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Amazonian northern mid-latitude glaciation on Mars: A proposed climate scenario

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ABSTRACT

Recent geological observations in the northern mid-latitudes of Mars show evidence for past glacial activity during the late Amazonian, similar to the integrated glacial landsystems in the Dry Valleys of Antarctica. The large accumulation of ice (many hundreds of meters) required to create the observed glacial deposits points to significant atmospheric precipitation, snow and ice accumulation, and glacial flow. In order to understand the climate scenario required for these conditions, we used the LMD (Laboratoire de Météorologie Dynamique) Mars GCM (General Circulation Model), which is able to reproduce the present-day water cycle, and to predict past deposition of ice consistent with geological observations in many cases. Prior to this analysis, however, significant mid-latitude glaciation had not been simulated by the model, run under a range of parameters.

In this analysis, we studied the response of the GCM to a wider range of orbital configurations and water ice reservoirs, and show that during periods of moderate obliquity ($\epsilon = 25$–$35°$) and high dust opacity ($\tau_{dust} = 1.5$–2.5), broad-scale glaciation in the northern mid-latitudes occurs if water ice deposited on the flanks of the Tharsis volcanoes at higher obliquity is available for sublimation. We find that high dust contents of the atmosphere increase its water vapor holding capacity, thereby moving the saturation region to the northern mid-latitudes. Precipitation events are then controlled by topographic forcing of stationary planetary waves and transient weather systems, producing surface ice distribution and amounts that are consistent with the geological record. Ice accumulation rates of $\sim$10 mm yr^{-1} lead to the formation of a 500–1000 m thick regional ice sheet that will produce glacial flow patterns consistent with the geological observations.

1. Introduction: evidence for northern mid-latitude ice presence and glaciation on Mars

Evidence for the influence of non-polar ice deposition on geomorphic features and processes became available as a result of the comprehensive global coverage provided by the Viking Orbiter imaging system. For example, Squyres (1978, 1979) attributed a variety of landforms (e.g., lobate debris aprons, lineated valley fill, concentric crater fill, terrain softening) to the creep of the martian regolith aided by the deformation of ground ice at latitudes higher than $\sim$30°. Other workers (e.g., Lucchitta, 1981) noted that many of these features appeared to represent not just ice-assisted creep, but rather more substantial glacial-like flow. More recently, new high-resolution data have shown the presence of deposits interpreted to represent the remnants of extensive glacial landsystems that formed in the parts of the northern mid-latitudes during the Amazonian (e.g., Head et al., 2006b,a; Head and Marchant, 2006; Dickson et al., 2008). These recent analyses show the widespread development of valley glaciers, piedmont glaciers, plateau glaciation, and the development of extensive glacial landsystems across the northern mid-latitudes (see Fig. 1). Detailed examination of these deposits shows that ice may have reached thicknesses of up to 2–2.5 km in some regions along the dichotomy boundary (e.g., Head et al., 2006b,a; Dickson et al., 2008). Clearly, the current atmosphere and climate do not permit the accumulation of snow and ice at the level necessary to produce such deposits. This raises the question: Under what past climate conditions could the accumulation of snow and ice occur to produce the types of glacial deposits seen in the northern mid-latitudes?

Despite several climate modeling studies (Haberle et al., 2000; Mischna et al., 2003; Levrard et al., 2007; Forget et al., 2006; Montmessin et al., 2007), the origin of the northern mid-latitude glaciation has remained an enigma. Here, we extend this previous work to a wider range of climate parameters, and show that this broad-scale glaciation occurs if we assume that atmospheric dust content is higher than today (Newman et al., 2005), and that water ice deposited on the flanks of the Tharsis volcanoes is available for

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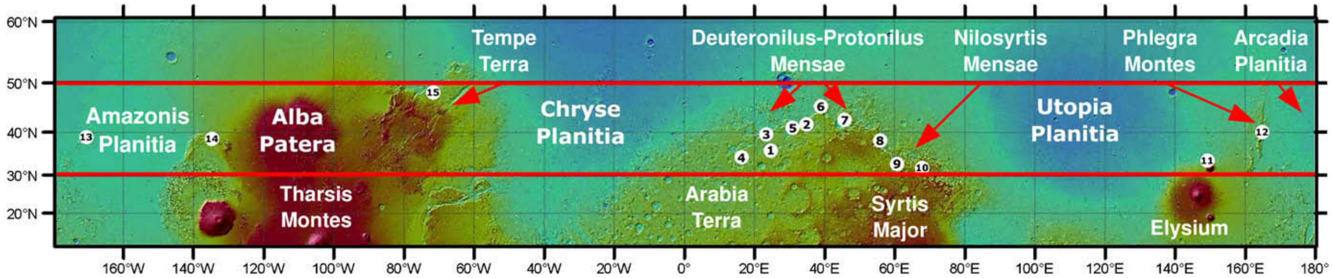

Fig. 1. Regions showing evidence of glaciation. The different sites are described in Head and Marchant, 2006.

sublimation (Forget et al., 2006). Using the LMD (Laboratoire de Météorologie Dynamique) Martian Global Climate Model (Forget et al., 1999), we thus address the following questions:

(1) What climatic mechanism can explain the formation of water–ice deposits of hundreds of meters thickness in the northern mid-latitudes of Mars?
(2) What accounts for the regionally heterogeneous longitudinal distribution of the deposits in the 30–50°N band?
(3) How are these glaciations related to orbital variations and can we determine the probable geologic periods of activity?
(4) What are the impacts of these deposits on the recent history of the martian water cycle?
(5) Is there any evidence for ice sequestration (removal of water ice from the system) during these glacial phases?

