DECIPHERING THE LATE AMAZONIAN CLIMATE HISTORY OF MARS: ASSESSING OBLIQUITY PREDICTIONS WITH GEOLOGICAL OBSERVATIONS AND ATMOSPHERIC GENERAL CIRCULATION MODELS.

J. W. Head[1], D. R. Marchant[2], F. Forget[3], J. Laskar[4], J.-B. Madeleine[3], J. L. Fastook[5] (james_head@brown.edu). [1]Brown Univ., Providence RI 02912; [2]Boston Univ., Boston MA 02215; [3]LMD, CNRS/UPMC/IPSL, Paris, France; [4]IMCCE, Observatoire de Paris, Paris, France; [5]Univ. of Maine, Orono 04469.

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, and 6) the implications for environments conducive to the origin and evolution of life [1]. 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.

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.

Analysis and Discussion: 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: **Baseline 1 (~25°):** Current mean obliquity; robust water-ice polar caps, high-latitude ground ice [18], surface/near-surface ice unstable in equatorial and mid-latitude regions [19]. **Baseline 2 (~15°):** Very low mean obliquity; CO_2 atmosphere collapses, condenses at poles [20]; **Baseline 3 (~35°):** Intermediate mean obliquity; no polar cap [14], mid-latitude glaciation with appropriate dust opacity [21]. **Baseline 4 (~45°):** Moderate mean obliquity; equatorial reservoir dominates [22]; tropical mountain glaciers [23-28]. For the geological record, we use the summary of non-polar ice occurrences and chronology compiled in [10]. We now use these four mean baselines as a framework to evaluate the 15 candidate obliquity scenarios for the last 250 Ma. First, the 15 candidates can be classified into four different groups on the basis of total duration of time, and consistency of time, spent at different mean obliquities: **Group 1:** At or below 20° for periods of more than 100 Ma (Fig 2-1;10;11;13). **Group 2:** At or above 45° for periods of more than 100 Ma (Fig. 2-3;5;7;9;12;14). **Group 3:** Intermediate between these two mean values for the majority of the period (Fig. 2-2;4;6;8;15). Within these groups, clear variations are seen in: 1) the duration of time spent at a specific mean obliquity (compare 2-1 and 2-4); 2) the linearity or sinuosity of the mean obliquity path over 250 Ma (Fig. 2; compare 7, highly linear, with 4 and 15, highly sinuous); and 3) the episodicity of the amplitude of oscillations about the mean (Fig. 2-2; compare 50-125 Ma to 125-200 Ma BP).

We can now apply the geological observations, in terms of interpreted latitude and time [10], to assess the candidate obliquity scenarios. The Tharsis Montes tropical mountain glacier deposits (Arsia, Pavonis, Arcraeus) [24-26;29] have been dated to a period estimated to lie in the range between >50 Ma (superposed lava flows) and ~650 Ma (the deposit itself) [29], with Ascraeus ~25-380 Ma [25] and the nearby Olympus Mons glacial deposits in the 130-280 Ma range [30]. Recurring, smaller scale deposits were emplaced at Arsia in the last ~35-115 Ma (model age ~65 Ma) [26]. GCM simulations [21] predict the formation of mid-latitude glaciers in the northern midlatitudes at ~35° obliquity with appropriate dust opacity; deposits interpreted to be mid-latitude glaciers [31-32] formed at ~ 200-300 Ma BP [33], and similar mid-latitude debris covered glaciers formed at about 75 Ma in the southern mid-latitudes [34]. The presence of these deposits in these time periods argues against all Group 1 (very low obliquity) candidate scenarios (1;10;11;13), all Group 2 (high obliquity) scenarios (3;5;7;9;12;14), and almost all Group 3 (intermediate obliquity) scenarios (2;4;6;15). The remaining candidate obliquity scenario that could plausibly be consistent with the age and obliquity constraints (Fig. 2-8) is characterized by 45° oblquity at the times of both the early and late TMGs, and obliquity at or close to 35° during mid-latitude glaciations.

Conclusions: Examination of the geological record of non-polar ice deposits can help significantly in distinguishing among candidate Late Amazonian obliquity histories. It is important to note that even the remaining candidate obliquity scenario (Fig. 2-8) is not necessarily the correct one as none of the solutions are deterministic; nonetheless, the ability to reject the vast majority of the candidate scenarios underlines the usefulness of the approach. Further, these results suggest that the actual obliquity history was not likely characterized by long-term (>150 Ma) periods at extreme values. Additional dating of these non-polar, ice-related deposits [10] can help populate the constraint space for the last 250 Ma, providing an increasingly more detailed and realistic Late Amazonian obliquity and climate history. Because spin-axis/orbital parameter prior to 20 Ma are not currently uniquely predictable [3], the geological record provides the basis to: 1) further test predictions, and 2) construct the actual obliquity history, one of the major input parameters necessary to characterize the Late Amazonian climate history. Similar approaches can be applied to earlier periods of Mars history.

