GEOLOGICAL EVIDENCE FOR HESPERIAN-AMAZONIAN CLIMATE CHANGE ON MARS: NORTH POLAR LAYERING, SOUTH POLAR BASAL MELTING AND CIRCUMPOLAR LAKES, MID-LATITUDE PLATEAU ICEFIELDS/DEBRIS-COVERED GLACIERS, AND TROPICAL MOUNTAIN GLACIERS. James W. Head, Dept. Geological Sciences., Brown University, Providence, RI 02912 USA (james_head@brown.edu).

A wide variety of geological evidence indicates that the climate on Mars has changed during its past history. This evidence is useful for helping to define the nature of past climates and the range of atmospheric and climatic conditions necessary to account for the geological evidence. Here we present a summary of recent work documenting some of these deposits, focusing on geological evidence related to the distribution of water in solid and liquid form. Evidence for these changes ranges in physical scale from layering in the polar caps [1] and sediments, to meters-thick layers extending from high to mid-latitudes [2], to kilometers-thick polar and circumpolar deposits [3]. The evidence is found throughout the geologic record of Mars, ranging from interpreted Amazonian mid-latitude valley glaciers [4], to tropical mountain glaciers [5], to much longer-term trends implied by the temporal distribution of geological features such as valley networks and outflow channels [6]. Furthermore, there is strong evidence for changes in the hydrological cycle of Mars that reflect long-term climate change [7, 8]. For the last ~80% of Mars' history, Mars appears to have been a very cold, hyper-arid polar desert, similar to parts of the Antarctic Dry Valleys [9]. The hydrologic system has been horizontally layered [7] with the hydrologic cycle consisting of a globally continuous cryosphere with liquid water occasionally emerging to the surface during magmatic events that cracked the cryosphere [10,11]. Most of the surface water was tied up in the polar caps and in the regolith, and variations in orbital parameters caused significant surface redistribution of ice and dust. In the first 20% of Mars' history, many believe that Mars was "warm and wet", there was no global cryosphere [6], and that the hydrological cycle was vertically integrated [8].

Atmospheric general circulation models are becoming more and more sophisticated and can now be analyzed at various scales, and include variations in atmospheric water vapor content, orbital parameters and surface properties [12-16]. New orbital parameter solutions provide robust insolation predictions for the last 10-20 million years [17], but assessments prior to this time are uncertain because solutions are chaotic. Nonetheless, simulations suggest a range of candidate solutions which can be compared to the geologic record, and statistical assessments predict that high obliquity periods were common in the earlier history of Mars. Synergism is developing between studies of the observed geological record, predictions of orbital parameter scenarios, and results of climate models. Highlighted here are some of the geological units and features that may provide insight into causes and magnitudes of climate change, and thus aid climate modelers in reconstructing the climatic evolution of Mars.

