodies of water on the scale of Lake Baikal and the Caspian Sea on Earth. An important goal in the next decade is 1) to provide better geological constraints on the nature and evolution of the atmosphere of Mars, 2) to determine the climate history of Mars by assessment and understanding of the nature and state of non-polar ice and water-related deposits, and 3) to provide data in which meso-scale atmospheric models and general circulation models can be formulated and explored to understand the nature and evolution of the atmosphere and climate. Determination of the water cycle and the water budget through geological time is a major theme that can tie these endeavors together. We are currently working toward a synthesis of the Mars water cycle in the Amazonian, Hesperian and Noachian, and a census and budget of surface water and ice deposits back into time.

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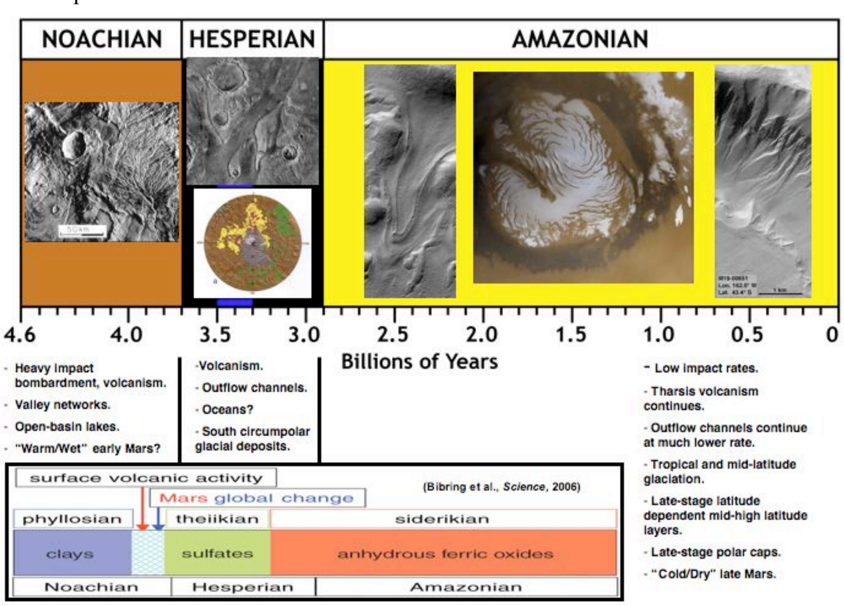

Figure 2. Main periods of the geological history of Mars showing the major phases of geological activity that provide clues to the history of the atmosphere and climate as outlined in this abstract. Also shown are the major phases of alteration as interpreted by Bibring et al. (2006) [70].