After a short review of the recent climatic history and description of our methods, we analyze in the following sections the climate of the northern mid-latitude glaciation. Then, we study its sensitivity to climate parameters, and finally discuss an updated climatic scenario for late Amazonian ice ages.

2. Geological evidence for orbital-driven climate change on Mars

2.1. Geomorphological settings

Accumulations of snow and ice, and glacial and periglacial landforms on Mars exhibit a range of morphologies typical of different types of deposits, glaciers and glacial subenvironments. Many of these show a stratigraphy which has been interpreted to record climate shifts due to orbital variations. In addition to the mid-latitude glacier deposits described in Section 1, numerous other examples of ice accumulation and glacial morphologies have been reported (Head, J.W., Marchant, 2008), the major ones being (1) the North and South Polar Layered Deposits, (2) the Latitude Dependent Mantle, and (3) the Tropical Mountain Glaciers.

Polar layered deposits consist of alternating dark and bright layers of ice mixed in different proportion with dust. They are visible on the walls of the north polar cap, and form a thick stratigraphic sequence seen in outcrop (Milkovich and Head, 2005) and in the subsurface with the SHARAD radar instrument on board Mars Reconnaissance Orbiter (Phillips et al., 2008). Recent detailed analysis by the High-Resolution Imaging Science Experiment (HiRISE) on board MRO revealed layers whose true thickness is as low as 10 cm, and whose apparent brightness is not only the result of layer composition, but also of surfacial frost and roughness (Herkenhoff et al., 2007), explaining why the interpretation of the polar layered deposit frequency signals is so difficult (Laskar et al., 2002; Milkovich and Head, 2005; Levrard et al., 2007).

The north and south latitude-dependent mantles are meters thick layered deposits draped on both hemispheres above 50°, and present in partially degraded states from 30° to 50° latitude. They are revealed in MOLA data by a latitudinal trend of roughness and concavity at 0.6 km baseline (Kreslavsky and Head, 2000, 2002), and in MOC images by various latitude-dependent geomorphologies (Mustard et al., 2001; Milliken et al., 2003). These results led to the conclusion that the latitude-dependent mantle was an ice and dust cover of atmospheric origin, deposited during recent ice ages and currently undergoing desiccation at lower latitudes (Head et al., 2003).

Tropical mountain glaciers refer to large mountain glacial systems on the western flanks of the Tharsis Montes and Olympus Mons (Head and Marchant, 2003). The largest of these, at Arsia Mons, covers an area of $\sim$170.000 km^2. Exploration of cold-based glaciers in the Antarctic Dry Valleys, one of the most Mars-like environments on Earth, has led to an understanding of the cold-based nature of most Mars glaciers and the interpretation of cold-based glacial deposits such as drop moraines, sublimation tills and debris-covered glaciers (Marchant and Head, 2007). The identification of deposits interpreted to result from cold-based glaciation in high-resolution images has permitted the reconstruction of these tropical mountain glaciers (Head and Marchant, 2003; Shean et al., 2005; Shean et al., 2007; Milkovich et al., 2006; Kadish et al., 2008), identification of the climatic conditions necessary for their formation (e.g., Forget et al., 2006), and the formulation of glacial flow models consistent with the geological features and settings (e.g., Fastook et al., 2008). Multiple arcuate ridges have been interpreted as drop moraines, lobate deposits represent debris-covered glaciers, and knobby terrain is interpreted to represent sublimation tills formed as the glaciers collapsed. These deposits show numerous episodes of advance and retreat during the late Amazonian.

Ages obtained through crater size-frequency analyses span the period from less than 10 Myr for the latitude-dependent mantle (Head et al., 2003) to 10–200 Myr for the tropical mountain glaciers (Shean et al., 2005). These data, together with the distribution of several other latitudinally distributed ice-related deposits (e.g., Head, J.W., Marchant (2008)) suggest long-term glacial activity during the Amazonian.

2.2. Mars orbital variations

Climate changes on Mars are driven by insolation variations comparable to terrestrial Milankovitch cycles. Spin-axis and orbital parameter variations of Mars are much larger than on Earth, and their evolution can only be calculated over a few millions of years (Laskar and Robutel, 1993) due to the strongly chaotic nature of the solutions prior to this time. A robust solution for the last 10 Myr, however, has been derived by Laskar et al. (2004), and is currently used as a guideline to explore recent climate changes. Variations of obliquity and eccentricity are given in Fig. 2. Insolation varies with a short 51 kyr period due to climatic precession, a 120 kyr period in obliquity, two 95 and 99 kyr periods in eccentricity, with the whole signal being finally modulated with a 2.4 Myr period (Laskar et al., 2002).