MARS CLIMATE HISTORY: A CRATERING PERSPECTIVE. James W. Head[1], [1]Brown University, Department of Earth, Environmental and Planetary Sciences, Providence RI 02912 USA (james_head@brown.edu).

Introduction and Approach: Deciphering climate history has been one of the major goals of the scientific exploration of Mars because of the significance of climate as a proxy for understanding: 1) planetary volatile accretion, 2) outgassing history, 3) the distribution and stability of water and the nature and evolution of the water cycle, 4) the surface weathering environment, 5) the presence, stability, and abundance of liquid water, 6) the implications for environments conducive to the origin and evolution of life [1], and 7) the influence of climate on the cratering process. Recent intensive exploration has contributed significantly to the understanding of current Mars weather, and lengthening observational baselines are beginning to reveal the basic elements of climate. This baseline knowledge is essential to the proper understanding of the longer-term history of climate. Assessing longer-term climate change and its history can be approached from a process-response standpoint through the identification of cause and effect [2] (Fig. 1). Among the most important causes of climate change (input parameters) are external forcing functions linked to spin-axis and orbital variations, elements whose nature and history have recently become much more well-understood in both the time and frequency domain [3]. The influence of these external forcing functions on the climate system (the internal response mechanism) are becoming more well known through increasingly more sophisticated atmospheric general circulation models [4-7], including the behavior of water. Finally, the consequences of the causes (the external forcing functions, spin-axis/orbital parameters, operating on the internal response mechanism, the climate system) produces an effect in the time and frequency domain (the geological record); increasing availability of global data is providing a more comprehensive view of over four billion years of geological history [8]. Specifically, increased knowledge of the structure of current polar deposits [9], the location of geological deposits that chronicle the distribution and history of non-polar ice [10], and the context in which to interpret ice deposits in extremely cold hyper-arid Mars-like conditions [11], have all contributed to an increased understanding of the climate history of Mars. We assess the impact on the cratering process.

Amazonian: (present to ~3 Ga; [20-22]) A robust prediction of the spin-axis/orbital parameter-based insolation input to the climate system has been developed for the last 20 Ma [3] and these predictions have been used to begin to decipher the history of the polar cap [12-14], the nature of recent ice ages [15], the timing of active layers at high latitudes [16], and the conditions under which liquid water might form gullies during this time [17]. Prior to the last 20 Ma, deterministic predictions are not currently possible because solutions based on the input parameters become chaotic; nevertheless exploring this parameter space, Laskar et al. produced 15 scenarios showing candidate obliquity histories over the last 250 Ma (Fig. 2), and predicted that mean obliquity would be ~38° [3]. Analysis of these 15 examples shows the huge range of options for Late Amazonian climate history. In contrast to the last 20 Ma, where input parameters to the climate system are well-known, there is no robust prediction for a specific input parameter history to use as a test in interpreting the geological record. Therefore, we have adopted a different approach and use the geological record of non-polar ice deposits [10] (the output of the external forcing function and climate system) and a general knowledge of the behavior of the GCM and climate system under different obliquity baselines, to evaluate the 15 candidate scenarios of the obliquity component of the external forcing function.

Earlier Amazonian: Using a general knowledge of the behavior of the GCM under different obliquity conditions, we chose four mean baselines to form a framework for evaluating the 15 candidate obliquity scenarios for the last 250 Ma (Fig. 2) [18]. We applied the geological observations, in terms of interpreted latitude and time [10], to assess the candidate obliquity scenarios and found that the obliquity scenario that was most consistent with age and obliquity constraints (Fig. 2-8) is characterized by 45° obliquity at the times of both the early and late TMGs, and obliquity at or close to 35° during mid-latitude glaciations. Examination of the geological record of non-polar ice deposits, together with related information strongly suggests that the climate of Mars throughout the Amazonian was much like at is today, but with migration of surface ice in response to variations in spin-axis/orbital parameters, primarily obliquity. A corollary is that the hydrological cycle was horizontally stratified during the Amazonian [19].

