Icarus 245 (2015) 122–144

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Amazonian modification of Moreux crater: Record of recent and episodic glaciation in the Protonilus Mensae region of Mars

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ARTICLE INFO

Article history:
Received 19 December 2013
Revised 12 September 2014
Accepted 15 September 2014
Available online 22 September 2014

Keywords:
Mars
Ices
Mars, climate
Mars, atmosphere
Mars, surface

ABSTRACT

Morphologic characteristics of ice-rich landforms in the martian mid-latitudes record evidence for significant modification of the landscape in response to spin–axis/orbital parameter-driven shifts in the Late Amazonian climate. These landforms are spatially distributed across the mid-latitudes and their co-existing presence has so far not been observed from a single crater to infer how exactly a terrain has been modified while Mars was undergoing major–moderate–minor shifts in its Late Amazonian climate. We have therefore carried out an in-depth investigation of Moreux crater (~135 km, centered at 41.66°N, 44.44°E in the Protonilus Mensae region) for identification of features associated with recent and episodic glacial events and for emphasizing the role played by these glacial events in the modification of the crater. Evidence for extensive modification of the surfaces over crater rim/wall and around central peak by emplacement of multiple scales of ice-rich landforms that represents large history of glacial activities was found. From our results we document phases of major–moderate–minor glacial activities within the crater as: (1) piedmont lobes/lobate debris aprons/linear valley fills (~1 Ga–100 Ma), (2) viscous flow features (~30–0.1 Ma) and (3) gullies/thermal contraction crack polygons (~2.1–0.4 Ma). The form and distribution of the random valleys observed within Moreux suggests their formation by pressure-induced melting and flow occurring beneath an extensive layer of ice. We also suggest that central peak of Moreux probably acted as the locus for accumulation of ice/snow and the diversity of glacial/periglacial features within the crater was possibly controlled by differences in the amount of accumulated ice/snow and the rate at which the terrain responded to the shifts in climate during subsequent periods of obliquity changes. Taken together, these ice-rich deposits within Moreux suggest that sequential modification of the crater surfaces over the rim/wall and around central peak has occurred over the last tens of millions of years of martian history. This new evidence thus adds another well-documented case to rapidly accumulating evidences for widespread glacial activity in the middle latitudes of Mars in recent martian history.

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1. Introduction

There exist definite geomorphic evidences in the mid-latitudes of Mars that substantiate onset-and-completion of multiple episodes of ice-rich processes during the Late Amazonian geological history (Carr and Schaber, 1977; Squyres, 1979; Lucchitta, 1981; Squyres and Carr, 1986; Kargel and Strom, 1992; Kargel et al., 1995; Carr, 1996; Baker, 2001; Kargel, 2004; Dickson et al., 2008; Baker et al., 2010; Head et al., 2006, 2010; Hubbard et al., 2011; Sounness and Hubbard, 2012; Sinha and Murty, 2013a, 2013b; Fastook and Head, 2014). These glacial activities have likely resulted from the accumulation and compaction of snow and ice on plateaus as well as in alcoves within the plateau walls and crater slopes during periods of higher obliquity excursions (Laskar et al., 2004; Head et al., 2003; Forget et al., 2006; Milkovich et al., 2006; Fastook et al., 2011; Dickson and Head, 2009). A variety of glacial/periglacial landforms have been observed between 30° and 50° latitude of both the hemispheres, as an outcome of pertinent glacial processes during the past ~1.0 Ga–0.4 Ma (Milliken et al., 2003; Neukum et al., 2004; Arfstrom and Hartmann, 2005; Milkovich et al., 2006; Dickson and Head, 2009; Baker et al., 2010; Levy et al., 2007, 2009; Morgan et al., 2009, 2010, 2011). More than a decade of analyses of these landforms using multi-resolution images from post-Viking missions has helped to characterize the extent of glacial processes and their origin. Together, these observations have suggested thick deposits

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http://dx.doi.org/10.1016/j.icarus.2014.09.028
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of non-polar ice impounded below a surface wrap in these regions from the past hundreds of millions of years, and preserved to date (Holt et al., 2008; Plaut et al., 2009). Therefore, the studies of interrelationships between these small-large scale glacial/periglacial landforms, amount of ice/snow involved for their formation, and the extent of modification they caused have always been given preference for understanding the role they played in modifying the regional mid-latitude terrain.

Global maps of these glacial/periglacial features from the mid-latitude terrain integrated with the modeling-based predictions of possible scenario for past deposition of ice/snow have implicated the following sources for ice/snow: (1) direct condensation and compaction of seasonally deposited ice/snow (Squyres, 1978), (2) remnants from the pre-existing aquifers (Lucchitta, 1984; Carr, 2001), and (3) obliquity driven precipitation of snow from the atmosphere (Forget et al., 2006; Head et al., 2006). The atmospheric emplacement of ice/snow during the past higher obliquity excursions, which is the most favored scenario for accumulation and compaction of ice/snow, was observed to be mainly focused in individual alcoves within the plateau/crater walls or they were deposited as kilometer-thick latitudinal scale cold-based ice sheets (Dickson et al., 2009a; Fastook et al., 2011). The intermittent ablation of these exposed or accumulated packs of ice/snow via sublimation/localized melting have resulted in chronological formation of landforms that includes, (1) lobate debris aprons/linear valley fills (LDA/LVF) (~1 Ga–100 Ma) (Levy et al., 2007; Morgan et al., 2009; Baker et al., 2010), (2) concentric crater fill (CCF) (~300–60 Ma) (Levy et al., 2010), (3) viscous flow feature (VFF) (~30–0.1 Ma) (Milliken et al., 2003; Arfstrom and Hartmann, 2005), and (4) young gullies/thermal contraction crack polygon (TCP), etc. during the recent glacial epoch (~2.1–0.4 Ma) (Head et al., 2003; Levy et al., 2009; Morgan et al., 2010). The remarkable fact is that co-existing presence of all these conventional landforms has not been observed so far from a single crater-like template or a confined region in the mid-latitude. A unique combination of different types of features can lead to a holistic understanding of how exactly a terrain has formed or modified while Mars was undergoing significant shifts in its climate during the past (Kargel and Strom, 1992; Kargel, 2004). These landforms are rather scattered and largely dependent on the orientation of host surfaces, elevation of the terrain/crater on/in which they have formed, and its location in both the hemispheres (Dickson et al., 2007, 2012). As a function of latitude, they are distributed, (1) mainly at the northwestern foot of the Tharsis and Olympus Mons (<30°), (2) at the preferred pole-facing slope of craters/plateaus (30–45°), and (3) at the crater/plateau slopes of all orientations (>45°) (Milkovich et al., 2006; Head and Marchant, 2009; Dickson et al., 2012).

