GEOLOGICAL EVIDENCE FOR CLIMATE CHANGE ON MARS.

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Summary: A wide variety of geological evidence indicates that the climate on Mars has changed during its past history. Evidence for these changes ranges in physical scale from layering in the polar caps and sediments, to meters-thick layers extending from high to mid-latitudes, to kilometers-thick polar and circumpolar deposits. The evidence is found throughout the geologic record of Mars, ranging from interpreted Amazonian tropical mountain glaciers to much longer term trends implied by the temporal distribution of geological features such as valley networks and outflow channels. Furthermore, there is strong evidence for changes in the hydrological cycle of Mars that reflects long-term climate change. For the last ~80% of Mars' history, Mars appears to have been a very cold, hyper-arid polar desert. The hydrologic system has been horizontally layered 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. 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, and that the hydrological cycle was vertically integrated.

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. We are now approaching the time when synergism is developing between studies of the observed geological record and predictions and results of climate models. The purpose of this paper is to highlight some of the geological units and features that may be related to climate change, and to encourage climate modelers to assess the potential significance of these.

Introduction: One of the key aspects of mapping climate change is to assess the distribution and behavior of water on Mars [1,2]. What does the geology tell us about the presence, sources, residence times, stability, duration and evolution of water on Mars [2]? The Hesperian and Amazonian periods represent the last ~80% of the history of Mars [3-5]. MOLA data have shown that the major topographic features of Mars formed early and have changed little over geologic time [6]. Thus, analysis of topography, slopes and roughness data, as well as other data sets, can test previous hypotheses for volatile-rich deposits and standing bodies of water, provide important new information, and allow us to explore the implications of these results for climate change on Mars.

The Amazonian Period: (present back to ~3 billion years ago; [3-5]): The finely laminated layers observed in exposed troughs and walls in the North Polar cap are thought to provide the best record of martian climate change and variability [36,38]. 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 [41]. Laskar et al [36] proposed that the pattern of alternating bright and dark layers for the upper 350 m of section in one of the troughs is correlated to the variation in summer polar insolation driven by orbital forcing over the last 900 kyr. The rate of accumulation changed 400 kyrs ago from 0.025 cm/yr to 0.05 cm/yr. This corresponds in time to the switch from net transport of volatiles from the polar regions to the mid-latitudes to the reverse in the ice-age model of [37]. 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.

These results imply a general consistency between studies of detailed processes in the polar cap and the global geologic evidence and modeling result-supported evidence for recent climate change. Nevertheless there are significant questions raised regarding the record of climate change in the polar caps. What is the actual process of accumulation on the caps and how do the individual layers form? Does the cap accumulate but at a slower rate during high obliquity periods or is there wide spread sublimation and a decrease in cap thickness. What are the sources of volatiles during all periods of orbital variations over thousands to millions of years?

Present polar deposits consist of Late Amazonian ice (Api) and underlying layered terrain (Apl). A large deep trough in the north polar deposits, Chasma Boreale may have been produced by basal melting [8-9]. Recent analysis suggests that this melting could have been as recently as several million years ago, during a period of enhanced mean obliquity [10-11]. This interpretation also suggests that much of the polar layered terrain could predate this time and that Api could be related to deposition following the enhanced emplacement of volatiles into the atmosphere. Much uncertainty exists about the age of earlier components of the polar deposits and indeed whether they largely disappear and reform during obliquity extremes [see review in 12]. Prediction is made less certain by the difficulty in predicting the past, but recent studies are improving these calculations [13].

An alternate approach to assessing the presence of subsurface groundwater [14] 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 [15-18]. On the western margin of the Elysium Rise, extensive deposits interpreted to be water-rich flows and lahars [19-20] 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 [21]. Evidence for tropical mountain glaciers adjacent to the Tharsis Montes and Olympus Mons provides further evidence for climate change [39].

The Hesperian Period: (about 3 to 3.6 billion years ago; [3-5]): The martian outflow channels debouched into the northern lowlands primarily in the Late Hesperian Period [2] and their characteristics suggest to many workers that a large standing body of water, or ocean, was produced as a result [22]. Characteristics of northern lowland deposits in the Early Amazonian Period suggest that by this time such an ocean was gone [23]. 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 [24-25]. 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, melting, and water flowed in discrete channels, emptying into the Argyre Basin. 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 [27-28]. In addition, there is clear evidence of interaction of these volcanic deposits and large volatile-rich deposits in the south polar region [29-30], 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 [31] and in martian meteorites [32]. 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 [33] 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 melt-back, 4) global hydrostatic equilibrium, and 5) cryospheric seal disruption. Alternatively, early Mars may have been cold and dry [34,35].

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