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Glaciation in the Late Noachian Icy Highlands: Ice accumulation, distribution, flow rates, basal melting, and top-down melting rates and patterns

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ABSTRACT

Geological evidence for extensive non-polar ice deposits of Amazonian age indicates that the current cold and dry climate of Mars has persisted for several billion years. The geological record and climate history of the Noachian, the earliest period of Mars history, is less certain, but abundant evidence for fluvial channels (valley networks) and lacustrine environments (open-basin lakes) has been interpreted to represent warm and wet conditions, including rainfall and runoff. Alternatively, recent atmospheric modeling results predict a "cold and icy" Late Noachian Mars in which moderate atmospheric pressure accompanied by a full water cycle produce an atmosphere where temperature declines with elevation following an adiabatic lapse rate, in contrast to the current situation on Mars, where temperature is almost completely determined by latitude. These results are formulated in the Late Noachian Icy Highlands (LNIH) model, in which these cold and icy conditions lead to the preferential deposition of snow and ice at high elevations, such as the southern uplands. What is the fate of this snow and ice and the nature of glaciation in such an environment? What are the prospects of melting of these deposits contributing to the observed fluvial and lacustrine deposits?

To address these questions, we report on a glacial flow-modeling analysis using a Mars-adapted ice sheet model with LNIH climate conditions. The total surface/near-surface water inventory is poorly known for the Late Noachian, so we explore the LNIH model in a "supply-limited" scenario for a range of available water abundances and a range of Late Noachian geothermal fluxes. Our results predict that the Late Noachian icy highlands (above an equilibrium line altitude of approximately +1 km) were characterized by extensive ice sheets of the order of hundreds of meters thick. Due to extremely cold conditions, the ice-flow velocities in general were very low, less than a few mm/yr, and the regional ice-flow pattern was disorganized and followed topography, with no radial flow pattern typical of an equilibrium ice sheet. Virtually the entire ice sheet is predicted to be cold-based, and thus the range of wet-based features typically associated with temperate glaciers (e.g., drumlins, eskers, etc.) is not predicted to occur. Wet-based conditions are predicted only locally in the thickest ice (on the floors of the deepest craters), where limited subglacial lakes may have formed.

These LNIH regional ice-sheets provide a huge reservoir of potential meltwater as a source for forming the observed fluvial and lacustrine features and deposits. Top-down melting scenarios applied to our LNIH ice sheet model predict that periods of punctuated warming could lead to elevated temperatures sufficient to melt enough snow and ice to readily account for the observed fluvial and lacustrine features and deposits. Our model indicates that such melting should take place preferentially at the margins of the ice sheets, a prediction that can be tested with further analyses.

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1. Introduction

The record of non-polar ice deposits throughout the Amazonian suggest a cold and dry climate not significantly different from the present climate observed on Mars (Head and Marchant, 2008), where latitudinal movement of ice is largely in response to the varying obliquity component of the spin-axis/orbital parameters (Laskar et al., 2004).

When one looks further into the past to the Noachian, the record is less clear and the characterization of the early martian climate is less certain. The existence of liquid water that flowed across the surface (Carr, 1995); Irwin et al., 2005; Fassett and Head, 2008a; Hynek et al.,

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2010) as well as open- and closed-basin lakes (Fassett and Head, 2008b) has led many to suggest that early Mars was "warm and wet" with rainfall (pluvial) activity (Masursky et al., 1977; Craddock and Maxwell, 1990; Craddock and Maxwell, 1993; Craddock et al., 1997; Clifford and Parker, 2001; Hynek and Phillips, 2001; Craddock and Howard, 2002; Pondrelli et al., 2008; Achille and Hynek, 2010). Furthermore, many studies suggest prolonged periods of rainfall in amounts at least comparable to that occurring in Earth's arid or semi-arid regions (Barnhart et al., 2009; Hoke et al., 2011; Howard, 2007; Irwin et al., 2011; Matsubara et al., 2013). Associated lakes, deltas, and alluvial fans show complex histories of fluctuating water and sediment discharges (Malin and Edgett, 2003; Moore and Howard, 2005; Di Achille et al., 2006; Fassett and Head, 2005, 2008; Di Achille and Hynek, 2010; Ponderelli et al., 2010; Grant et al., 2011; Buhler et al., 2011, 2014; Hoke et al., 2014), and these have often been interpreted to imply extended periods of precipitation and runoff (Moore et al., 2003; Jerolmack et al., 2004; Matsubara et al., 2011). Lacustrine and fluvial strata in Gale Crater, some of it examined in detail in situ, could represent millions of years of warmer and wetter condition in early Hesperian time (Grotzinger et al., 2014). Debated are 1) the total duration of the fluvial periods, 2) whether the fluvial erosion was continuous or episodic, and 3) the nature of the specific climate conditions that prevailed before and after (or during and between) the fluvial activity.