In mid-latitudes of both the hemispheres, Mars has already been shown to have preserved water ice in its subsurface as well as experiencing controlled (seasons and obliquity) accumulation and compaction of ice/snow during the past (Head et al., 2003; Laskar et al., 2004; Forget et al., 2006; Holt et al., 2008; Plaut et al., 2009). The modified form of impact craters in this region of Mars would definitely demonstrate the collective influence of geomorphic processes, mostly the potential role of glaciation that has contributed to their modification (Kumar et al., 2010). The exact nature of relationships between the changes in the surface morphology of craters (rim, wall, central peak and floor) and changes in the extent and style of glacial activities are still not entirely clear. Therefore, it becomes essential to demonstrate the sequential transition of martian surface while it was responding to the periodic changes in obliquity and associated accumulation, flow and ablation of ice/snow. In view of this, we have chosen Moreux crater (~135 km, centered at 41.66°N, 44.44°E) (Fig. 1) for identification of diagnostic signatures associated with specific geomorphic processes and comparing the previously observed glacial/periglacial features to what is observed for constraining the relative importance of the recent and episodic glacial processes and their contribution to the modification of the crater surfaces.

2. Geological context and objective of study

Geomorphic signatures of ice-related flow have long been recognized in the martian mid-latitudes and quoted as evidence for extensive glaciation (Carr and Schaber, 1977; Lucchitta, 1984; Kargel and Strom, 1992; Baker, 2001; Kargel, 2004; Head et al., 2006; Levy et al., 2007; Dickson et al., 2008; Baker et al., 2010; Sinha and Murty, 2013b). Moreux crater is among one of the largest craters in the Deuteronilus–Protonilus–Nilosyrtis Mensae fretted terrain zone, where presence of subsurface ice and atmospheric accumulation of ice/snow have already been reported (Plaut et al., 2009). The dichotomy boundary that divides the planet into two unequal halves is one of the most important geological and geophysical constructs of ancient Mars (Wilhelms and Squyres, 1984; McGill and Squyres, 1991; Sleep, 1994; Citron and Zhong, 2012). Moreux crater has significantly modified this boundary as more than half of its portion from south was superimposed on the regional scarp. Perhaps the southern portion of Moreux rim in fact represents the dichotomy at that place (Fig. 1) and subsequently the majority of pre-existing mesas that characterizes the dichotomy boundary along this region have been densely obliterated (Marchant et al., 2006). Only the western-most rim of Moreux represents its actual rim in terms of its elevation at the time of formation, as from other three (N–S–E) sides it has unequal shape and elevations due to impact over a pre-existing undulated topography. The western rim that has maximum slope while trending from top–bottom is elevated at height of ~3 km from the floor of crater, whereas the other parts of the rim and floor are relatively undulated and are elevated at unequal heights from floor to rim (Fig. 2a and b). Along the southern portion of crater floor, near to its rim, there exists a large heap of deposited materials sourced from the glacial valley at the head of rim. From all the other portions, several flow features that certainly bear a resemblance to flow of ice/snow rich materials in the form of channels and lobe-like impression are scattered over the surface at the proximity of rim/wall. Otherwise, the crater floor is relatively less altered from the portions between the rim and central peak. At the central peak, the flanks and their margin are mostly surrounded by long and large lobate flows that appear to originate from the varying size alcoves at the top of central peak. The ~3 km tall original central peak and the proximal surface have undergone heavy modification, leaving behind cluster of multiple small-elevated mountains on which glacial flows have draped, folded and merged into larger lobes at flanks (Fig. 3). Overall, glacial folding/flow, channelized flows from top of rim, incision of floor and rim by valleys, and flow of ice-rich debris from adjacent plateaus in the region appear as the prime causes that have contributed in modification of the crater surfaces over rim/wall and around central peak.

In this paper, we primarily aim to address the processes and extent of crater modification by the analysis of geomorphic signatures extracted from rim, wall, floor, and central peak of crater for demonstrating the periodic changes (recent and episodic) in glacial/periglacial activities from past ~1 Ga–0.4 Ma (Fig. 4). A geomorphic map was prepared based on identification of landforms associated with ice-rich processes, which are then analyzed with MOLA topography to assess their downslope flow characteristics and stratigraphic relationships. This has enabled us to assess the evidence for multiple shifts in martian climate that led to induce variation for ice/snow accumulated during this period and their

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