The Hesperian Period: (~3-3.6 Ga; [20-22]): The martian outflow channels debouched into the northern lowlands primarily in the Late Hesperian Period [1] and their characteristics suggest to many workers that a large standing body of water, or ocean, was produced as a result. Characteristics of northern lowland deposits in the Early Amazonian Period suggest that by this time that if such an ocean existed it was gone. The evolution of water loaded with sediments emplaced by outflow channel formation has been modeled [23]; results suggest that it would freeze and sublime on very short time scales. The Late Hesperian Vastitas Borealis Formation may be the sublimation residue of the ocean [23]. 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 [24-25]. In addition, there is clear evidence of interaction of these volcanic deposits and large volatile-rich deposits in the south polar region [26], 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 [27] and in martian meteorites [28]. 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: (>3.6 Ga; [20-22]): Geological evidence has been cited to support a 'warm, wet' era [29] in the late Noachian Period (e.g., valley networks, degradation rates, etc.). Critical assessment of this evidence and new data lead 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. This traditional view has recently been challenged by several developments [19]: 1) The growing evidence that mineralogic indicators for early phyllosilicates (interpreted to support warm and wet surface conditions [30]) could also be explained by subsurface hydrothermal effects in an early period of high thermal flux [31]; 2) The difficulty of producing and maintaining an atmosphere that could lead to a warm and wet early Mars with pluvial activity [32]; 3) Evidence that south circumpolar ice deposits are consistent with cold lower latitude surface temperatures [33]; 4) The poor integration of the surface hydrologic system (valley networks, open-basin lakes [34-35], suggesting short term activity, rather than long term integrated pluvial systems; 5) Emerging evidence in the Antarctic Dry Valleys that Mars-like fluvial and lacustrine activity can occur under surafce climate conditions with mean annual temperatures (MAT) well below 0°C [11]; 6) The possibility that surface drainage features could be explained by top-down transient atmospheric effects caused by punctuated volcanism during the late Noachian-early Hesperian (LN-EH) [36]. Three alternate scenarios for a "non-warm and wet" early Mars appear to be consistent with the six new developments outlined above [19]. Could Mars have been cold and dry or cold and wet, instead of the pluvial warm and wet early Mars envisioned by many [e.g., 29]? Our current data and analyses suggest that Mars was more likely to have been characterized by a "cold and icy" early history and a horizontally stratified hydrologic system throughout most of its history. In this scenario, the Hesperian represents a *perturbation* on the historically horizontally integrated hydrological system, rather than a *transition* from vertical integration to horizontal stratification. We continue to test these scenarios.

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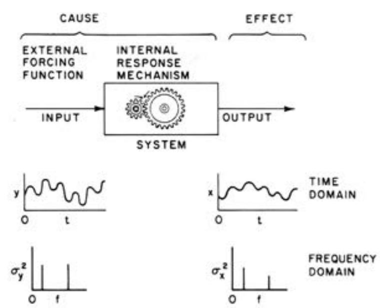

Fig. 1. Process-response framework for analysis of the climate system on Mars [2].

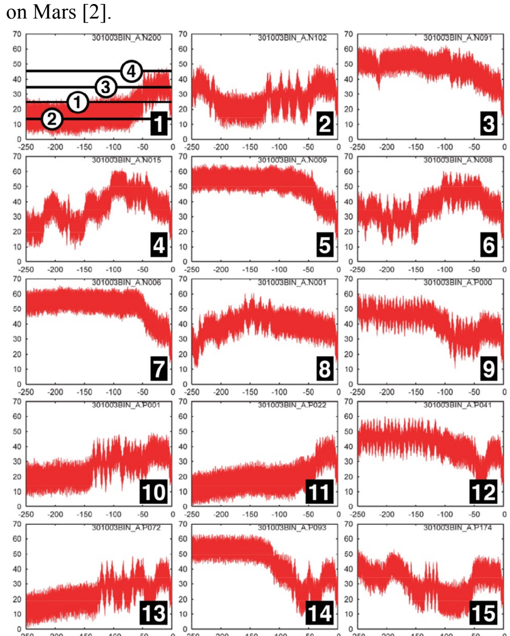

Fig. 2. Examples of possible evolution of Mars' obliquity over the past 250 Myr [3]. Numbered lines in 1 indicate four obliquity scenarios.