Others argue that the early martian climate was more likely to have been much colder and considerably drier (Gaidos and Marion, 2003; Fairen, 2010; Head et al., 2014) based on a number of lines of evidence that include proposed phyllosilicate formation mechanisms (Ehlmann et al., 2011), low erosion rates (Golombek et al., 2006), poorly integrated valley networks with the open-basin lakes that suggest short-term episodic fluvial formation rather than long-term pluvial activity (Stepinski and Coradetti, 2004), as well as the possibility that the form of most precipitation might have been snowfall (nivial) (Scanlon et al., 2013). However, little geomorphic evidence for typical wet-based glacial landforms (e.g., drumlins, eskers, etc.) dating from the Noachian has been cited in the southern uplands and elsewhere. Late Noachian eskers have been mapped locally in the south polar Dorsa Argentea Formation (Kress and Head, 2014), an extensive unit interpreted to represent the existence of a Late-Noachian/Early Hesperian south circumpolar ice sheet (Head and Pratt, 2001; Kress and Head, 2014). Even with evidence for Late Noachian eskers beneath an extensive south circumpolar ice sheet, and the ice thicknesses required to produce them, glacial flow modeling studies suggest a mean-annual temperature during the Late Noachian well below freezing (Fastook et al., 2012), also arguing for a "cold and icy" early martian climate.

Terrestrial analogs from the Antarctic Dry Valleys demonstrate that fluvial activity can take place at mean annual temperatures well below freezing (Marchant and Head, 2007; Head, 2014; Head and Marchant, 2014). Recent estimates of the rate of water lost to space (Chassefiere and Leblanc, 2011) indicate reduced amounts of water available for a "wet" Mars. Modeling results based on data from a martian meteorite (Cassata et al., 2012) are used to interpret the meteorite measurements as requiring lower atmospheric pressures. These data and interpretations, when coupled with the faint young Sun, make it very difficult for atmospheric modelers to produce a "warm and wet" early Mars (Haberle, 1998). "Extreme" events such as meteorite impacts have been proposed whereby an ephemeral "steam" atmosphere lasting a few thousand years might exist and produce the observed landforms (Segura et al., 2002; Segura et al., 2008; Toon et al., 2010); however, landform evolution modeling seems to contradict these findings (Moore et al., 2003; Jerolmack et al., 2004; Barnhart et al., 2009 Matsubara et al., 2011). Punctuated volcanic outgassing (Halevy and Head, 2014) has also been proposed as an ice-melting scenario.

Recent atmospheric modeling results (Forget et al., 2013; Wordsworth et al., 2013) demonstrate that moderate atmospheric pressures accompanied by a full water cycle produce a Late Noachian atmosphere where temperature declines with elevation following an adiabatic lapse rate, in contrast to the current situation on Mars, where temperature is almost completely determined by latitude. Lower temperatures at higher elevations encourage the movement of water from the "warmer" lowlands to the colder southern highlands, where it is sequestered in the form of regional ice sheets above an ice stability line (ISL) that occurs close to 1000 m elevation. The hydrological system is thus globally horizontally stratified (Head et al., 2003), with a global permafrost layer separating the surface from vertical integration and communication with any deeper groundwater. Furthermore, the horizontally stratified hydrologic system in the Late Noachian Icy Highlands model means that water migrates from the lowlands to the highlands, precipitates, and accumulates as snow and ice in a "one-way" direction. Once water in the lowlands is exhausted, the hydrological cycle becomes "dormant" until the system is activated by some source of melting (top-down or bottom-up), and meltwater drains to the lowlands to temporarily renew the cycle. Thus, this ice, effectively "stored" at higher elevations, might then be released by "extreme" events, such as meteorite impacts or volcanism, without the need to invoke a "steam" atmosphere. Further geological implications of this "cold and icy" scenario are explored in Head (2014) and Head and Marchant (2014) who suggest that meltwater produced seasonally during these episodes might flow naturally toward the lowlands in the areas where the geologic record requires liquid water to be present and flowing across the landscape. In this scenario, as the climate cooled again, water frozen below the ISL would sublime and return to the highlands as snowfall (Wordsworth et al., 2013; Scanlon et al., 2013). On Earth, water sources for large ice-sheet growth come primarily from oceanic evaporation, but oceans are not predicted on Mars in the LNIH model. Rather, any water or ice at low elevations is rapidly transported to the highlands and remains frozen there until a significant warming event occurs.

In this analysis, we explore the implications of glaciation predicted by the Wordsworth et al. (2013) Late Noachian Icy Highlands (LNIH) model. We analyze the nature and development of the "icy highlands" using glacial flow models and address the following questions: What is the available reservoir of surface and near-surface water? What is the areal distribution of snow and ice? What is the average ice thickness and thickness distribution? Is the ice wet-based or cold-based, and if wet based, in what locations? What are the flow rates of the ice? What are the regional patterns of ice flow (equilibrium ice sheet or local topography dominated)? What are the predictions for resulting glacial and periglacial landforms that might be recognized in the geological record? Could the glacial deposits be a source of meltwater for the observed fluvial and lacustrine features? Under what scenarios might melting of these deposits provide sufficient meltwater to account for the observed fluvial and lacustrine features?

2. Methodology

In order to address these questions, a modeling exercise is run using a Mars-adapted University of Maine Ice Sheet Model (Fastook et al., 2012). Note that all time units are reported in Earth years) with a climate defined by Wordsworth et al. (2013), (i.e., with both a latitudinal and an elevation lapse rate, warmer toward the equator and colder at higher elevations). How much water is available during the LNIH scenario? The nature and distribution of Late Noachian equilibrium Icy Highlands ice deposits are related to the total available supply of water in the Noachian, a poorly known

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