References: 1) M. Carr, *Water on Mars*, 1996; 2) J. Imbrie, *Icarus* 50, 408, 1982; 3) J. Laskar et al, *Icarus* 170, 343, 2004; 4) F. Forget et al., *JGR* 104, 24155, 1999; 5) M. Richardson and J. Wilson, *JGR* 107, 5031, 2002; 6) M. Mischna et al., *JGR* 108, 5062, 2003; 7) R. Haberle et al., *JGR* 106, 23317, 2003; 8) M. Carr, *The Surface of Mars*, Cambridge, 2006; 9) R. Phillips et al., *Science* 320, 1182, 2008; 10) J. Head and D. Marchant, *LPSC 39* 1295, 2008 and this volume; 11) D. Marchant and J. Head, *Icarus* 192, 187, 2007; 12) J. Laskar et al, *Nature* 419, 375, 2004; 13) S. Milkovich and J. Head, *JGR* 110, 2349, 2004; 14) B. Levrard et al, *JGR* 112, E06012, 2007; 15) J. Head et al., *Nature* 426, 797, 2003; 16) M. Kreslavsky et al., *MAPS* 41, 1659, 2006; 17) F. Costard et al. *Science* 295, 110, 2002; 18) W. Boynton et al., Science 296, 8, 2002; 19) M. Mellon and B. Jakosky, *JGR* 100, 11781, 1995; 20) M. Kreslavsky and J. Head, *GRL* 32, L12202, 2005; 21) J-B Madeleine et al, *LPSC 38* 1778, 2007; 22) F. Forget et al. *Science* 311, 368, 2006; 23) J. Head and D. Marchant, *Geology* 31, 641, 2003; 24) D. Shean et al., *JGR* 110, 05001, 2005; 25) S. Kadish et al, *Icarus* 197, 84, 2008; 26) D. Shean et al, *JGR* 112, 2761, 2007; 27) S. Milkovich et al., *Icarus* 181, 388, 2006; 28) J. Fastook et al., *Icarus* 198, 305, 2008; 29) D. Shean et al. *LPSC 37* 2092, 2006; 30) G. Neukum et al., *Nature* 432,971, 2004; 31) J. Head et al. *EPSL* 241, 663, 2006; 32) J. Head et al., *GRL* 33, L08S03, 2006; 33) N. Mangold, *JGR* 108, 8021, 2003; 34) J. Head et al. *Nature* 44, 336, 2005.
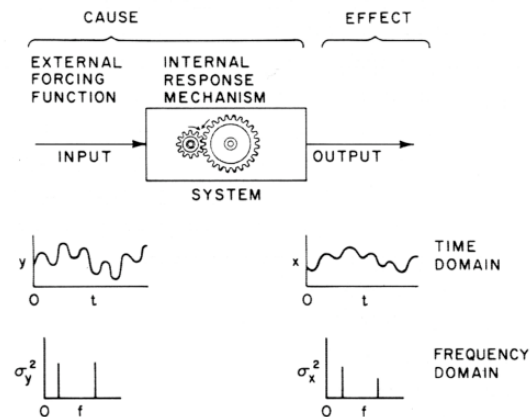

Fig. 1. Process-response framework for analysis of the climate system on Mars [2].
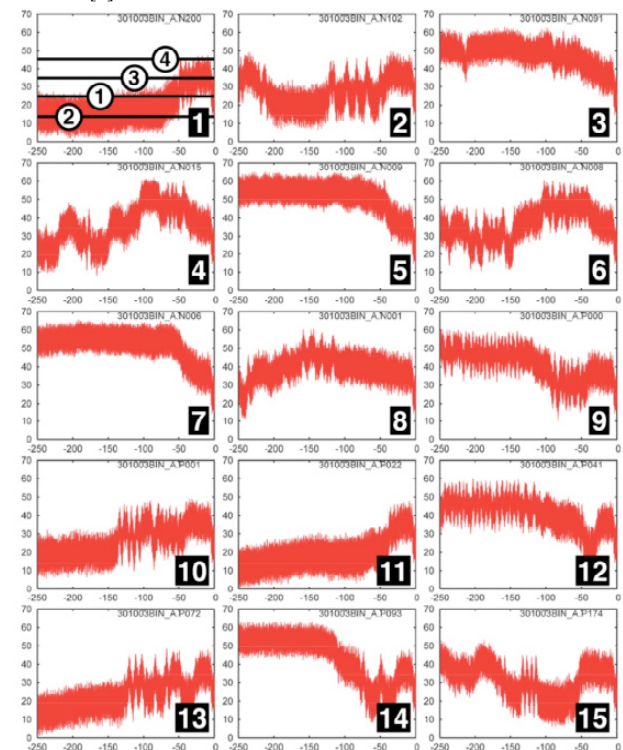

Fig. 2. Examples of possible evolution of Mars' obliquity over the past 250 Myr [3]. Numbered lines in 1 indicate four obliquity scenarios.