

INVENTORY OF ICE-RELATED DEPOSITS ON MARS: EVIDENCE FOR BURIAL AND LONG-TERM SEQUESTRATION OF ICE IN NON-POLAR REGIONS AND IMPLICATIONS FOR THE WATER BUDGET AND CLIMATE EVOLUTION. James W. Head¹ and David R. Marchant², ¹Dept. of Geological Sciences, Brown Univ., Providence, RI 02912 USA (james_head@brown.edu), ²Dept. of Earth Sciences, Boston Univ., Boston MA 02215 USA (marchant@bu.edu)

Introduction: Estimates of the total water abundance on Mars and the nature and magnitude of sources and sinks throughout its history has been a matter of controversy for decades [see summary in 1]; estimates range over several orders of magnitude. Because the nature of earliest Mars history and the processes operating then are so poorly known, our strategy has been to start with the present environment, when climate conditions are more well-known, and work backward in time, using the geologic record as a measure of the presence, location, and state of water. We first identify elements of the current water cycle, assess their volumes, and then turn to the Amazonian geological record to trace the history of the climate and water cycle as recorded in non-polar ice deposits. This inventory permits us to assess the migration paths and behavior of water during long-term climate change and to document changes in the nature and volumetric significance of the water cycle in the past geologic history of Mars. We first identify non-polar ice deposits and then assess their significance compared to the major surface reservoir on Mars, the current polar caps. Studies of the spin-axis/orbital parameter history of Mars provide a robust solution for climatic driving forces 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]. Recent Mars history is dominated by a global hyperarid very cold environment and glacial conditions at non-polar latitudes. 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].

The Current Environment and Climate History: The current hydrological cycle on Mars is horizontally stratified, separated from the subsurface by a global permafrost layer [6]; seasonal variations and longer-term climate change result in migration between the largest reservoir (the polar caps), the atmosphere, vapor diffusion into and out of the regolith, and surface deposition in non-polar regions. Current polar layering is 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]. We outline examples of non-polar ice-related deposits that have implications for the climate history of Mars. **(1) The Latitude-Dependent Mantle and Recent Ice Ages:** Numerous lines of evidence show the presence of geologically very young, meters-thick, multiple latitude-dependent surface layers emplaced to 30° latitude in both hemispheres that were ice-rich when formed and whose deposition and modification were driven by spin-axis/orbital parameter induced climate change [summarized in 9]. Poleward of 60° the terrain is characterized by bumpy polygon-like features interpreted to be contraction-crack polygons, thought to mark the presence of shallow ice-rich deposits undergoing thermal cycling. A distinct pitted mantle texture between 30°-60° latitude is interpreted to be the

dissected remnant of a former ice-rich dust deposit; associated viscous-flow features and gullies are seen in microenvironments in this zone [10]. These data compellingly point to climate-driven water ice and dust mobilization and emplacement during very recent periods of higher obliquity. Degradation and dissection of the deposit in mid-latitudes further point to recent climate change [11], 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:** Lobate concentric ridges draped across crater walls/floors, and around central peaks have been interpreted to be drop moraines, deposited during the advance and retreat of a lobate cold-based glacier, originating on the crater rim [12]. **(3) Mid-High Latitude Concentric Crater Fill (CCF):** Initially thought to be ice-assisted talus creep [13], new data show details of morphology and structure that support the role debris-covered glaciers [14] related to regional glaciation [15]. **(4) Mid-Latitude Lineated Valley Fill (LVF) and Plateau Glaciation:** Interpreted earlier as vapor-diffusion-assisted emplacement of ice in slope-related talus causing plastic flow [13], new data strongly support some earlier interpretations [16] that debris-covered glacial flow formed regional valley glacial landsystems [17-18]. **(5) Mid-Latitude Lobate Debris Aprons (LDA):** Earlier thought to represent ice-assisted creep [13], the intimate association of LDA with LVF [19], and LDA internal structure and morphology now point to a debris-covered glacier mode of origin for many LDAs [20-21], recently confirmed by SHARAD data [22-23]. **(6) Mid-Latitude Ice Highstands:** Evidence of highstands of ice (e.g., perched lobes, trimlines, moraines) suggest that almost a kilometer of ice has been lost from LVF [24]. **(7) Low Mid-Latitude Phantom LDAs:** Evidence for the former presence of ice-rich deposits surrounding massifs at latitudes even lower than the LDA suggest former ice lobes [25] at even lower latitudes (<30°) than LDAs. **(8) Tropical Mountain Glaciers:** Fan-shaped deposits on the Tharsis Montes and Olympus Mons NW flanks represent huge tropical mountain glaciers [26-31] formed during periods of high obliquity [32] during the Late Amazonian. **(9) Near-Equatorial Outflow Channel Rim Deposits:** Glacial-like features on the Mangala Valles outflow channel (18°S) rim suggest that earlier Amazonian climate was cold enough near the equatorial to cause glaciation, rather than runoff [33]; lack of evidence of melting suggests that the water outflow did not radically change the climate. **(10) Pedestal and Excess-Ejecta Craters (EEC):** Recent analysis of pedestal craters has shown their latitudinal distribution [34] and revealed strong evidence for ice below pedestal protective veneers [35]. EEC characteristics [36-37] further support regional mid-high latitude ice cover during the Amazonian and thicknesses of several tens to over a hundred meters. Some adjacent areas show evidence for related ice-rich deposits of comparable thickness [38]. **(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; 39-40] has