The Amazonian Period: (present back to ~3 billion years ago; [18-20]): The finely laminated layers observed in exposed troughs and walls in the North Polar cap are thought to provide the best record of recent climate change and variability [21]. Their importance lies in the possibility that the record is continuous and that rates of volatile exchange between mid-latitude and polar reservoirs may be derived. Laskar et al [22] proposed that the pattern of alternating bright and dark layers for the upper 350 m in one of the troughs is correlated to the variation in summer polar insolation driven by orbital forcing over the last 900 kyr. Fourier analysis of North Polar layer vertical sequences [1] revealed a characteristic and repetitive wavelength of ~30 m thickness throughout the upper ~300 m (Fig. 1, zone 1) interpreted to represent a 51 kyr insolation cycle. Analysis, characterization and dating of a meters-thick latitude-dependent mantling layer extending from 30^o N and S latitude to the poles [2, 23-25] led to the interpretation that this deposit represented a recent "glacial" period on Mars that occurred from ~2.4 to 0.4 Myr ago (Fig. 2) in response to the changing stability of water ice and dust during variations in obliquity reaching 30-35^o. Currently Mars is in an "interglacial" period [2] (Fig. 2). Unlike Earth, martian ice ages are characterized by warmer polar climates and enhanced equatorward transport of atmospheric water and dust to produce widespread mantling deposits down to mid latitudes. Apparently the rate of accumulation changed 400 kyrs ago from 0.025 cm/yr to 0.05 cm/yr [22]. This corresponds in time to the switch from net transport of volatiles from the polar regions to the mid-latitudes, to the reverse (Fig. 2) [2]. Calculations show that a mid-latitude surface layer 10 meters thick between 30-50° with an ice content of 10-100% is the equivalent of a north polar cap thickness of 30-300 meters. The lower limit is the estimated thickness of the youngest deposits on the north polar cap. Thus the mass of volatiles that can be transported among these reservoirs is broadly consistent with the observed geologic characteristics. Further analysis of the North Polar layered terrain [1] revealed a ~100 m thick sequence (Fig. 1, zone 2) containing no signal, and interpreted to represent a sublimation lag produced during the recent period of polar water mobilization and transport equatorward [2]. These studies support earlier interpretations that orbital parameter variations could cause significant erosion, and possibly complete removal of the polar caps. The polar caps represent a water reservoir available for redistribution during earlier periods of climate change. But what about earlier in the Amazonian, when obliquity variations are thought to have been even more extreme [17]? During periods of lower obliquity than present, polar ice accumulation will be at a maximum, and during very low obliquity, the atmosphere is likely to collapse [25a]. The presence of ice-rich deposits in circumpolar crater interiors indicates that significant local accumulations of ice can be emplaced and remain in microenvironments at lower latitudes [26-27] during periods of higher obliquity. Indeed microenvironments in some crater interiors show evidence for recent cold-based glacial deposits at 70^{o} N latitude [28]. Mid-latitude lobate debris aprons and lineated valley fill have long been thought to be related to atmospheric vapor diffusion and ice-assisted debris flow [29]. Recent studies with high-resolution data have revealed compelling evidence for integrated plateau/valley glacial landsystems [4, 30-35], where ice and snow accumulation in alcoves and on plateaus has led to the formation of debris-covered glaciers in very widespread areas at mid-latitudes [35], piedmont-like flows (Fig. 3, 4), and converging flows of valley glaciers producing major fold-like loops (Fig. 5, 6). These deposits indicate that there were times during the Amazonian when ice was stable at mid-latitudes and accumulated to significant thickness both in local alcoves and on adjacent plateaus [36]. Furthermore, local valley networks produced on some volcanic edifices at these latitudes appear to form when localized magmatic heating occurs at times of edifice snow cover, causing melting and channel formation [37].

New spacecraft data and an understanding of the nature of cold-based glacial processes and landforms [5], has led to the more confident interpretation of the fan-shaped deposits on the NW flanks of the Tharsis Montes [5, 38] and Olympus Mons [39] as tropical mountain glaciers up to ~180,000 km^2 in areal extent (Arsia), and likely reaching at least two km in thickness during their emplacement. We used five scenarios of possible past obliquity histories [17] to drive an ice sheet model with a parameterization of climate that allows for variations as the obliquity changes and as the ice sheet grows and shrinks [40]. Geological and glacial modeling evidence show that inner portions of these deposits may be active long after the major ice sheet largely disappears [40,41]. Detailed examination shows evidence for a Late Amazonian age and multiple phases of advance and retreat [42].

What conditions might lead to the formation of tropical and mid-latitude glaciers? Forget et al. [16] used high-resolution climate simulations to show that the present-day water cycle, under 45^{o} obliquity conditions, predicts ice accumulations on the western flanks of the Tharsis Montes due to adiabatic cooling and precipitation (Fig. 10, 11). This agreement provides support for the idea that the combination of geological observations and atmospheric modeling may help to unravel the climate history of Mars.