been interpreted to be a volatile-rich polar deposit [40] representing more than twice the area of the present Amazonian-aged layered terrain and residual polar ice, which it currently underlies. The deposit characteristics (e.g., smooth, pitted and etched deposits, pedestal craters, sinuous ridges interpreted as eskers, fluvial channels around the margins, and marginal plains thought 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 [40].

Discussion and Conclusions: 1) Current Volatile Inventory: The current polar caps are the dominant active reservoir in the present water cycle; estimates of current volume and global equivalent layer (GEL) thickness are (North, $1.14 \times 10^6 \text{ km}^3$, GEL $\sim 7.8 \text{ m}$; South, $1.2 \times 10^6 \text{ km}^3$, GEL $\sim 8.3 \text{ m}$) [41]. The current polar caps are transient features, becoming unstable at increased obliquity [42]. **2) Alternate Volatile Reservoirs During Climate Change Evolution:** This survey supports the presence of several non-polar ice reservoirs that are currently not an active part of today's hydrological cycle but that were active in the Late Amazonian or earlier: 1) tropical mountain glaciers (TMG); 2) mid-latitude plateau and valley glaciers (MLG); 3) mid-high latitude regionally extensive ice mantles (LDM); 4) south circumpolar DAF. **3) Relationship of Climate Change Drivers and Alternate Volatile Reservoirs:** GCMs and related simulations support the interpretations that: 1) the current polar caps become unstable at obliquities $>30^\circ$ [42]; 2) LDMs form at obliquities between the current mean and $\sim 35^\circ$ [5]; 3) MLGs form at $\sim 35^\circ$ obliquity with appropriate dust opacity [43], 4) TMGs form at obliquities of $\sim 45^\circ$ [32]. Some uncertainty exists in the detailed transport mechanisms and timing [5, 32, 42]. **4) Sequestration: Evidence for Removal of Ice from the Active Climate System:** Abundant evidence (e.g., ring-mold craters (RMC) [20-21] and SHARAD data [22-23] in LDA/LVF and related deposits [38]; viscously relaxed craters [44] in TMGs; sublimation pits in pedestal craters [34]; RMCs, altimetry data, and surface textures in EECs [45]; and altimetry data and RMCs in CCF [14-15, 48] suggests that significant quantities of ice remain sequestered in association with ancient volatile reservoirs. These deposits have been sequestered by development of sublimation lags, sealing them off from significant participation in the current water cycle. This sequestration represents a process of removal of water from the active system and a corresponding decrease in the total volume involved in the active water cycle with time. **5) Amazonian Climate History:** Analysis of Amazonian-aged deposits suggests that the climate was largely cold and hyperarid throughout the Amazonian, with variations in spin-axis/orbital parameters causing migration of ice from the poles to form equatorial and mid-latitude glaciers, and mid-high latitude regional blankets of snow and ice. Statistical studies suggest that typical Amazonian conditions did not include the presence of polar ice cap reservoirs [2]. **6) Transition to the Hesperian-Noachian Climate:** The DAF, interpreted as a volumetrically very significant sequestered ice deposit [40], represents a step-function in the evolution of the climate of Mars. Estimated current DAF volumes ($\sim 2.19 \times 10^6 \text{ km}^3$; GEL $\sim 15 \text{ m}$ [40]) are close to the current combined polar cap volumes (GEL ~ 16) [41] and may be largely remnant water ice [46]. 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 hundred 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 [47]. 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, because of both their latitude and altitude. 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. **7) History of Climate Change:** On the basis of the inventory of water-related deposits to date, the DAF appears to represent the sequestered record of a significantly different climate that characterized the early history of Mars. This was followed in the Amazonian by a hyperarid cold climate with a lower-volume water cycle dominated by mobilization and lateral migration of surface snow and ice in response to variations in spin-axis/orbital parameters; the active water inventory decreased with time due to progressive sequestration of snow and ice beneath sublimation lags [17-24].