Is there currently extensive groundwater in the subsurface? An approach to assessing the presence of subsurface groundwater [43] involved using the large Amazonian-aged crater Lyot as a 'probe'. Lyot should have penetrated through the cryosphere and well into the subsurface groundwater table, creating an 'artesian well' situation that should have resulted in significant outflow of impounded groundwater. However, there is no compelling evidence for release and outflow of water, leading to the conclusion that significant subsurface water may not have been present below at least this part of the northern lowlands during this time in the Amazonian. On the other hand, outflow of subsurface water has clearly occurred in the Amazonian in the region surrounding the Elysium Rise. First and most recently, to the east in Elysium Planitia and into Amazonis Planitia, very recent lava flows and fluvial episodes have occurred [11, 44-46]. On the western margin of the Elysium Rise, extensive deposits interpreted to be water-rich flows and lahars [47-48] occur, and were emplaced at several times in the Amazonian. These two events have delivered sub-surface water to the surface, suggesting the presence of either abundant groundwater beneath the cryosphere and/or remelting of significant portions of the cryosphere, at least in the Elysium Rise area. Where did this water go? Obviously some could be soaked up in the dehydrated upper layers in the near equatorial regions. Much of it could have gone to cold traps at the poles or to local areas of upwelling and deposition, such as that represented by the Medusae Fossae Formation [49] and tropical and mid-latitude glaciers [4-5].

The Hesperian Period: (about 3 to 3.6 billion years ago; [18-20]): The martian outflow channels debouched into the northern lowlands primarily in the Late Hesperian Period [50] and their characteristics suggest to many workers that a large standing body of water, or ocean, was produced as a result [51]. Characteristics of northern lowland deposits in the Early Amazonian Period suggest that by this time such an ocean was gone [52]. What would be the fate of such standing bodies of water under climatic conditions similar to the present? The evolution of water loaded with sediments emplaced by outflow channel formation would include three phases. (1) Violent emplacement of warm water followed by a short period of intensive evaporation and convection. Water vapor would strongly influence the climate, at least for a geologically short time; when the water reached 277 K, boiling and intensive convection ceased and sediments were deposited. (2) Geologically fast (10^4 years) freezing accompanied by weak convective water movement. (3) Sublimation of the ice lasted longer than freezing, but for a geologically short period. The rate and latitudinal dependence of sublimation, and locations of water vapor condensation, crucially depend on planetary obliquity, climate, and sediment veneering of the ice. Several observations support the hypothesis that the Late Hesperian Vastitas Borealis Formation is the sublimation residue of the ocean [53-54]. Glacial deposits at the source region of Mangala Valles [55], and residual ice-rich deposits on the floor [56], suggest that the water erupted into an environment similar to that of the present. The Dorsa Argentia Formation, a very extensive south circumpolar deposit [26] of Hesperian age, may represent the accumulation of volatiles following the emplacement and sublimation of the northern lowlands 'ocean'. These deposits, in turn, underwent retreat and melting, and flowing water formed eskers and channels, emptying into the Argyre Basin [57]. In the Early Hesperian Period, a significant flux of volcanism occurred in the form of the Hesperian ridged plains, and this may well have represented a major pulse of volatiles into the atmosphere [58,59]. In addition, there is clear evidence of interaction of these volcanic deposits and large volatile-rich deposits in the south polar region [60,61], causing melting and drainage of liquid water.

Over the last 80% of the history of Mars, permafrost and the cryosphere dominate the surface. Although there is compelling evidence that liquid water formed occasionally on the surface and moved locally, there is no compelling evidence that indicates that the global cryosphere was absent at any time throughout the most recent 80% of the history of Mars. Mars surface conditions appear to have been cold and dry throughout most of its history, very similar to the way they are now. Further evidence of this is the limited amount of aqueous chemical alteration detected from orbit [62,63] and in martian meteorites [64]. Obliquity extremes, and intrusive volcanic activity related to the two major rises, Tharsis and Elysium, appear to have redistributed some water but liquid water was transient on the surface for the vast majority of Mars' history.

The Noachian Period: Geological evidence has been cited to support a 'warm, wet' era [65] in the earlier Noachian Period (e.g., valley networks, degradation rates, etc.) and standing bodies of water under these earlier conditions have different origins and could have significantly longer residence times. Critical assessment of this evidence leads to several scenarios for the emplacement style, location and fate of water on early Mars during the first 20% of its history, and the important transition to conditions similar to those of today. Candidate early Mars emplacement styles include: 1) pluvial, 2) sapping and groundwater recharge, 3) ice sheet meltback [66], 4) global hydrostatic equilibrium, and 5) cryospheric seal disruption. Alternatively, early Mars may have been 'cold and dry'.

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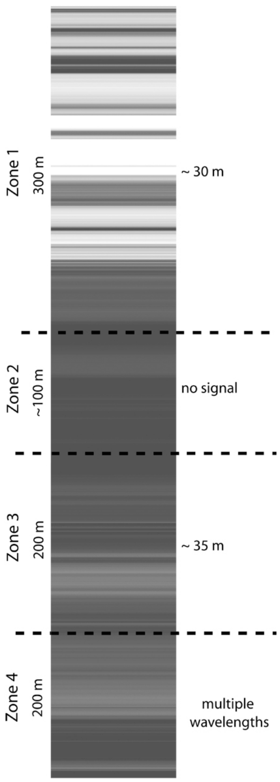

Fig. 1. Composite NP stratigraphic column [1].

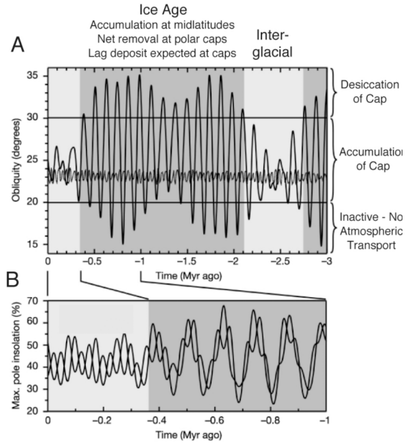

Fig. 2. Orbital forcing of climate [2].

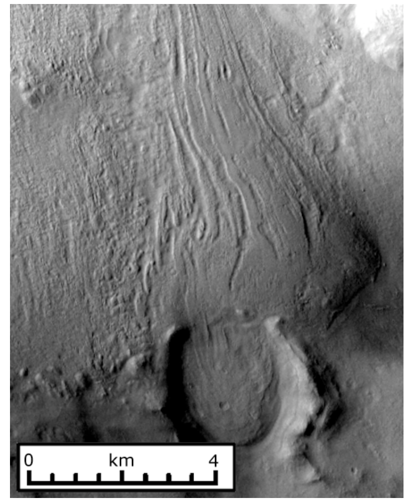

Fig. 3. Piedmont-like lobe in distal LDA.

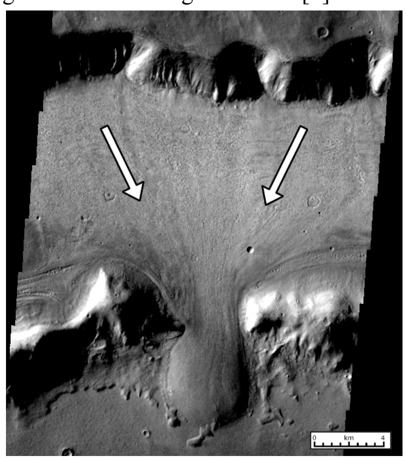

Fig. 4. Linear LDA blocked by parallel ridges, merges to form LVF and piedmont lobe in gap.