References: 1) M. Carr, *Water on Mars*, 1996; 2) J. Laskar et al., *Icarus* 170, 343, 2004; 3) D. Marchant and J. Head, *Icarus* 192, 187, 2007; 4) M. Richardson and J. Wilson, *JGR* 107, 5031, 2002; 5) M. Mischna et al., *JGR* 108, 5062, 2003; 6) J. Head et al., *Micro* 38 MS032, 2003; 7) J. Laskar et al., *Nature* 419, 375, 2004; 8) S. Milkovich and J. Head, *JGR* 110, 2349, 2004; 9) J. Head et al., *Nature* 426, 797, 2003; 10) R. Milliken et al., *JGR* 108, 2005, 2003; 11) J. Mustard et al., *Nature* 412, 4211, 2001; 12) J. Garvin et al., *MAPS* 41, 1659, 2006; 13) S. Squyres et al., *Mars*, U of AZ Press, 523, 1992; 14) M. Kreslavsky et al., *MAPS* 41, 1659, 2006; 15) J. Head et al., *Vernadsky-Brown Micro* 46, 2007; 16) B. Lucchitta, *JGR* 89, B409, 1984; 17) J. Head et al., *EPSL* 241, 663, 2006; 18) J. Head et al., *GRL* 33, L08S03, 2006; 19) J. Head and D. Marchant, *LPSC* 37 #1126, 2006; 20) L. Ostrach and J. Head, *LPSC* 38, #1100, 2007; 21) A. Kress and J. Head, *GRL* 35, 35501, 2008; 22) J. Holt et al., *Science* 322, 1235, 2008; 23) J. Plaut et al., *GRL* 35, 36379, 2008; 24) J. Dickson et al., *Geology* 36, 411, 2008; 25) E. Hauber et al., *JGR* 113, EO2007, 2007; 26) J. Head and D. Marchant, *Geology* 31, 641, 2003; 27) D. Shean et al., *JGR* 110, 05001, 2005; 28) S. Kadish et al., *Icarus* 197, 84, 2008; 29) D. Shean et al., *JGR* 112, 2761, 2007; 30) S. Milkovich et al., *Icarus* 181, 388, 2006; 31) J. Head et al., *Nature* 44, 336, 2005; 32) F. Forget et al., *Science* 311, 368, 2006; 33) J. Head et al., *GRL* 31, L10701, 2004; 34) S. Kadish et al., *GRL* 35, L16104, 2008; 35) S. Kadish et al., *LPSC* 39 1766, 2008; 36) B. Black and S. Stewart, *JGR* 113, EO2015, 2008; 37) S. Meresse et al., *MAPS* 41, 1647, 2006; 38) G. Pederson and J. Head, *EPSC* A-00422, 2008; 39) K. Tanaka and E. Kolb, *Icarus* 154, 3, 2001; 40) J. Head and S. Pratt, *JGR* 106, 12275, 2001; 41) D. Smith et al., *JGR* 106, 23689, 2001; 42) B. Levard et al., *JGR* 112, E06012, 2007; 43) J-B Madeleine et al., *LPSC* 38 1778, 2008; 44) J. Head and D. Marchant, *EMSEC-ESTEC*, 2007; 45) G. Pederson and J. Head, *LPSC* 40, 2008; 46) J. Plaut et al., *LPSC* 38 2144, 2007; 47) F. Forget et al., *AGU Fall Meeting*, P11A-0964, 2004; 48) J. Levy and J. Head, *EPSC2008* 00458, 2008.