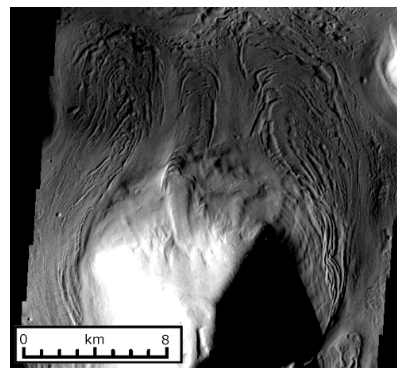

Fig. 5. LDAs flowing around mesa.

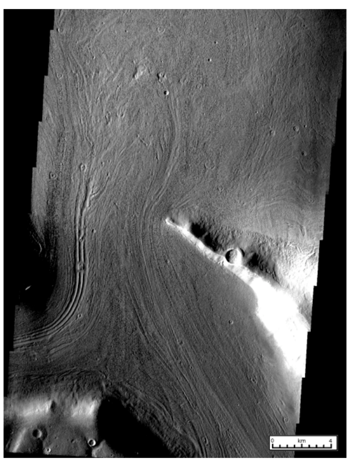

Fig. 6. Large fold where LVF converges and becomes LDA. Themis V11433004.

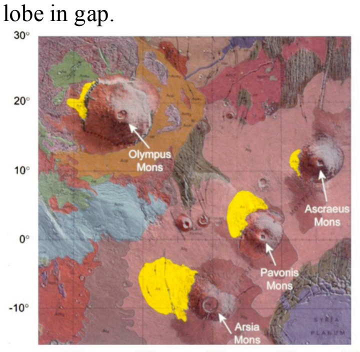

Fig. 7. Fan-shaped deposits [16].

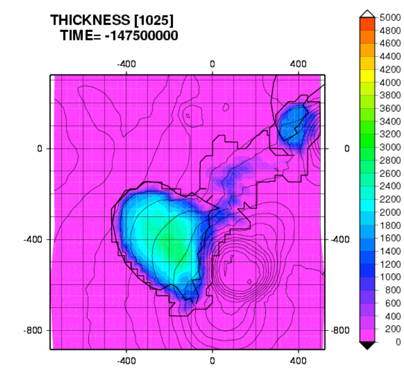

Fig. 8: N001_N at 147.5Ma peak configuration. [40]

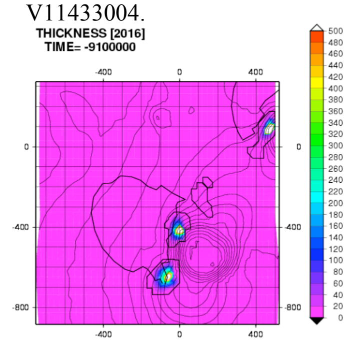

Fig. 9. N001_N at 9.1 Ma late configuration. [40]

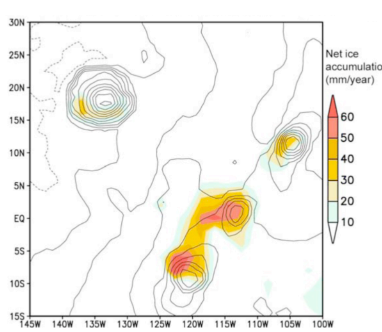

Fig. 10. Net surface water ice accumulation [16].

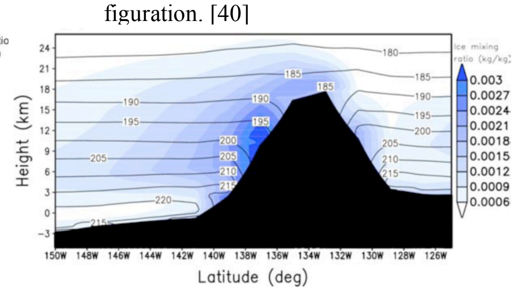

Fig. 11. Cross-section of Olympus Mons [16].